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Behavioral Patterns of Individuals and Groups during Co-located Collaboration on Large, High-Resolution Displays

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Abstract

Large display environments such as high-resolution, tiled display walls are highly suitable for different types of collaborative work, including remote and partially distributed, but in particular, also co-located collaboration. Systems often implement a whiteboard metaphor with novel interaction techniques and devices to resemble collaboration principles that have been known to be effective over decades. However, putting multiple users in such environments results in intricate behavioral patterns and group dynamics that – if not handled correctly – might negatively affect the overall groups' efficiency.

To unfold the real potential of large, high-resolution displays in the context of co-located collaborative work, adequate instruments in the form of groupware must be provided. For that, however, the specifics of groups' work expressed through such phenomena as collaborative coupling, territoriality, and workspace awareness must be investigated. Although there are many works that address this issue, there are still many open questions. Especially, group behavior in the context of co-located work with fixed-position data on ultra-large vertical displays was barely investigated.

To gain a deeper understanding of co-located collaboration on vertical, large high-resolution displays, this dissertation builds on previous research in this domain and gains new insights through new observational studies. The gathered results reveal new patterns of collaborative coupling, indicate that territorial behavior is less critical as was shown in previous research, and show that workspace awareness might also negatively affect the effectiveness of individual users.

Moreover, the investigation process led to the development of two software artifacts. One of them makes use of widespread and well known in the research community Unity game engine and allows to implement rapidly new applications for any type of large, high-resolution displays or to adopt the already existing desktop application. Another provides a software infrastructure for groupware implementation that can be used for any type of creative tasks.

Kurzfassung

Große hochauflösende, gekachelte Display-Wände eignen sich sehr gut für verschiedene Arten der kollaborativen Arbeit, einschließlich der entfernten und partiell verteilten, aber vor allem auch der co-located Zusammenarbeit. Die Systeme implementieren oft eine Whiteboard-Metapher mit neuartigen Interaktionstechniken und Geräten, um den seit Jahrzehnten als effektiv bekannten Prinzipien der Zusammenarbeit zu gleichen. Wenn jedoch mehrere Benutzer in solchen Umgebungen arbeiten, ergeben sich komplizierte Verhaltensmuster und Gruppendynamiken, die - wenn sie nicht richtig gehandhabt werden - die Effizienz der gesamten Gruppe negativ beeinflussen können.

Um das tatsächliche Potenzial großer, hochauflösender Displays im Kontext von co-located kollaborativer Arbeit zu entfalten, müssen adäquate Instrumente in Form von Groupware bereitgestellt werden. Dazu müssen jedoch die Besonderheiten der Gruppenarbeit, die sich in Phänomenen wie kollaborativer Kopplung, Territorialität und Workspace Awareness ausdrücken, untersucht werden. Obwohl es bereits einige Arbeiten gibt, die sich mit diesem Thema befassen, gibt es noch viele offene Fragen. Insbesondere wurde das Gruppenverhalten im Kontext von co-located Zusammenarbeit mit fest positionierten Daten auf ultragroßen vertikalen Displays kaum untersucht.

Um ein tieferes Verständnis der co-located Zusammenarbeit auf vertikalen, großen, hoch-auflösenden Displays zu erlangen, baut diese Dissertation auf früheren Forschungen in diesem Bereich auf und gewinnt neue Erkenntnisse durch neue Beobachtungsstudien. Die gesammelten Ergebnisse offenbaren neue Muster der kollaborativen Kopplung, deuten darauf hin, dass territoriales Verhalten weniger kritisch ist, als in früheren Forschungen gezeigt wurde, und zeigen, dass Workspace Awareness auch die Effektivität der einzelnen Benutzer negativ beeinflussen kann.

Außerdem führte der Untersuchungsprozess zur Entwicklung von zwei Software-Artefakten. Eines davon nutzt die weit verbreitete und in der Forschungsgemeinschaft bekannte Unity Spiele-Engine und ermöglicht es, schnell neue Anwendungen für jede Art von großen, hochauflösenden Displays zu implementieren oder die bereits vorhandene Desktop-Anwend-ung zu adaptieren. Das andere bietet eine Software-Infrastruktur für die Groupware-Implementierung, die für jede Art von kreativen Aufgaben verwendet werden kann.

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List of Abbreveations

- CSCW - computer-supported cooperative work
- DR - different roles
- ER - equal roles
- HCI - human-computer interaction
- LED - light-emitting diode
- LHRD - large, high-resolution display
- LOP cursor - level of precision cursor
- PCE - prior collaboration experience
- USE - usefulness, satisfaction, and ease of use
- UTAUT - unified theory of acceptance and use of technology

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Chapter 1

Introduction

The introduction chapter presents the motivation for using vertical, large, high-resolution displays (LHRDs) for co-located collaboration. The chapter describes LHRD groupware's problem, identifies the knowledge gap, introduces the research objective, and provides an overview of the thesis activities and contributions. Finally, it outlines the thesis's organization and briefly describes each chapter.

1.1 Research Motivation

For many years, whiteboards have provided a comfortable environment for different collaboration tasks such as brainstorming, sensemaking, design, and layout. However, such collaboration was limited in multiple aspects due to its analog nature. For instance, the whiteboards' dimensions were relatively small so that the user could reach all areas. To move a drawn asset on the whiteboard, the user must remove it and recreate it at another spot. The simultaneous activities of multiple users in a mutual area were problematic due to occlusions, input constraints, and reachability issues.

Researchers have become able to engineer digital, whiteboard-like environments through technological advances in digital computing and visual displays. Elrod et al. [29] introduced one of the first concepts of a digital whiteboard called Liveboard in 1992. Over time many other researchers introduced their visions of the concept. Early prototypes of digital whiteboards suffer from multiple issues such as low-resolution, small size, immature interaction, and visualization techniques. Many of these issues researchers could solve with time. Nowadays, there are ultra-large wall-sized displays that provide a vast number of pixels for detailed visualization. Different interaction devices and techniques allow interaction with such displays from arbitrary distances.

Research of large, high-resolution displays in the domains of computer-supported collaborative work and human-machine interaction revealed that such display systems often outperform systems with standard desktop displays in terms of user efficiency and effectiveness. The study from [18] indicates that users generally prefer LHRDs to standard screens. Other researchers [161, 84] observed an increase in the precision and efficiency of users during the performance of information analysis tasks, as well as a reduction in frustration with search and navigation tasks [124]. Additionally, LHRDs allow virtual navigation replacement by the more efficient and less mentally demanding physical navigation. This navigation type allows a faster acquisition or creation of spatial relationships between individual virtual objects. It supports the user's sense of orientation, thus reflecting in more intelligent navigation decisions [9]. Gutwin et al. [38] argued that in comparison to systems with standard desktop displays, LHRDs are capable of improving co-located collaboration. For instance, LHRDs increase communication's richness, fostering perceptual and physical abilities. Additionally, LHRDs allow for observation of the entire workspace (physical and digital), thus exposing subtle contextual cues useful for effective communication.

While outperforming standard desktop displays in multiple areas and becoming more affordable and powerful through rapid hardware improvements, LHRDs exposed aspects regarding a co-located collaboration that require in-depth investigation with subsequent optimization of user interfaces to unfold the full potential of these displays. For instance, co-located collaboration often exposes intensive group dynamics. Among others, team members might frequently switch between individual and shared tasks (mixed-focus collaboration) [39] in many different ways (collaborative coupling) [136]. Moreover, they can partition, and re-partition display's real estate (territoriality) [119], repeatedly adjust their strategies, or become distracted. Thus, there is a need for understanding these socio-physiological phenomena to design adequate groupware that fosters co-located collaborative processes.

1.2 Research Context

This research explores the intra-group behavior of small groups (e.g., two users) and individuals' behavior during co-located collaboration processes on vertical LHRDs. In general, the research belongs to the human-computer interaction (HCI) domain, which investigates interfaces humans use to interact with computer systems. More specifically, this research lies within the intersection of the following domains:

- computer-supported cooperative work (CSCW) – investigates ways to support collaborative activities employing computer systems such as shared desktop computers, tabletops, and digital whiteboards.
- co-located groupware – investigates collaborative processes to acquire user needs in functionality, visualization, and interaction design.
- large, high-resolution display – investigates the effects of LHRDs characteristics (e.g., size, bezels, orientation) on users.

The research encompasses multiple studies. These studies' tasks emerged from two application domains: sensemaking and creative design. These domains cover three of four collaborative activities listed by McGrath [94]: planning, creative, intellective, and contest. The research did not consider the contest task since it rarely appears in real-world applications. The sensemaking task facilitated the investigation of planning and intellective activities. Sensemaking is a mentally demanding process that appears in many tasks, e.g., analytical [2, 16] or incident and disaster management tasks [150]. In general, the sensemaking process consists of two major loops of activities [93]: an information foraging loop [92] and a sensemaking loop [105]. The information foraging loop includes seeking, filtering, reading, and extracting information. During this loop, the user works with small information portions to learn about individual data items. The sensemaking loop includes activities such as connecting facts and building representations. During this loop, the user has to work with the entire data and overview it. Thus, different loops require different visualization and interaction modalities, leading to different task conditions.

While working in groups, sensemaking becomes an even more complicated process. Social phenomena like collaborative coupling and territoriality emerge and accompany the entire process. For effective and efficient collaboration, appropriate environments are of significant importance. Here comes LHRDs into play. Marai et al. [74] mentioned the following advantages of LHRDs in the sensemaking context:

- large display size and pixel density to show multiple representations simultaneously
- ability to show context plus detail
- enough space for group work

Thus, LHRDs provide a more practical setting for co-located computer-supported collaboration than conventional desktop computer systems.

Moreover, LHRDs allow users to establish correspondences between their spatial position and orientation and data elements on display (e.g., "I will see the document if I turn my head to the left"). As a result, users can use virtual and physical landmarks for object finding (e.g., "The document is next to the chair" or "The document is further to the right from this one"). Hence, more useful and intuitive physical navigation can replace virtual-navigation [9]. Many researchers consider it pertinent to study the sensemaking process at LHRDs due to the many advantages of these displays.

Collaborative sensemaking allows for looking at the problem from different perspectives and can profit from shared engagement and more qualitative communication that provides subtle physical cues [157]. Moreover, researchers demonstrated the effectiveness of collaborative sensemaking in the context of real-world examples. For instance, exploration of ice-covered Lake Bonney [74], analysis of large-scale cosmological simulation data [46], intelligence analysis [146].

Another application domain that appears in the studies is creative design. This domain often contains creative and planning activities. The creative process was investigated on LHRDs to a limited extent only. For instance, Azad et al. [5] conducted a controlled experiment where the participants had to solve jigsaw puzzles in non-collaborative and highly-collaborative configurations. They looked into on-display behavior, off-display behavior, and combined behavior. Jakobsen et al. [55] conducted a study on an LHRD comparing touch input to mouse input. The study consisted of two tasks: the newspaper task and the puzzle task. In both tasks, participants had to layout either puzzle pieces or articles. Liu et al. [68] executed a study where the participants had to find similarities or connections between the pictures and arrange them in a meaningful way. Ryall et al. [107] let the participants assemble target poems using word tiles.

The tasks used in the previous research set constraints that did not allow to unfold creativity. They allowed only to layout assets but not create them. Additionally, in the jigsaw and text composition cases, the outcomes were more or less predefined. Moreover, researchers investigated the creative process mostly on tabletops. On the vertical displays, the analytical process was more in focus, e.g., [2], [147], [154].

The investigation of the collaboration process in creative design took place using special groupware. The groupware allows for creating 2D game levels on LHRDs using tablet-PCs for interaction. The groupware allows not only to place/layout assets but also to create them. Previous studies [108, 71, 148, 75] show that gaming on LHRDs not only possible but also well accepted by players. Thus, it represents a potential new development branch for computer games. The prototyping process of game levels for LHRDs on standard desktop displays might be tedious because of the small workspace.

Therefore, it can be advantageous to develop LHRD groupware that will allow for level prototyping directly on LHRDs.

1.3 Problem Statement

As mentioned in the first section of this chapter, the study of collaborative processes on LHRDs has revealed socio-physiological aspects that did not appear (or were insignificant) in systems with standard desktop displays. These aspects caused by the human factor represent a more profound challenge for groupware designers than typical technical problems. The questions arose: *Is focusing on ergonomics only while developing tools for interaction with the system still enough? Can we rely on social protocols as a tool for the regulation of intra-group interaction? Or do we need coordination strategies, frameworks, and mechanics to support the collaboration process?* A deeper understanding of the socio-physiological aspects is required to answer these questions. What are these aspects, however? They are collaborative coupling, territorial behavior, workspace awareness, and physical navigation.

Collaborative coupling indicates the intensity of user-user interaction for task accomplishment. Researchers usually define two ranges: tightly, and loosely-coupled [39, 80, 118, 143]. Within these, the intensity level may vary depending on a coupling style. Initially, tightly-coupled work describes work that could barely occur without user-user interaction, while loosely coupled work describes a workflow where users act independently [39, 42, 111]. The concept of user roles also belongs to collaborative coupling. Previous research detected that during collaboration on LHRDs, users occasionally undertake different roles to approach the task more efficiently [147, 101]. As a result, researchers suggested considering user roles when building groupware and providing groupware mechanisms to support them.

Human territoriality is a social phenomenon that influences interaction and communication processes during computer-supported cooperative work (CSCW). Sack has defined human territoriality as *"... the attempt to affect, influence or control actions and interactions (of people, things, and relationships) by asserting and attempting to enforce control over a geographic area"* [109]. Territories can vary in scale [110, 138] (e.g., from seats to cities) and can be controlled or claimed either by a single individual or by a group of persons (territory sharing) [110].

Gutwin and Greenberg first defined workspace awareness in 1996 [38]. They defined it as an ability to "...maintain awareness of others' locations, activities, and intentions relative to the task and space...". The effects of workspace awareness were the focus of studies in shared computational workspaces [40]. The results showed that collaborators performed better if the system provided a better workspace awareness. Additionally, researchers investigated workspace awareness in mixed-focus collaborative situations [39]. The authors argued that while workspace awareness increases a team's efficiency, it will likely decrease individuals' efficiency during loosely coupled work stages.

Physical navigation is a concept that describes a process of data inspection employing body, head, and eye movements. During physical navigation, the data remains in place on display while the user moves himself to bring regions that contain data into her visual field of view. A counterpart of physical-navigation is virtual navigation. During virtual navigation, the user remains in place, giving commands that move data on display to the system.

These complex socio-physiological phenomena were investigated primarily in the context of tightly-coupled collaboration. Collaborative processes, however, consist not only of tightly coupled shared activities. Various studies have investigated user behavior during collaborative work in single display environments, partly looking into the specific underlying processes and stages [39, 49, 66, 119, 147]. These studies have shown that collaboration processes consist of multiple work phases: loosely-coupled (individual) work and tightly-coupled (shared) work.

While tightly-coupled work targets an effective combination of gained knowledge into a solution, loosely-coupled work demonstrates the processing of multiple tasks in parallel. For instance, users can split datasets to process only a part of the data, a typical approach to process input data more effectively. Such collaboration processes where users alternate between tightly-coupled and loosely-coupled work are called mixed-focus. Mixed-focus collaboration is typical for different collaborative tasks, e.g., sensemaking, construction, design, planning.

Loosely-coupled and tightly-coupled work are of entirely different natures. In the case of tightly coupled work, users expose different intricate, collaborative coupling patterns that must be considered and reflected in the interface design so that these patterns could be supported or reshaped. In loosely-coupled work, the patterns are less intricate, yet territorial behavior might become more critical. Moreover, through extended workspace awareness, the risk of interferences might increase. In the context of CSCW, interference indicates an unexpected user's act that unintentionally causes distraction and discomfort (mental or physical) to collaborators [80, 91, 162], e.g., the user blocked the view for another user or took an item of the other user. Increased interference can cause mental discomfort, and the team's decreased efficiency.

To ensure efficient and effective collaboration, groupware engineers must understand and consider both phases of mixed-focus collaboration in terms of socio-physiological phenomena and provide suitable user interfaces that support and foster teamwork. Therefore, this thesis aims to broaden the knowledge about socio-physiological phenomena during mixed-focus, co-located collaboration on vertical LHRDs.

Additionally, the research focuses on fixed-position spatial data since previous research investigated it scarcely. Spatial data – data where the position of individual data elements and their shape and size have a meaning – is a part of many group activities, like network analysis, route creation, interior/exterior design, and disaster planning. Typical data examples within the mentioned application scenarios are city maps, floor plans, and weather data [136]. Due to the vast number of pixels, LHRDs can often visualize the entire spatial data. Thus, data can maintain a fixed display location. In co-located collaboration, fixed-position data allows maintaining a mutual context for all users, thus ensuring the natural transition from loosely to tightly coupled work.

1.4 Research Objective and Thesis Statements

This research discusses and investigates the socio-physiological aspects in the given context to support groupware engineers in creating effective and efficient interfaces for co-located collaboration on vertical LHRDs. For that, this research aims to deepen the understanding of intra-group behavioral patterns that fall into the categories of collaborative coupling, territorial behavior, workspace awareness, and physical navigation. While filling the knowledge gap in that area, the thesis pursues an understanding of how critical individual phenomena are for maintaining unimpeded collaboration processes. The research findings should provide developers guidelines and enhance the groupware design through a more profound consideration of socio-physiological aspects.

The following main goal states the research objective:

To provide more profound understanding of co-located collaboration processes on vertical LHRDs during work with fixed-position data through investigation of socio-physiological phenomena reflecting in behavioral patterns of users/groups.

Defining the bounds of the research, the following hypotheses that cover different socio-physiological phenomena emerged:

Collaborative Coupling

H1: Collaborative coupling behavior during focus phases of work will differ from collaborative coupling behavior during overview phases of work

H2: During creative tasks, participants will expose more tightly-coupled work in comparison to analytical tasks

H3: Transitions between loosely-coupled and tightly-coupled work contain distinct cues that allow their detection

Territoriality

H4: Territoriality will play a significant role during work with fixed-position data in analytical and creative tasks

H5: Territoriality will not take place during overview phases of work

Workspace Awareness

H6: Visual events in peripheral vision might affect the performance of individual users

H7: Visual events in peripheral vision will not affect low mental load tasks

Physical Navigation

H8: Physical navigation during focus phases of work will differ from physical navigation during overview phases of work

1.5 Thesis Activities

The research conducted within the scope of the thesis encompassed numerous activities. The results of these activities became a part of the thesis. The list below provides an overview of the activities:

1. Studying theories and concepts of human factors
2. Studying theories and concepts of empirical research and experiment design
3. Compiling a survey of research on approaches for interaction with LHRDs.
4. Compiling a survey of research on the socio-physiological behavior of groups during collaboration on LHRDs and Tabletops
5. Identifying challenges for experimental research in the context of LHRDs
6. Selecting methods for the execution of experimental research
7. Implementing and evaluating a tool for the rapid implementation of experiment applications
8. Implementing and evaluating a groupware prototype for creative tasks
9. Designing and coordinating a group-based study with an analytical task
10. Designing and coordinating a group-based study with a creative task

11. Designing and coordinating two controlled experiments for the investigation of workspace awareness effects
12. Evaluating study results

1.6 Ethics

According to Germany's law, it was not obligatory to approve experiment designs by an ethics committee at the time of writing this thesis. However, all participants had access to detailed information about the experiments' procedures before registering for experiments. Additionally, prior to the experiment, all participants read detailed information about the procedure of the experiment and signed a written consent form confirming their desire to participate in the experiment. Moreover, the participants received instruction saying that they could abort the experiment at any time if they felt uncomfortable or because of any other reason. The experiments were designed not to cause any health problems or impairments. The gathered data was immediately anonymized and stored safely.

1.7 Apparatus

For all experiments, we used the same apparatus. Thus, this section provides the apparatus's description to avoid repetitions by experiments' descriptions.

The study utilized a large, curved tiled-display (henceforth display) comprising 35 LCDs (henceforth display units) ordered through a seven (column) by five (row) grid. Each of the columns has a relative angle difference of 10 degrees along the Y-axis to adjacent columns, as such, creating a slight curvature (Figure 1.1). Each display unit has a bezel of fewer than three millimeters, minimizing the visual rim effect. The display units are 46" panels with a 1080p resolution, resulting in 72 megapixels. Please note, the display in question is a rigid installation. Therefore it could not be changed without tremendous effort. Although the display's curvature might influence user awareness at such display dimensions and considering the experiments' tasks, the effect will be like one on a flat display of the same size. For instance, staying together, users will perceive as much information regarding partner's activities as with a flat display, while staying at the sides of the display, users will not be able to perceive partner's activities.

An array of seven infrared cameras (ARTTrack, Figure 1.1) was used to track users' heads through head-worn helmets within an area of around 20 square meters directly in front of the display. For interaction purposes, two smartphones with similar per-

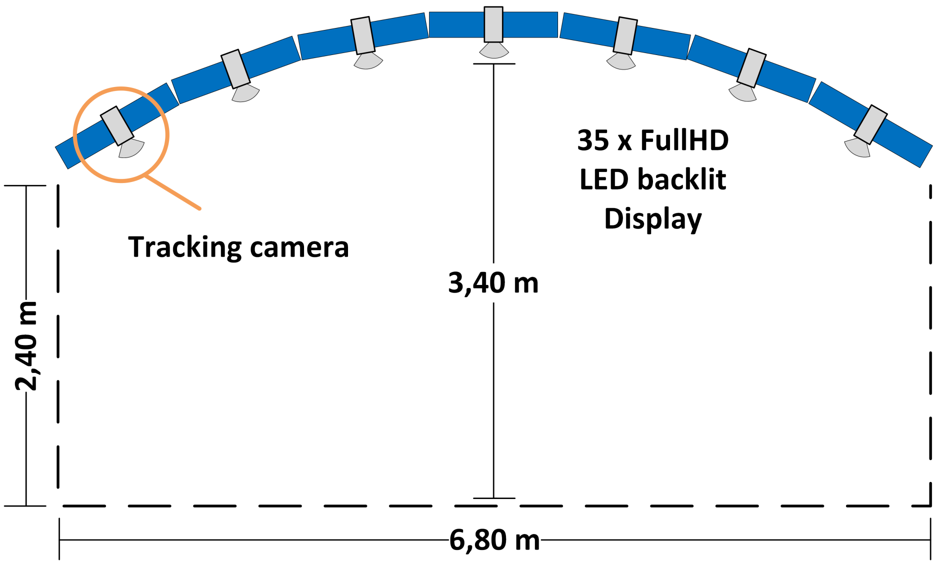

Figure 1.1: Apparatus (top view): a curved display built of 35 Full HD displays with seven tracking cameras on it that allow for tracking in front of the display within an area of around 20 square meters.

formance characteristics were utilized. The smartphones ran an application to control pointer properties and position on the display. The application captured swipe and tap gestures and conveyed that data to the main application that used the data in different ways depending on its internal state. Though the smartphone's latency was not measured, the system allowed for smooth and highly responsive interaction with the wall display content.

1.8 Contributions

The thesis contributes new ideas, insights, and software artifacts to the domains of HCI and CSCW in computer science. There are five significant contributions from this research:

1. The thesis identifies important users' and groups' behavior during mixed-focus collaborative work with fixed-positioned data in LHRD environments. Moreover, the research in this thesis encompasses analytical tasks and creative tasks. Previous research on co-located collaboration on LHRDs focused mainly on non-fixed-positioned data. It did not isolate the individual stages of the mixed-focus collaboration, thus not providing as deep insights as those presented here.

2. The thesis identifies important behavioral patterns of groups in the context of collaborative coupling and territoriality. It reveals insights not mentioned in the previous research, such as new territory area or new collaborative coupling style.

Moreover, it also provides an extended classification of transitions between loosely and tightly coupled phases. Moreover, it investigates the possibility of affecting group coupling employing fixed user roles.

3. The thesis identifies the effects of extended workspace awareness. It detects that extended workspace awareness can positively impact users during creative tasks, providing users with new ideas, and inspiring them. However, it also detects that extended workspace awareness can negatively impact the user during tasks with a high mental load.

4. The thesis provides a set of design recommendations based on the results of studies and experiments. These recommendations can improve future groupware for co-located collaboration on vertical LHRDs since they consider ergonomics and social aspects.

5. Finally, the thesis provides two software artifacts that allow for the rapid implementation of experiments and studies. That is a significant contribution since the development of LHRD applications is still an issue that significantly curbs the research.

1.9 List of Publications

The list below contains an overview of peer-reviewed publications (poster, conference paper, journal article) that emerged from the thesis's activities. The first author presented all conference publications. Chapters of the thesis that incorporate parts of the publications will contain a corresponding note.

Sigitov, A., Kruijff, E., Trepkowski, C., Staadt, O., Hinkenjann, A. (2016). The Effect of Visual Distractors in Peripheral Vision on User Performance in Large Display Wall Systems. In Proceedings of the 2016 ACM on Interactive Surfaces and Spaces - ISS '16 (pp. 241–249). New York, New York, USA: ACM Press.
https://doi.org/10.1145/2992154.2992165

Sigitov, A., Staadt, O., Hinkenjann, A. (2016). Distributed unity applications evaluation of approaches. In C. Stephanidis (Ed.), Communications in Computer and Information Science (Vol. 617, pp. 138–143). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-40548-$3_2$3

Sigitov, A., Scherfgen, D., Hinkenjann, A., Staadt, O. (2015). Adopting a Game Engine for Large, High-Resolution Displays. Procedia Computer Science, 75, 257–266. https://doi.org/10.1016/j.procs.2015.12.246

Sigitov, A., Staadt, O., Hinkenjann, A., Kruijff, E. (2018). Column Major Pattern: How Users Process Spatially Fixed Items on Large, Tiled Displays. In Proceedings of the 2018 Conference on Human Information InteractionRetrieval - CHIIR '18 (pp. 305–308). New York, New York, USA: ACM Press.
https://doi.org/10.1145/3176349.3176870

Sigitov, A., Hinkenjann, A., Kruijff, E., Staadt, O. (2019). Task Dependent Group Coupling and Territorial Behavior on Large Tiled Displays. Frontiers in Robotics and AI, 6. https://doi.org/10.3389/frobt.2019.00128

Sigitov, A., Staadt, O., Hinkenjann, A. (2018). Towards Intelligent Interfaces for Mixed-Focus Collaboration. In Adjunct Publication of the 26th Conference on User Modeling, Adaptation and Personalization - UMAP '18 (pp. 287–292). New York, New York, USA: ACM Press. https://doi.org/10.1145/3213586.3225239

Sigitov, A. (2016). Effects of Workspace Awareness and Territoriality in Environments with Large, Shared Displays. In Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces (ISS Companion '16) (pp. 1–6). ACM Press.
https://doi.org/10.1145/3009939.3009940

Sigitov, A., Hinkenjann, A., Staadt, O. (2020). Effect of User Roles on the Process of Collaborative 2D Level Design on Large, High-resolution Displays. In Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications (pp. 118–129). SCITEPRESS - Science and Technology Publications. https://doi.org/10.5220/0008933801180129

1.10 Outline of the Thesis

This section provides an overview and a short description of the remaining thesis's chapters.

Chapter 2 looks at related work in the domain of vertical and horizontal (tabletops) large, high-resolution displays. The review covers multiple domain-aspects incorporating findings from the computer-supported collaboration and human-computer interaction research literature. Specifically, the chapter focuses on the socio-physiological phenomena that emerge during the co-located collaboration on LHRDs. These phenomena are also known as territoriality, collaborative coupling, workspace awareness, and physical navigation.

Chapter 3 describes an extensive study that incorporated two tasks: a task that resembles the information foraging loop and a task that resembles the connecting facts activity. Both tasks represent essential sub-processes of the sensemaking process in visual analytics and cause distinct space/display usage conditions. The information foraging activity requires the user to work with individual data elements to investigate details. Here, the users predominantly occupy only a small portion of the display. In contrast, the connecting facts activity requires the user to work with the entire information space. Therefore, the user must overview the entire display. The study results provide new insights into multiple aspects of co-located collaboration on vertical LHRDs.

Chapter 4 describes a study in the context of a creative task. Like the study in Chapter 3, this study investigated the group behavior in the context of socio-physiological phenomena. Additionally, the study investigated the effect of different interface types on the collaboration process.

Chapter 5 describes two controlled experiments investigating the effects of workspace awareness. In particular, the experiments investigated the impact of visual distractors (which, for instance, might be caused by other collaborators' input) in a peripheral vision on short-term memory and attention. The distractors frequently occur when multiple users collaborate in large wall display systems and may draw attention away from the primary task, potentially affecting performance and cognitive load. However, the effect of these distractors is hardly understood. Thus, gaining a better understanding may provide valuable input for designing more effective user interfaces. The experiments revealed that depending on when and where the distractor becomes visible in the task performance sequence, user performance can be disturbed.

Chapter 6 describes a rapid prototyping tool and groupware for creative tasks developed within the thesis's scope. The rapid prototyping tool allows – with a small overhead – to implement applications that are apt to run on both single-display and multi-display systems. It takes care of the most common issues of distributed rendering like frame, camera, and animation synchronization. In conjunction with Unity, which significantly simplifies creating different kinds of virtual environments, the extension affords to build mock-up virtual reality applications for large, high-resolution displays and implement and evaluate new interaction techniques and metaphors and visualization concepts. Using the rapid prototyping tool, groupware for creative tasks was developed to support and investigate the 2D level design process on LHRDs using tablet-PCs for interaction. It allows not only to place/layout assets but also to create them. Additionally, the chapter provides evaluation insights regarding performance and a report regarding the user acceptance of the groupware.

Chapter 7 concludes the thesis. It summarizes the studies and experiments' findings and the contributions presented throughout the chapters. Moreover, it discusses possible future research directions that might provide further insights into the topic.

Appendices provide additional material. They contain surveys and tasks used during the studies and experiments.

Chapter 2

Related work

This chapter provides a survey of selected works previously done in the area of large, high-resolution displays. It focuses explicitly on the socio-physiological phenomena that occur during co-located collaborative work. First, the chapter provides information regarding LHRDs, their properties, interaction possibilities, and the effects these displays have on users and users' work. Next, it renders a review of collaborative coupling research and discusses different facets of this phenomenon. Afterward, it gives an overview of the concept of territoriality. Finally, it describes the concept of workspace awareness and provides an overview of works in this field.

2.1 Large, high-resolution Displays

LHRDs differ from mainstream desktop displays in two aspects: physical size and resolution. They can be defined as a combined visual output perceived as a single, continuous visual space, which provides significantly more pixels and is distinctly larger by comparison with a regular display. LHRDs are usually built from an array of projectors, an array of LCD-Displays (e.g., see Figure 2.2), or an array of LEDs. All three technologies have their advantages and disadvantages. For example, an LCD-based display's solitary tiles are disjoint because of bezels. As a result, the display provides a discontinuous or distorted image output. Projector-based displays have to struggle with a color and brightness inconsistency and permanent changing alignment, which requires complex and frequent calibration. LED displays do not suffer from those problems; however, they are currently costly.

Although the construction and management of LHRDs involve much effort, these displays became interesting for the research community because of their impact on users' behavior. Indeed, due to inherent LHRDs' properties, users can shape their work pro-

Figure 2.1: LHRD at the University of Rostock

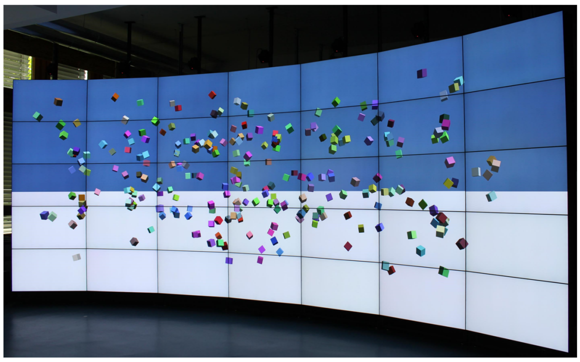

Figure 2.2: Hornet: LHRD at the Bonn-Rhein-Sieg University of Applied Sciences

cesses utterly different compared to regular desktop displays. This section provides a brief overview of related work that studied the effects of large, tiled displays on users' effectiveness, efficiency, and behavior. Moreover, the section includes an overview of interaction possibilities with vertical LHRDs and an overview of challenges related to co-located collaborative work on LHRDs.

2.1.1 Effects of LHRDs' Properties on Users' Work

Andrews et al. [3] lists the main properties of LHRDs: size, pixel density, resolution, brightness, contrast, viewing angle, bezels, display technology, and form factor. These properties are also applicable to regular desktop displays. In the case of LHRDs, they vary stronger and might significantly impact users' behavior. This section provides a brief overview of related work that investigated the effects of size and resolution, bezels, and form factor of LHRDs on users' behavior and perception. Other properties were either barely investigated or yielded results that do not fit this research's scope.

Size and Resolution.

Tan et al. [134] executed a study intending to quantify the benefits of large display sizes for individual users. They compared a large display with a regular desktop monitor in terms of user performance. In doing so, they held the visual angle constant and adjusted only the distance between participants and the displays. The study revealed that the participants performed better on a spatial orientation task while working on a large display. Moreover, they could detect that the large display provides a better sense of presence.

Subsequently, Tan et al. [135] conducted additional studies to investigate the detected effect in more complex tasks like 3D navigation and mental map formation. The later experiments' outcomes confirmed the observed positive effect of large display sizes. The results revealed that large displays enable users to adopt an egocentric frame of reference during navigation. That, in turn, led to better map formation and better results during the memory task.

Ni et al. [84] investigated the effects of the individual and combined effects of display size and resolution in the context of an Information-Rich Virtual Environment. In a controlled experiment, they isolated display size and resolution as independent variables and observed these variables' effects during navigation, search, and comparison tasks. The study revealed that users were most effective at performing tasks on LHRDs. Moreover, they found that LHRDs facilitate mental map construction, making users less dependent on wayfinding aids.

Ball et al. [9] investigated a correlation between display size and physical navigation, and user task performance. They measured performance time for the four tasks: navigation, search, pattern finding, and open-ended insight for a group of targets. As a result, the study revealed that increased display size caused an increase in physical navigation and a decrease in virtual navigation. Moreover, they found that users performed faster while working on LHRDs.

Bi et al. [19] conducted a week-long diary study in a realistic context comparing users' behavior and performance on an LHRD and more common desktop display setups. The study revealed that users preferred the LHRD to other displays because it offered a more immersive experience and reduced window interleaving operations while working with multiple windows.

Andrews et al. [2] compared how users conduct a sensemaking task in front of an LHRD and a standard desktop display. They observed that users made extensive use of space to manage documents and applications. The study revealed that LHRDs could facilitate activities typically done with physical artifacts. As a result, the users became able to use the virtual space as a form of rapid access to external memory. Moreover, arranging multiple documents on large virtual desktop users created semantic layer encoding relationships between data, documents, display, and analyst.

Liu et al. [69] investigated what effects display size and navigation type have on a classification task. They compared physical navigation in front of a large display with virtual navigation on a standard desktop display. The study revealed that desktop displays are more suitable for straightforward tasks, while large, high-resolution displays are significantly more efficient for demanding tasks.

Reda et al. [98] explored the effect of LHRDs' size and resolution on knowledge discovery during visual analysis. They conducted a small-scale open-end study in the context of criminal activity analysis. The study had a between-subjects design with a single independent variable, namely, display size. During the study, the researchers measured the quantity and breadth of produced insights by analyzing participants' verbal statements. The study revealed a strong correlation between display size and resolution and the number of discoveries. The participants, who worked on the LHRD, produced on average 74 percent more observations compared to the participants who worked on a standard desktop display.

Like Ball et al. [9], Ruddle et al. [104] investigated the effect of display size and resolution on search activity. They compared three display sizes. The displays' total resolution ranged from 2 million pixels to 54 million pixels. As a result, they found that participants who worked on the LHRD with 54 million pixels were 30 percent faster than other participants. They ascribed that positive effect to physical navigation and the fact that the entire dataset could fit onto the LHRD.

Bezels.

Ball and North [8] observed and analyzed users' actions in front of a high-resolution tiled display. They detected that most users have found bezels inconvenient and irritating. However, users tended to use bezels to partition the display into regions with specific semantics and dedicated them to particular applications.

Bi et al. [17] investigated the effects of tiled display interior bezels on user performance and behavior by visual search, straight-tunnel steering, and target selection tasks. Three types of large displays were simulated and compared with each other: 1x1 - display with no interior tiles; 2x2 - large, tiled display consisting of four 40" display units; 3x3 - large, tiled display consisting of nine 26" display units. They found that interior bezels did not impact visual search and target selection performance. Both tasks utilized fixed-position items. On the other hand, interior bezels hindered straight-tunnel steering performance and affected steering behavior. Moreover, they observed that users tend to apply a grid-by-grid search strategy, as an entire surface was divided into grids.

Gruninger et al. [37] conducted a large-scale study to explore how bezels on LHRDs might affect users' stereo perception. To evaluate the study results, they developed a set of surveys focusing on stereo perception, display size, bezels size, bezels color, and size of display tiles. The study results revealed that stereo perception is significantly better with larger displays, larger tiles, and smaller bezels. In contrast, the bezels' color does not have any significant effect.

Wallace et al. [156] investigated how bezels impact magnitude judgment, an important aspect of perception, especially for spatially fixed data applications. They detected an increase in judgment error for conditions where bezels were wider than 0.5 cm.

In a subsequent study, Wallace et al. [155] investigated how interior bezels' presence and width impact visual search performance across tiled displays. They could not detect significant differences in visual search time, though they found that participants were more accurate in test conditions where targets were split across a bezel. They hypothesized that this improved performance was ascribed to a change in the user's behavior: the participants performed a more accurate two-phase search.

Form factor.

Shupp et al. [124] executed a study to compare a flat LHRD to a curved LHRD in terms of performance time in the context of geospatial search, route tracing, and comparison tasks. They assumed that utilization of a curved display would allow for more efficient physical navigation since users would only need to turn themselves to bring the display's region of interest into their focus view. In contrast, with a flat display, users would need to walk to achieve the same result. The study confirmed the hypothesis. Indeed, participants were more efficient while working on the curved displays and performed the tasks in less time. As expected, physical navigation changed from standing and walking to turning. Shupp et al. took into account both results and concluded that the latter type of physical navigation is more efficient.

Subsequently, Shupp et al. [123] conducted another experiment to explore in more depth the effect of the display curvature in the context of fix-positioned spatial data. In particular, they aimed to explore how curvature affects the finding data process (search task), the comparing data process (comparison task), the reasoning process (insight task). The results revealed that users who worked with a curved display were more efficient during the search task and produced more insights during the insight task. Moreover, the participants showed a distinct preference towards the curved display while working on the comparison task.

Rogers et al. [101] conducted a study to compare the effect of the display orientation (vertical vs. horizontal) on group collaboration. They detected differences between collaboration flows on a tabletop and a wall-based display. Observations showed that participants who used tabletop switched more roles, explored more ideas, and better understood co-users' actions and intentions. They also stated that groups who worked with a wall-based display perceived the collaboration process as awkward.

Later on, Pavlovych et al. [89] executed an empirical study to explore the effects of technical system constraints on group performance in collaborative tasks. Among other things, they compared how vertical LHRDs would perform compared to horizontal displays. The results revealed that participants were more efficient in the vertical LHRD condition and less efficient in the tabletop condition. The result also differed from the findings of Rogers et al. [101] in terms of user-user communication. The participant of the vertical LHRD condition communicated more frequently. Finally, they found that the vertical LHRD was easier for interaction. They concluded that vertical LHRDs should be considered for tasks where more efficient interactivity is desired.

2.1.2 Interaction with LHRDs

Once LHRDs emerged, they introduced many exciting challenges. One of the challenges refers to interaction possibilities with LHRDs. First, researchers attempted to adopt interaction devices common for the desktop environment, namely, keyboard and mouse. However, these tries revealed soon that desktop interaction paradigms do not fit into LHRDs environments resulting in a broken interaction flow.

For instance, Robertson et al. [100] identified two issues connected with mouse interaction on LHRDs. The first problem is that users often lose the mouse cursor. To compensate for the large display size, users increased the speed of the cursor. However, they failed to keep track of the cursor at this speed. A large display size also makes it difficult to find a non-moving cursor if the user has lost sight of it. Robertson et al. proposed two techniques *high-density cursor* and *auto-locator cursor* to overcome the problems of tracking and locating the mouse cursor. The high-density cursor technique filled the gap between the current and the previous cursor positions rendering some cursors in-between. As a result, the user could see a trail leading to the current cursor position. The auto-locator technique aimed to help find a stationary cursor by drawing an animated circle around it.

Another issue, identified by Robertson et al. [100], relates to distal information access. Using a mouse with an LHRD, users often have to do many hand movements and clutching to access distant areas of the display. The issue becomes even more critical if the user has not only to move the cursor but, for instance, drag an object to that area. The researchers propose a "missile mouse" technique to solve the issue. The missile mouse enabled the user to initiate the cursor's movement in the desired direction with a small gesture. Afterward, the cursor continued the movement until the users moved the mouse again.

However, not only mouse interaction is susceptible to the distal access problem, but also LHRDs with touch capability. In the latter case, there is no problem when moving the cursor, but there is when dragging objects across the display. Baudisch et al. [11] tackled the problem and proposed a technique called *drag-and-pop* that beams potential interaction partners to the element that the user begins to drag.

The research community quickly confirmed the drawbacks of common desktop interaction paradigms in the context of LHRDs (e.g., [10, 6]. Later, as LHRDs became even larger and further research was conducted on physical navigation advantages, researchers added another probably more critical disadvantage to the list. Namely, such devices require stationary installation and therefore do not allow physical navigation [60].

Subsequently, researchers began to utilize new interaction devices and develop new interaction modalities. By introducing new devices, especially wireless, interaction possibilities with LHRDs became more versatile. Based on the type of utilized input device, there are three ways to interact with LHRDs (Note that all three interaction modalities can be additionally extended by supporting interaction techniques, e.g., voice input):

- direct from up close using touch devices
- from up close or from a distance using mid-air devices
- from a distance using stationary devices

Additionally, to the attempts to adopt stationary devices from the desktop world, some researchers tried to invent new stationary interaction devices. So, for instance, Malik et al. [73] explored how vision-based hand tracking over a tabletop surface can be utilized for interaction with LHRDs from a distance. They developed a set of interaction gestures and techniques that allowed for fast targeting and navigation to any part of the display while the user remained sited. They also supported multiple user interactions by utilizing tags that enabled user identification. Interestingly enough, the researchers emphasized in their paper that the developed device's stationarity was one of the leading design principles since their goal was to maximize comfort for the user.

After initial publications on the effectiveness of physical navigation (e.g., [9]), the research community lost interest in stationary devices and focused mainly on mid-air devices and direct interaction using touch capability. Nevertheless, stationary devices are still in use, primarily when LHRDs are used for presentation purposes.

Up close interaction. The idea of up close interaction with touch-capable LHRDs is appealing to many researchers and users. Indeed, such an interaction concept has several advantages. Badillo and Bowman [6] list some of the advantages: no need for an intermediary device, ability to manipulate data by directly touching it, easy to use, fast learning curve, no need for the pointer that can be lost.

However, the up close interaction also has some significant drawbacks apart from an obvious one that not all LHRDs are touch-capable. Potter et al. [95] mentioned three of them: high error rates, lack of precision, and arm fatigue. The first two issues were due to technology's infancy and nowadays are not critical anymore. The latter, however, is still valid.

Multiple researchers pointed out another critical issue, namely distal access (e.g.,[100, 10, 84]). According to Ni et al. [84], the issue of reaching distant objects is one of the main LHRD usability issues. Unfortunately, up close interaction techniques via touch are more prone to that issue than any other. Not only can it be challenging to reach distant objects or areas, but depending on the display size and stature of the user, it can sometimes be impossible.

Some techniques were proposed to address the issue of distal access in the context of up close interaction. Baudisch et al. [11] proposed *drag-and-pop* and *drag-and-pick* techniques. As already described above, drag-and-pop brings potential interaction counterparts when the user starts dragging an item. Thus, it enables the user to interact with distant objects using only small hand movements. The drag-and-pick is a modification of drag-and-pop and enables the user to perform default actions on distant objects. The user has to start to drag on empty screen space to activate drag-and-pick. As a result, distant objects that lie in the direction of the drag gesture will be brought into the user's proximity. Moving the cursor over an object and releasing the button will activate the default action associated with the object.

Bezerianos and Balakrishnan [15] developed an interaction technique called *vacuum* that enables quick access to items of remote display areas. The vacuum allows controlling an *arc of influence* through a circular widget. All items on the display that fall into the area of influence defined through the arc will be placed on the widget in the form of proxies. That gives the user the possibility to interact with them. The researchers conducted an experiment to compare the vacuum to existing technologies (including drag-and-pick described above). The results showed that vacuum outperforms other techniques when selecting multiple or single items located moderately far away from the user. However, vacuum performed worse for the scenarios when the target item was far away, and there were many other items along the path.

Another significant issue is that up close interaction is sometimes not enough [6]. LHRDs have a unique ability to provide an intuitive and smooth transition between the focus view and overview. The user can get closer to the display to focus on details and then step back to gain an overview.

Designing LHRDs in a manner that allows only up close interaction allows the user to interact only with details. In the overview mode, the user has no means to interact with the display. There are, however, some cases for which interaction from a distance would be a better choice, for instance, sorting photos or navigating a high-resolution map [145].

Finally, touch-capable LHRDs are hard to adopt for multi-user scenarios because of lack of user identification [112]. To implement user identification capability, a token associated with the user is required. Such token is usually provided in the form of a portable device [149]. However, this approach eliminates one of the most appealing advantages of up close interaction using touch, namely *no need in intermediary device*.

Interaction using mid-air devices. In the context of LHRD Interaction, mid-air devices can be divided into those that enable direct interaction and those that implement indirect interaction. Direct interaction allows pointing mid-air device devices with appropriate techniques that "project" pointer onto the display surface using ray-casting. The position and orientation detection of pointing devices usually occur through tracking systems (e.g., [62, 113, 67]).

Although mid-air pointing devices allow for swift cursor movements and provide intuitive interaction techniques for object selection, they also expose several critical drawbacks. So, for instance, Kopper et al. [62] identified five issues related to such devices:

- natural hand tremor
- Heisenberg effect
- mapping varies with distance
- no parkability
- no supporting surface

Moreover, Nancel et al. [83] demonstrated that mid-air pointing devices are not suitable for high-precision pointing on LHRDs. Finally, mid-air pointing devices designed for object selection, however, purely support other, more complex interaction types like, for example, text input [82].

Mid-air devices for indirect interaction are usually represented through a smartphone or a tablet PC. The touch-capable display surface serves as a trackpad that allows manipulating a pointer on the LHRD (e.g., [76, 82, 82]). These devices have some drawbacks. For instance, they usually require two-handed interaction since at least one hand is used to hold the device. This circumstance can also lead to fatigue. Moreover, they are less intuitive because of indirect interaction, thus having a slow learning curve.

On the other hand, these devices are apt to mitigate many problems the other devices could not solve, for instance, problems of pointing devices listed by Kopper et al. [62]. Moreover, they possess the capabilities needed for mature and versatile interaction scenarios. For instance, smartphones or tablet PCs can serve as a personal token enabling the system to recognize the user (e.g., [149]) and to provide a custom user experience and user interfaces for users (e.g., [106].

Besides, such devices with a secondary screen can mitigate privacy issues, allowing the user to enter private data through the device without others watching [72, 4] or the user can use the smartphone screen to show private data intended for his eyes only [140].

Using the level of precision (LOP) cursor metaphor [26], these devices can be utilized for scenarios where high-precision pointing, on the one hand, and fast display traversal, on the other hand, are necessary. The techniques may vary from very simple like ARC-Pad [76], where the user uses the tap gesture to beam the cursor to any position on the screen, to very complex like ContPad or DiscPad [83], where a complex, angle depended transfer function is used. Also, the user can be given a possibility to freely adjust mapping functions of interaction (similar to [64]), so it fits the user's current needs. Additionally, the LOP cursor metaphor can be used to control the cursor's precision and constrain the interaction [112]. In that case, the boundaries of the coarse cursor define the user's functional space.

Another advantage of smartphones and tablet PCs is that they can acquire various gestures that can be mapped to different actions. Thus, they can provide much more versatile interaction compared to pointing devices. Moreover, these devices provide support for comfortable text input, which is somewhat awkward when using pointing devices [82].

Finally, the secondary screen of a smartphone or tablet PC can be used to render a user-specific graphical interface on it. That can provide several advantages. First, this approach de-clutter the shared display keeping it clean and enhancing the collaborative work. The graphical user interfaces of multiple users do not occlude any data on display and do not cause any task-irrelevant stimuli, such as movements or animations, that can distract co-users. Second, groupware designers can provide different user experiences depending on the role of individual users they undertake during collaborative work. Such an approach might positively affect collaborative work [146, 68].

Other interaction possibilities. Additionally to the above-described interaction possibilities, there are other techniques and devices, which do not fall into any of the mentioned categories. There is a broad range of hybrid devices that comprise multiple technologies. One of the common approaches is to combine a smartphone with a pointing device. For instance, Nancel et al. [83] developed ContHead and DiscHead interaction techniques where they used head tracking for movements of the coarse pointer and drag gestures on a tablet PC for movements of precise pointer. The evaluation results confirmed the effectiveness of these techniques. Also, Liu et al. [67] combined a pointer device with a smartphone to provide a shared interaction experience. The pointer devices allowed users to move the pointer on display, while the smartphone contained a graphical interface enabling users to trigger different actions.

There were also attempts to combine smartphones with touch-capable LHRDs. Schmidt [114] presented PhoneTouch technique where a smartphone was used as a stylus. PhoneTouch enabled users to pick objects from the LHRD, transfer them to the smartphone, and then drop the objects at another spot of the LHRD. Smartphones were also used as tokens, allowing differentiation between multiple users, thus supporting collaborative scenarios. von Zadow et al. [149] developed a SleeD technique where the user used an arm-mounted smartphone together with a touch-capable LHRD. Here, the smartphone served as an authentication token, thus enabling a broad range of user-specific operations.

Finally, there were some exotic interaction mechanics. Shoemaker et al. [122], for instance, developed a set of body-centric interaction techniques. They employed a virtual light manipulated by the user to cast a virtual shadow on display. As a result, the user could perform direct interaction with the LHRD from a distance using her shadow. Since the shadow's size was larger than the user's real size, the user could reach any distant display area without problems.

Additionally, they developed a set of body-based tools associated with real physical locations on the user's body. So, for instance, body-based storage allowed for access to personal data. The preliminary evaluation of the shadow metaphor and body tool showed that the participants needed some time to grasp how it works and that there is a potential for improvement.

This section provided an overview of different ways to interact with LHRDs. Apart from hybrid and exotic approaches, there are three ways to interact with LHRDs based on the type of a utilized device: (a) direct from up close using touch devices, (b) from up close or from a distance using mid-air devices, or (c) from a distance using stationary devices.

Direct interaction, however, is not always possible due to the dimension/construction of some displays and suffers a lack of interaction at a distance. Stationary input devices, like mouse and keyboard, and workstations like laptops used for input tether the user, thus reducing physical navigation benefits. Additionally, the interaction modalities developed for mouse work well in a desktop environment yet often broke in an

LHRD environment. Also, pointing devices have several drawbacks and do not allow for sophisticated interaction.

Consequently, mobile device based interaction techniques seem to provide a fair tradeoff untethering the user and allow them to operate from any distance. Additionally, they avoid most pointing devices issues, ensuring distal access to objects, and provide a comfortable way for text input.

2.1.3 Challenges of Co-located Collaborative Work

Stewart et al. [133], who – one of the first – proposed and investigated co-located collaboration on a single shared desktop display, pointed out that limited screen space might have negative drawbacks on the collaboration process. First, it may reduce application functionality. Second, conflicts might merge if users have different incompatible intentions. Especially navigation was a serious concern since small displays can only encompass a small part of the virtual workspace. Thus, users might want to work in different areas, although these areas could not be visualized simultaneously laying far away from each other.

LHRDs solve the problem of small display real estate easily. Sometimes users even do not utilize the entire display (e.g., [5]). However, as later research revealed, increasing the display size does not entirely solve the problem of conflicts. The sharing of a single LHRD between multiple users still might cause interferences and, as a result, impede collaborative work. Zanella and Greenberg [162] defined interference as "*the act of one person hindering, obstructing, or impeding another's view or actions on a single shared display*".

One can differ between interferences with direct impact and interferences with indirect impact. Interferences with direct impact make task execution impossible. The user cannot work on the task until the interference is resolved. For instances, Zanella and Greenberg [162] stated that in multi-user scenarios, opaque graphical user interface elements might be a source of interference since they could occlude important parts of the virtual workspace. Thus, they could prevent users from doing their work. They proposed to utilize semi-transparent GUI elements to mitigate the issue. They investigated how opaque and semi-transparent GUI elements will affect users' performance in a controlled experiment. Indeed, the results showed that semi-transparent elements lessen interferences. However, the difference was not significant.

Izadi et al. [51] identified interferences with a direct impact, which they called "overlap"-situations while testing their communal multi-user interactive surface. For instance, some users closed documents that belonged to someone else to make room for their documents. They considered two possibilities to resolve conflicting situations: either implement a strict policy that will prescribe who can do what or let users solve the problems employing social protocols. As a result, they proposed a hybrid approach enabling the user to establish private territories and give access to these territories to co-users if needed.

Morris et al. [80] listed interferences with a direct impact they observed during multiple studies. For instance, users switched views while co-users were still working in that view, rotated documents while the co-user was reading it, or even took resources away co-users were working with. As a result, they suggested coordination policies for groupware designers that should shape manipulation mechanics in a way that will mitigate conflicts.

By contrast, interferences with indirect impact somewhat slow down the user during task completion. For instance, a semi-transparent pop-up window will allow the user to read the text, or a high-frequency, faint noise will allow the user to make a verbal report. However, the task's mental load will be much higher due to interferences.

Interferences with indirect impact might have an immediate or delayed effect. For instance, interruption of the memorization process or drawing the user's attention represents an immediate effect. In contrast, overloading of user's awareness through irrelevant visual events represents a delayed effect that accumulates over time, and which might, for instance, lead to mental fatigue, and subsequently to performance decrease. Both short-term memory and attention are essential factors for analytical work (e.g., compare objects, find relationships, find an object based on information just gained from another object). Multiple studies have shown that both can be affected by distractors [32, 56, 58].

Some other works investigated interferences during co-located collaboration. Some of them showed that in particular scenarios, interferences could be managed or even avoid naturally through social protocols and spatial subdivision of a task (e.g., Tse et al. [143]). Some others investigated what interaction type (direct or indirect) will cause fewer interferences. Hornecker et al. [48] determined that touch input interaction leads to more interferences than mouse input interaction. Again others, proposed coordination techniques that will reduce conflicts (e.g., Pinelle et al. [91]).

However, most proposed coordination strategies were designed with a loosely-coupled work style in mind. However, for complex, mentally demanding tasks, mixed-focus collaboration, which contains frequent switches from loosely to tightly coupled work and vice versa, is a more probable scenario. Thus, groupware systems should adjust a deployed coordination strategy depending on the current coupling state. For instance, Pinelle et al. [91] showed that users had a strong preference for a technique with an adaptive, system controlled access to objects. However, more in-depth knowledge regarding group and user behavior is needed to provide such a possibility.

2.1.4 Summary

In the beginning, the LHRD research community focused on a single technical question: *How to increase the display real estate to provide a larger virtual workspace?* While the researchers and engineers were getting better at mastering this technical challenge, new problems were emerging.

One of the problems is related to the interaction with LHRDs. Common desktop interaction paradigms and devices did not work well or even not at all in LHRD environments. First solutions tried to adjust or improve existing techniques. However, these techniques utilized mainly stationary interaction devices that tethered the user and disabled physical navigation together with the advantages it offers. Thus new interaction paradigms were developed, and new interaction devices were utilized.

As researchers gained experience in building LHRDs and developing better interaction devices, they found that LHRDs are well suited for complex problems that require collaboration among multiple experts. However, attempts to adopt LHRDs for co-located collaborative work introduced a new complex issue, namely group behavior.

Researchers detected that users expose very different behavior while working collaboratively on LHRDs compared to single user scenarios in desktop environments. Therefore, user and group behavior must be thoroughly studied to provide groupware designers with insights that enable them to develop groupware that promotes, rather than hinders, the flow of interaction and collaboration.

Foretaste regarding the complexity of co-located collaboration on LHRDs was given in section 2.1.3. In the next sections of this chapter, other even more complex facets of user and group behavior in the context of co-located collaboration on LHRDs will be covered.

2.2 Collaborative coupling

The users' behavior during collaborative work in digital environments can be subdivided into two categories: *user-user interaction* and *user-system interaction*. To describe behavioral patterns of user-user interaction, researchers introduced the term *collaborative coupling*. This section provides an overview of research that investigated collaborative coupling in the context of LHRDs.

2.2.1 Definition

Collaborative coupling describes the process of user-user interaction for task accomplishment. Researchers describe it as collaboration tightness, coupling styles, user roles, and task subdivision strategies.

In general, researchers subdivide collaborative coupling into two ranges: *tightly* and *loosely* [39, 80, 118, 143]. Within these, the intensity level may vary depending on a coupling style.

Initially, researchers defined tightly coupled work as work that barely could occur without user-user interaction, while loosely coupled work describes instead a workflow where users act independently, e.g., [39, 42, 111]. Tang et al. [136] adjusted the term collaborative coupling as *"the manner in which collaborators are involved and occupied with each other's work"* to highlight the social aspects of the phenomenon.

2.2.2 Coupling Styles

Tang et al. [136] conducted two observational studies and examined how different viewing techniques affect collaborative coupling during mixed-focus collaboration. The participants completed independent and shared tasks while working over a tabletop with a spatially fixed visualization. The studies revealed insights into group coordination strategies. Additionally, the researchers could extract different coupling styles and analyzed the relationship of these styles to the task, physical location, and interference management.

The studies yielded the following coupling styles: Same problem same area, View engaged, Same problem, different area, View (one working another viewing), disengaged, different problems.

Following, Isenberg et al. [50] conducted another exploratory study around a tabletop system, where participants had to solve the VAST 2006 Challenge involving 240 documents. Opposite to the Tang et al. [136] study, data was not fixed-position but represented through a set of floating document windows. The study revealed eight different coupling styles that were described based on participants' data views and personal interactions. The results overlapped at some points with those obtained in the study by Tang et al. [136], while revealing four new styles.

A limited body of work exists that has focused on coupling styles during co-located collaboration on vertical LHRDs. Jakobsen et al. recreated the exploratory study of Isenberg et al. using a multitouch wall-sized display [53]. Again, the data was not fixed-position. Additionally, participants were forced to work next to the display because of touch input based interaction techniques. In contrast to the studies by Tang et al. and Isenberg et al., Jakobsen et al. used two codes to describe coupling: one for visual attention and one for verbal communication. They found five patterns of visual attention (e.g., same area - A and B looking at the same area) that, in combination with verbal communication patterns, could be used to describe coupling styles detected previously.

The experiment conducted by Liu et al. [67] used different collaborative coupling styles to investigate a shared interaction technique for data manipulation on a wall-sized display. However, this was a controlled experiment, and the system forced the participants to work in a particular manner. For instance, in conditions with shared interaction techniques, the participants could not solve the task individually. Thus they could not work loosely coupled. Such restrictions disallow to observe natural behavior.

The mentioned studies are most extensive in the domain of collaborative coupling. As can be seen, the research body is relatively scarce. Moreover, no studies investigated coupling styles during work with fixed-position data on LHRDs. Thus, many questions remain open. For instance: Are there any other coupling styles? Can the transition between individual coupling styles be captured and classified? Are the provided coding schemes for coupling styles classification sufficient, or must they be extended?

2.2.3 User Roles

User roles represent another manifestation of collaborative coupling. The concept of user roles describes a circumstance during collaborative work when the user takes on particular duties that require specific actions and results in specific user-user interaction, user-system interaction, and conversation patterns. The roles' distribution can be established right from the beginning or after the users learned the process and found an appropriate strategy for the task. Moreover, users can stick to the chosen role for the entire task or switch roles dynamically, depending on a current sub-task.

Rogers and Lindley [101] investigated group behavior around vertical and horizontal interactive displays and observed the interactor user role. The interactor functioned as an interface between the digital system and the rest of the group. Their task was to provide changes to the virtual workspace on demand of the other group members. Although interactors could also participate in the discussion of the problem, they frequently felt to be left outside the group.

However, the observed behavior and captured experience of the interactors could be ascribed to the utilized system design. Rogers and Lindley used a relatively small vertical display (96cm by 96cm) and only one input device per group. Therefore the interactors were forced to separate themselves spatially from the group to interact with the display.

Vogt et al. [146] investigated group behavior during collaborative sensemaking on a large, high-resolution display. They described group behaviors concerning activities (e.g., extract and cluster) and user roles. Based on the participants' activities and conversation, they identified two user roles: sensemaker and forager. The participants needed a considerable amount of time to define and shape their roles. Vogt et al. mentioned that roles were established *"normally after the half-way point of the study session"*. They could also detect that participants used the roles for a clear division of the responsibilities. Moreover, they could observe that groups that utilized user roles were more successful than other groups. Subsequently, Vogt et al. recommended providing appropriate tools that support the establishing of user roles, for instance, implementing *"specialized views"*.

Subsequently, Brudy et al. [21] designed Voyageur, a collaborative tool for trip planning. The tool aimed to support different user roles providing different views (personal and overview) on different mobile devices. Additionally, it supported dynamic switching of roles since the overview display could be passed to another person anytime. Evaluating the tool, Brudy et al. could observe that separation of the views resulted in more tightly-coupled collaboration and more intense communication.

Liu et al. [68] implemented an interface that utilized user roles to assign different responsibilities to users while interacting with an LHRD. They called this concept *cooperative gestures*. A cooperative gesture consists of two subsequently executed sub-gestures. Therefore, such gestures can be performed by two users: *action initiator* and *action follower*. Liu et al. conducted a study to compare cooperative gestures with traditional multi-touch gestures. The results suggested that cooperative gestures are apt to reduce physical fatigue. Moreover, they support tightly-coupled and loosely-coupled collaboration and facilitate s smooth transition between them.

Wallace et al. [152] investigated the role of a shared LHRD in the context of a sensemaking task. To evaluate different display configurations, they utilized a task where participants were assigned different investigative roles and were provided with different role-specific knowledge. Although the study did not aim to investigate user roles' impact but rather adopted them to mimic a real-world situation, the results showed that participants could unproblematically work under such conditions and successfully solve tasks. However, it is hard to say how significant the effect of roles' distribution was since no comparison took place.

Previous research showed that the concept of user roles is inevitable in the context of co-located collaboration since they are a natural product of the groups' self-organization process. Subsequently, user roles can serve as an indicator of collaboration states or an instrument for steering the collaboration process. Moreover, there are initial pieces of evidence that explicit distribution of user roles at the beginning of collaboration might positively affect groups' performance. However, investigation of user roles took place mostly in the context of sensemaking. Therefore, the effects of user roles must be investigated in other task types as well in order to deepen the understanding of them.

2.2.4 Summary

Research on collaborative coupling attempts to extract, understand, and categorize user-user interaction patterns during collaborative work. The in-depth understanding of collaborative coupling is vital for groupware design that supports and promotes collaboration and does not impede interaction flow.

Initial research on collaborative coupling aimed to project users' real-world behavior into a digital environment. Thus, for instance, researchers developed tools that allowed users to work and behave in such a manner as they would do with physical assets. However, the digital world provides many more possibilities and allows for creating more complex workspaces than the real-world. That, in turn, means that underlying causes of collaborative coupling and resulting impacts on groups' efficiency and effectiveness become more complex. Every single aspect like a task, LHRD size or shape, interaction device, and techniques might affect collaborative coupling. Therefore, researchers must conduct more in-depth investigations altering conditions and analyzing the results to provide a complete image of the coupling phenomenon for groupware designers.

Finally, collaborative coupling research yields knowledge about typical users' behavior, actions, and intentions in particular scenarios. This knowledge might be exploited to build user models. In turn, these models can be used to develop adaptive interfaces that alter behavior and representation of visual elements at runtime to match users' current needs and goals best.

2.3 Territoriality

Human territoriality is a social phenomenon that, among other things, has a significant effect on interaction and communication processes during CSCW. Multiple studies have explored territoriality in CSCW: on horizontal large, high-resolution displays [49, 117, 136], vertical, large, high-resolution displays [5, 53, 121, 143, 153], and on mobile devices used in conjunction with large, high-resolution displays e.g. [154]. The studies have shown that users tend to partition available workspace into multiple territories with different semantics, even if there were no tools explicitly provided.

This section summarizes the findings on territoriality in CSCW regarding territory types and properties. It provides a compilation of a large set of literature. This set was acquired by starting with the publications regarding initial findings on territoriality and iteratively extended through analysis of papers that cited these publications or were cited by them.

2.3.1 Definition

Territoriality is a relatively old term that comes from the psychology domain. So, for instance, Sack [110] defined human territoriality as: *"... the attempt to affect, influence, or control actions and interactions (of people, things, and relationships) by asserting and attempting to enforce control over a geographic area"*. Furthermore, territories vary in scale [110, 138] (e.g., from seats to cities) and can be controlled/claimed either by a single individual or by a group of persons (territory sharing) [110].

In her PhD thesis, Stacey D. Scott [117] summarized definitions from Fisher et al. [31], Gifford [33], Taylor [139], Altman [1], and Sack [110]. As a result, she concluded that territoriality can serve as a means: (a) *"to assert some level of control or ownership over a space"*, (b) *"of maintaining a desired level of personal space and privacy"*, or (c) *"to control or influence people, phenomena, or relationships"*. Since then, the term "territoriality" has become established in the CSCW community.

Of course, definitions in the provided forms are barely useful as guidelines for a specific implementation. Thus, many researchers conducted observational studies to acquire more information about territoriality to give it a more distinct shape. The next sections present and categorize the findings on territoriality.

2.3.2 Types

Considering previous research, territories can be categorized into primary and secondary territory types. Primary types define territory semantics, while secondary types represent specific territory instances. The prevalent primary territory types in the literature are personal territory, group territory, and storage territory. Apart from these, there are unused territories, input territories, GUI territories, and sandbox territories.

Personal Territory. A personal territory reserves a workspace area for its owner [117] and is usually located within the owner's proximity [63, 137]. The owner uses his personal territory to disengage partially (do actions related to the group activity in a more comfortable way) or entirely (do actions not related to the current group activity) [117, 136]. The owner acts irrespective of the group within the personal territory, e.g., orients assets towards himself [63]. The size and shape of a personal territory depend on multiple factors [117]: number of collaborators; the relative position of collaborators to the projection surface and each other; size and shape of the projection surface; current user's activity; type of virtual assets. Also, visible physical barriers of the projection surface [31], and collaborators' social norms can affect personal territories.

Group Territory. Group territory is a region where users perform main task activities [117]. Generalizing the main task as solution acquisition, we can define a group territory more precisely as a place for group discussions [49], group discussions accompanied by data manipulation [49], deposition of preliminary results [20, 117], and completion of deposited results [20, 117].

A group territory must be accessible for two or more users, does not require the simultaneous presence of multiple users, however. Thus, one can differ between synchronous work (multiple users are simultaneously within a territory) and asynchronous work (users enter and leave a territory alternately). Both types require tightly-coupled interaction. Tightly-coupled interaction forces the user to handle concerning other users within a group territory [137]. However, loosely-coupled interaction indicates that the user disengaged from the group and retreated into his territory.

The size, shape, and position of a group territory depend strongly on a task, the number of collaborators, and a system configuration. For instance, Kruger et al. [63] detected a group territory in the center of the table while observing pairs of participants seated face to face. Scott et al. [117] observed a group territory covering the entire table apart of regions occupied by personal territories.

There are two subtypes of group territories in terms of ownership: shared and public. A public group territory is accessible and controllable by all users. In contrast, a shared group territory belongs only to a subset of users. For instance, it can emerge between adjacent personal territories [117], or through the overlapping of personal territories [115].

Storage Territory. In contrast to group territories, storage territories represent a resource pool and not a results pool. It is a place to store task items (e.g., puzzle pieces), non-task items (e.g., food), and reference items (e.g., box lids of a jigsaw puzzle) [117]. The most frequent user activities in that territory are: searching for items, loose arrangement of items, and piling (if possible) [116]. Typically, there is more than one storage territory within a workspace. Storage territories turned up to be highly mobile (change shape, size, and position over time) and transient (disappear and emerge again later).

A collaborative jigsaw puzzle solving session exposes an exciting example of storage territory dynamics (e.g., [117]). At the beginning of the session, there is one large storage territory containing all the puzzle pieces. During the session, pieces travel most likely from the storage territory into personal territories, then into storage territories within the personal territories, or back into the public storage territory, or into a group territory as a part of a solution. Thus, the public storage territory vanishes over time, while the group territory becomes larger. At the end of the session (the puzzle is solved), only the group territory remains.

Another example is a route construction task on a map (e.g., [136]). The map represents a large storage territory that will remain throughout the session since it is a task resource, and it cannot be transformed into a solution. The solution will be either a route drawn on the map or a written down description of the route. Depending on how the solution should look like a group territory will appear either on top of the storage territory or at some different place where the results will be worked out.

Unused Territory. Azad et al. [5] identified an unused territory while investigating collaborative work on wall-sized displays. This territory represents a vacuum of virtual space; there are no assets here, and no user activities occur here. The apparent reasons for emerging of this territory type are: too large workspace for too few collaborators/assets; parts of the workspace are hard to reach (e.g., the display is too high), parts of the workspace where it is hard to interact with assets (e.g., read a text on a vertical display that is too low). We assume that unused territories signal that the provided workspace does not fit the requirements. However, the existence of an unused territory is only critical if collaborators experience a workspace deficit at the same time.

Input Territory. An input territory is a virtual space region where the system can acquire the user's input. It is constrained by the type of physical input devices and an implemented mapping function. Mostly, input territories are static, rigid, and span the entire visual display. There are examples of mobile input territories, however. For instance, Satyanarayan et al. [112] introduced virtual overlays in conjunction with mobile devices. A mobile virtual overlay on a shared display represents an input territory, and the system maps to it all user's touches and gestures made on the appropriate mobile device. In that case, we can talk about personal input territories.

Graphical User Interface (GUI) Territory. GUI territories are areas that provide virtual triggers (e.g., buttons, sliders) for interaction with a system, and labels for system state notification. If a collaborative system utilizes a user identification component, it can generate GUI territories with personalized content. Hence, one can distinguish between private, shared and public sub-types. A private GUI territory belongs to only one user and will typically be located within a user's personal territory, e.g., [106]. A shared GUI territory belongs to a sub-set of users and lies within shared territories. A public GUI territory has no owner and is accessible for every user.

Sandbox Territory. A sandbox territory is a safe place where users evaluate their ideas before presenting them to collaborators. It is like a piece of jotting paper during an exam. We use it to acquire preliminary results, to figure out if the idea will work out. A sandbox territory usually belongs to a personal territory, although there are pieces of evidence that it can emerge within other territory types as well, e.g., storage territory [5]. Working alone in a sandbox territory, people incline to conceal information from others by writing and drawing intentionally small [137].

The difference between a sandbox territory and a personal territory is rather blurred. However, compared to personal territories, sandbox territories can be expected to have a smaller dimension and a shorter life cycle.

2.3.3 Properties

The secondary territory types are specific instances of territories defined through visibility and ownership properties. Both properties may take on the values: private, shared, and public. The property values have the following meanings:

- Private – the territory belongs (ownership) / is visible (visibility) to only one user (owner).
- Shared – the territory belongs (ownership) / is visible (visibility) to a set of users (owners), not to all, however.
- Public – the territory has no owner (ownership) / is visible (visibility) to everyone.

Table 2.1 summarizes what secondary territory types can be derived from primary types.

By setting the visibility property to private, the user can conceal a portion of or all information from collaborators. For that, there are two general reasons: security [120], and awareness overload [39, 40]. Awareness overload often occurs when systems provide users with a large amount of data. Thus, it becomes more troublesome for users to tell apart essential and unimportant information. Moreover, Gutwin et al. [39] argued that increased group awareness would likely decrease individual users' effectiveness.

Table 2.1: Primary and secondary types of virtual territories in collaborative workspaces: the most left column contains the primary types; the value combinations of visibility and ownership properties identify what secondary territory types can be derived from a particular primary territory type. For instance, the first row indicates that a personal territory can be private in terms of ownership, yet visible for everyone (public visibility).

	ownership			visibility		
primary type	public	private	shared	public	private	shared
personal		•		•		
personal		•			•	
group	•			•		
group			•	•		
group			•			•
storage		•			•	
storage			•			•
storage	•			•		
storage			•	•		
storage		•		•		
GUI		•			•	
GUI		•		•		
GUI	•			•		
input		•			•	
input		•		•		
input	•			•		
sandbox		•			•	
sandbox			•			•
sandbox	•			•		
sandbox			•	•		
sandbox		•		•		
unused	•			•		

The security aspect is crucial for collaboration scenarios where participants have different access levels to information (e.g., teacher and student). There are two conventional approaches to ensure privacy in scenarios with a shared display. The first one incorporates a private display, e.g., a smartphone, laptop, and a shared display for each user [34, 81, 99]. Private information appears then on a private screen, and it is up to the user to limit access to that screen for collaborators. Another approach is to show private information within the context of a shared display, make information visible for the owner through special devices or filters [57, 78, 115, 121, 140].

The visibility property prevails and limits the ownership property. For instance, the private value of the visibility property discards the shared and public values for the ownership property.

Apart from the visibility and ownership properties, there are several other properties. Some of these properties, like transience or mobility, were mentioned in the literature on territoriality in CSCW previously [52, 119, 136]. Some other properties, like dimension and location, could be easily derived from the concept of territoriality. Finally, there are situations like overlapping that require the implementation of additional properties. Such properties can be the object compatibility property, territory compatibility, and precedence properties.

The transience property [54, 136] defines if a territory will stay permanently, or temporarily, on a screen (shared- or personal-screen). The possible values are transient and persistent. A pop-up menu is a typical transient GUI territory. It appears on request and remains as a rule only for a couple of seconds on a screen.

The flexibility property [5, 61, 117] specifies if a territory can change its shape and size. The possible values are: flexible and rigid. It is often a good idea to keep territories flexible since users know best how much space they need.

The mobility property [61, 117, 119, 136] defines if the system allows the user to change the position and orientation of territory on a screen. Possible values are: dynamic and static.

The interactivity property enables or disables users to interact with a territory. The possible values are: interactive and not interactive. The property has no effect if the territory does not overlap with an input territory. Non-interactive territories are, for instance, GUI territories that represent a state of a system (labels or other visualizations).

The object compatibility property addresses a situation when two or more territories share the same region on a screen. The possible values are: exclusive and inclusive. Two objects from different territories can share the same screen space region only if the object compatibility property is set to inclusive. Otherwise, the system should intervene by rearranging the object in layers, if necessary, reshaping layers. The result of rearrangement should be a state where no object overlaps another if they lay in two different layers. Figure 2.3 exemplifies the effects of the property values.

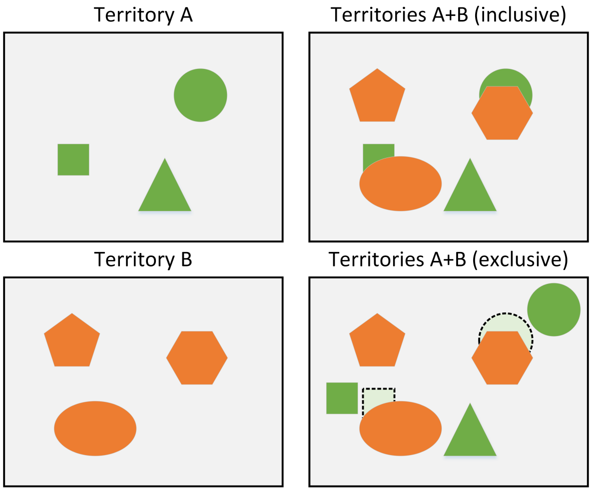

Figure 2.3: Object compatibility

The territory compatibility property addresses a situation when the user tries to put one territory onto another. The possible values are: exclusive and inclusive. An inclusive territory can overlap with another territory. Depending on the transparency level, it may occlude or not. Exclusive territories cannot overlap.

The synchronization property indicates if data units within the two territories are synchronized. The internal and visual state of a data unit will only be synchronized if both territories contain it. This property is especially important if users are distributed geographically and in linked views [158] applications.

The precedence property affects territories' position in a territory stack (overlap situation). A territory with higher precedence will lay on top of the territory with lower precedence. For instance, an input territory should always have the highest precedence; a group territory will likely have lower precedence.

The dimension property determines the size, and possibly the shape of a territory. It can be represented through a radius value, width and height values, a set of 2D or 3D vectors.

The location property reflects the position of territories in the physical world (e.g., by display id) and the virtual world (e.g., using screen- or world-coordinates).

2.3.4 Summary

Territoriality will always be a part of collaborative, digital, and non-digital environments. Even if the developer/designer of an environment ignores it, it will still emerge since it is the way humans think about space around them. Thus, it is smarter to accept it and provide support for it. In general, territoriality can improve existing user interfaces by providing better *user-user interaction* and *user-system interaction*, as well as ensuring *better privacy integration*.

Territoriality can improve *user-user interaction* in multiple ways. It allows for better coordination of workspace. Visible territories provide co-users with a better comprehension of how much virtual space the user requires. Thus, new territories can be established without distracting the user. Territoriality enables users to understand the co-users context and activities better. As a result, it might enhance communication by reducing unnecessary communication (e.g., "Do you need this document?" is unnecessary if it lies in a public storage territory). Moreover, it can foster necessary communication (e.g., "Do you need this document?" is necessary if it lies in a personal territory). Thus, territoriality allows for better data access coordination.

Moreover, territoriality allows for better users protection from visual system-generated distractors while users are working loosely-coupled. For instance, two users are working on spatial data (e.g., map or graph). The first user is working within the personal territory that encompasses a data subset. The second user is looking for particular data items and has requested that the system highlight all items that satisfy particular criteria. If the system lacks territoriality support, it will likely highlight all items, even if some lie in front of the first user, thus distracting the user from her task. However, with territoriality, the system can highlight all items apart from those that lie in the first user's personal territory and inform the second user about the situation.

Territoriality can improve *user-system interaction* as well. Having territories with predefined semantics and behavior, the system can understand the user, understand the activities of the user, and better understand the data. A data item is not any more simply a data item. It has an owner, activity status, semantics (e.g., if the item is in a group territory, it is probably a part of the solution). Building upon territoriality, developers can implement much more intelligent user interfaces. The following pipeline becomes possible:

- *Understand the user* - understand the current activity of the user/group of users; understand if users are working tightly-coupled or loosely coupled; determine the current direction of investigation (what information the user is looking for? / what document the user is preferring?)
- *Predict/Conclude* - Where investigations of individual users will cross? What document will the user likely process next? What question does the user want to answer? What structure does the user want to achieve?
- *Pre-calculate* - based on the prediction, the system can pre-calculate possible next steps of the user, execute them beforehand

- *Propose* - propose pre-calculated solutions to the user

However, if the rules territoriality is based on are too rigid, they can impede natural interaction flow. For instance, imagine an interface with explicit territories, where the personal territories implement a protocol for assets protection. The protocol says: no user can take an asset from other users' personal territory, and no user can put an asset into the personal territory of other users. Thus, the exchange of assets can only occur within a group territory. Some users will likely accept it ; other might find it unnatural.

2.4 Workspace awareness

Workspace awareness affects users from outside through others' actions, intentions, and emotions. Therefore, workspace awareness can expose interplay with territorial behavior or collaborative coupling behavior. For instance, consider a three user scenario: one user, while working on an individual task, recognizes (workspace awareness) that two co-users have just allocated some virtual space next to her to work on a shared task. As a result, the user can move her personal territory away (territoriality) to reduce workspace awareness and concentrate on her individual task; or dissolve her personal territory (territoriality), join the co-user (collaborative coupling) to increase workspace awareness, and work on the shared task (territoriality). In this scenario, workspace awareness caused a change in territoriality. Subsequently, changes in territoriality and collaborative coupling caused a change in workspace awareness.

This section provides an overview of research in the context of workspace awareness. In particular, it focuses on the advantages and disadvantages of extended workspace awareness that can be achieved through the utilization of LHRDs.

2.4.1 Definition

Engelbart and English [30] introduced one of the first groupware systems that incorporated extended workspace awareness techniques. However, the concept of workspace awareness was somewhat foggy, and implementations intuitively leaned onto specific system requirements. Later on, researchers recognized the necessity of providing information regarding co-users in a collaborative environment to foster collaboration (e.g., [137]). Moreover, the understanding emerged that awareness can aid transitions from loosely-coupled to tightly-coupled work [38].

Dourish and Bellotti [27] considered workspace awareness in the context of shared workspaces and provided one of the first definitions for it. They defined it as *"an un-*

derstanding of the activities of others, which provides a context for your own activity".

Later, Carl Gutwin and Saul Greenberg shaped the idea more precisely and provided a framework of workspace awareness [38, 42]. They considered workspace awareness as a key for groupware systems that aim to foster fluid interaction during co-located collaboration. They defined workspace awareness as *"the collection of up-to-the-minute knowledge a person uses to capture another's interaction with the workspace"* [38]. In other words, workspace awareness is an ability of users to *"maintain awareness of others' locations, activities, and intentions relative to the task and space"* [38].

2.4.2 Expected Advantages

Researchers address workspace awareness because it has the potential to improve the collaboration process significantly. Gutwin and Greenberg [38] stated that workspace awareness might enable users to work together more effectively and listed the expected advantages of extended workspace awareness:

- Better coordination of tasks and resources
- More fluent transition from individual to shared activities
- Better understanding of co-users' activities
- Better understanding/anticipation of co-users' intentions

Previous research could also demonstrate some positive effects of extended workspace awareness. So, for instance, Gutwin et al. [44] conducted a usability study to compare relaxed WYSIWIS ("what you see is what I see") widgets that extend workspace awareness, like radar views (e.g. [43, 7]), multi-user scrollbars (e.g., [7, 102]), graphical activity indicators (e.g., [13]), and auditory cues (e.g. [13, 25]). They examined what information each widget provides, widgets' interpretation easiness, and whether the widgets were distracting or useful. The study observed that some widgets indeed could improve users' performance in terms of speed and efficiency.

In a subsequent experiment, Gutwin and Greenberg [41] compared two groupware interfaces (with and without extended workspace awareness) using three construction tasks. The results showed that the participants were significantly faster and more efficient in two of three task types and were more satisfied while using the interface with extended workspace awareness.

Some other papers argued for extended workspace awareness. However, most of the conducted experiments took place in the context of remote collaboration and employed small desktop displays. In the context of LHRDs and co-located collaboration, where extended workspace awareness is usually given for free, this phenomenon was barely investigated.

2.4.3 Possible Disadvantages

While many researchers associate workspace awareness only with a positive impact on the collaboration process, some researchers also question whether it has any downsides. So, for instance, Ellis et al. [28] presumed that awareness of co-users' actions might distract the user. Thus they stated that *"A good group interface should depict overall group activity and at the same time not be overly distracting."*. Similarly, Gutwin and Greenberg [42] argued that extended workspace awareness would likely decrease individual users' effectiveness.

One reason why extended workspace awareness can distract users is that it can dramatically increase the number of visual stimuli in the user's field of view. Such visual stimuli could be of two types: *task-relevant* and *task-irrelevant*. Bundesen [22] defined task-relevant stimuli as stimuli that are similar to the target and the target's defining characteristics. By contrast, task-irrelevant stimuli carry no information concerning the task.

Both task-relevant and task-irrelevant stimuli may be of two conditions: *congruent* and *incongruent*. Congruent stimuli activate the same response as the target for the trial, while incongruent stimuli activate an incorrect response. For instance, imagine a scenario where two symbols - one on the left side of the display and one on the right side - are presented to the user. One symbol is a predefined trigger symbol the user was instructed to look for. Depending on the trigger symbol's position (left or right), the user has to push the left or the right button. Additionally, each time the symbols are shown, one side of the display becomes highlighted, thus drawing the user's attention. If the highlight stimulus draws the user's attention to the display side where the trigger symbol is, then the stimulus is congruent. Otherwise, it is incongruent.

Forster et al. [32] conducted several experiments on a 15" screen and showed that task-irrelevant stimuli distracted the user and, as a result, decreased their effectiveness. Mori et al. [79] investigated the effect of windows in the peripheral visual field on user task performance. They found that peripheral windows impaired users' efficiency more if peripheral windows were nearer to foveal vision. It was also shown that dynamic stimuli have a more negative impact than static stimuli.

Task-relevant peripheral stimuli can also decrease task performance. Chewar et al. [24] investigated secondary task display attributes (e.g., position, color) aiming to lessen interference of peripheral task-relevant stimuli with the primary task. The conducted experiments showed that users' primary task performance decreased due to peripheral stimuli.

Additionally, visual distractors might also have a delayed effect. This effect can accumulate over time, overloading users' awareness, leading to mental fatigue, and subsequently decreasing performance.

The downsides of extended workspace awareness have been investigated primarily on small displays. Thus the effect of visual stimuli was observed in the focus area or a narrow peripheral area near the focus area. However, in the context of LHRDs, visual stimuli can occur in almost all peripheral vision areas. Therefore, to better understand workspace awareness in the context of LHRDs, the effect of visual stimuli in peripheral vision must be investigated more deeply.

2.4.4 Summary

The necessity of extended workspace awareness emerged from two factors: large virtual workspaces that did not fit into small displays and geographical distribution of team members that reduced the number of cues (like gestures) useful for successful collaboration. As a result, several techniques emerged that aimed to increase workspace awareness and foster collaboration. With small displays, however, there is a choice of what information amount is provided to users so that awareness can be raised without distracting users.

On the other hand, LHRDs provide extended workspace from the start through their inherent characteristics. Additionally, in the case of co-located collaboration, all users are present at the same location, so the number of virtual and physical cues is not reduced but significantly increased. As a result, workspace awareness becomes comprehensive. It can provide a clue about collaborators' intentions for other users and allows for better territorial coordination. In turn, this allows for avoidance or at least mitigation of workspace conflicts (e.g., simultaneous access of a shared asset). On the other hand, users have to process more information, thus risking to reach mental fatigue sooner.

Multiple studies indicated that workspace awareness might negatively affect users' performance through visual distractors. Most of these studies, however, were conducted on standard desktop displays. Thus they investigated effects in very near peripheral vision areas only. Moreover, the experiments did not consider high load tasks that make heavy use of humans' memory (particularly short-term memory) and attention resources. Therefore, to understand how to handle workspace awareness in LHRDs environments, its effects in this specific condition have to be investigated first.

Chapter 3

Observational study: Mixed-focus Conditions - Effects of mixed-focus conditions on socio-physiological phenomena

As mentioned above, the thesis's goal was to deepen the understanding of socio-physiological phenomena during both analytical and creative tasks. This chapter describes a study that focused on an analytical task. Although previous research contains multiple studies with analytical tasks on LHRDs, e.g., [5, 53, 148, 153], most of these studies did not employ fixed-position spatial data. Moreover, they used different contexts compared to this study (e.g., public displays, gaming), and some did not allow for extensive physical navigation [53, 146]. The main difference of the study presented in this chapter to previous research is that it separates skillfully typical task conditions of an analytical task. That made it possible to gain insights regarding group behavior during these conditions.

Other studies focused on socio-physiological phenomena during collaborative work around tabletops, e.g., [119, 136, 154]. Although many findings from these studies can be generalized to vertical LHRDs, tabletop-based environments differ from those of vertical display environments. Tabletops' size is usually smaller since it is hard to utilize a large tabletop's center area. Additionally, users generally look down and not forward and may even have fixed seating places that restrict physical navigation. These and other differences might impact socio-physiological phenomena. As such, designers of interactive spaces for vertically oriented displays can highly benefit from further investigation.

Parts of this chapter were previously published in in the following papers:

Sigitov, A., Hinkenjann, A., Kruijff, E., and Staadt, O. Task Dependent Group Coupling and Territorial Behavior on Large Tiled Displays. *Frontiers in Robotics and AI 6* (11 2019)

Sigitov, A., Staadt, O., Hinkenjann, A., and Kruijff, E. Column Major Pattern: How Users Process Spatially Fixed Items on Large, Tiled Displays. In *Proceedings of the 2018 Conference on Human Information Interaction&Retrieval - CHIIR '18* (New York, New York, USA, 2018), ACM Press, pp. 305–308

Sigitov, A., Staadt, O., and Hinkenjann, A. Towards Intelligent Interfaces for Mixed-Focus Collaboration. In *Adjunct Publication of the 26th Conference on User Modeling, Adaptation and Personalization - UMAP '18* (New York, New York, USA, 2018), ACM Press, pp. 287–292

3.1 Research Objective

This study focused primarily on collaborative coupling and groups' territorial behavior during two task conditions typical for the sensemaking process while working on an LHRD. However, physical navigation was also considered during the analysis of the results. Workspace awareness was not investigated since the study contained many uncontrolled variables. Therefore, effects related to workspace awareness could not be isolated. The study was partially built upon the previously conducted studies, e.g., [53], to have a solid foundation. However, to not just repeat previous research, it provides three significant differences:

- In contrast to other studies, it controlled the task conditions, which means that the participants worked in the focus task condition first. Only after that, they have completed the task of that condition and moved to the overview task condition. That enabled an opportunity to get a clearer picture of group behavior during specific conditions.
- Next, the study utilized mobile devices for interaction. That allowed users to move freely in front of the display interacting from any position.
- The study used fixed-position data, thus disallowing the participants to move data assets. Fixed-position data is an essential component of applications that work with spatial data. Spatial data - data where the position of individual data elements and their shape and size, have a meaning – is a part of many group activities, like network analysis, route creation, interior/exterior design, and disaster planning. Typical data examples within the mentioned application scenarios are

city maps, floor plans, and weather data [136]. The use of fixed-position data created the possibility, on the one hand, to investigate users' attitudes towards critical display regions. On the other hand, we could observe how users handle territoriality being disabled to shape territories employing asset grouping.

The study's objective was to (a) gain new insights into collaborative work on vertical LHRDs during an analytical task; (b) gather results that can be later compared to the results of a study with a creative task.

3.2 Study

Two tasks were implemented to observe group behavior during collaboration on LHRDs. The tasks were carefully designed based on the sensemaking tasks used by [50], [53], [2], and [146]. From those tasks, the user-system interaction patterns were extracted. Additionally, the analytics part was simplified for two reasons: time and participants. The pilot studies showed that adding more documents (e.g., pilot studies contained 280 documents instead of 140 documents) or making the question more complex results in increased time for task accomplishment. Mere to open and close 280 documents without reading required over 30 Minutes. The accumulated time needed to read, understand and solve a quiz question would take more than 2 hours for the first task only. On the other hand, observation revealed that the strategy the participants used by the task approach crystallized after 5-10 Minutes from the beginning of the task, so there was no reason to make the tasks too long.

Another reason for easing the analytics part was the goal of getting rid of a domain. Having a domain in the experiment requires many domain experts for the experiment. Employing non-domain participants would likely result in the decreased motivation of the latter and, subsequently, less meaningful results. So the solution was to keep the participants motivated throughout the experiment by replacing domain texts with quiz questions.

As a result, the mentioned manipulations made the tasks more abstract. However, using an abstract task in experiments is a common method in HCI (e.g. [68], [17], [91]). Nevertheless, the tasks can be mapped in terms of user-system interaction processes to many real-world task (e.g. data exploration and sensemaking (e.g.[35, 50]), data classification and sorting (e.g. [67, 69]), route construction (e.g. [136]), etc.).

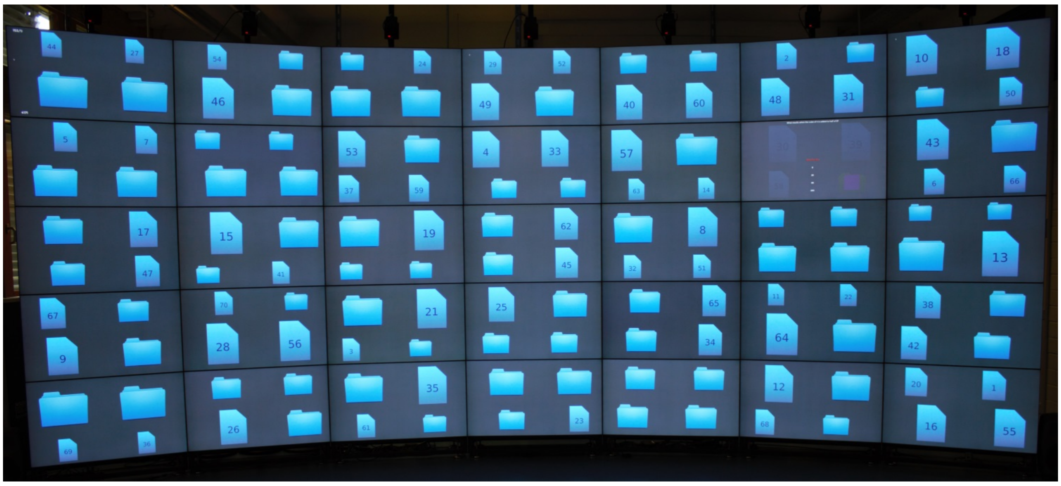

Figure 3.1: Focus Task: 140 symbols of folders and documents representing unprocessed and processed questions. The window in the top right corner shows a question with proposed answers.

Looking into all these tasks, one will find the same recurrent, canonical sub-processes:

- target identification - decide what target to approach first/next
- target selection - indicate the target for the system
- target understanding - learn and understand the content and properties of the target
- sensemaking - conclude the relevance/significance of the target

Moreover, this abstraction allowed for the separation of mixed-focus conditions, namely focus-condition and overview-condition. Subsequently, we could create two tasks for each condition.

3.2.1 Focus Task

The focus task resembled the information foraging process. This process is an integral part of a typical visual analytics task that involves the processing of many documents (e.g., [2, 35, 50]). The documents in the task had fixed positions on the display, which is a typical scenario for applications with spatial data, e.g., map-based applications. Use cases for such a scenario might include situations where analysts have to investigate a series of events at specific geographic locations, e.g., investigating home burglaries or identifying the best location for a new store in a particular region.

The task contained 70 processed, non-interactable documents and 70 documents with questions from mathematics and physics domains (see Appendix A.3). Mathematical questions required a medium level to a high level of concentration. It was expected that any person with the necessary math skills would be able to answer these questions. In contrast, many physics questions required advanced skills. Combining these two types of questions, we expected to promote transitions between different coupling styles: lack of knowledge in the physics domain should push participants towards tightly coupled collaboration. At the same time, mental arithmetic should instead dissolve tightly coupled collaboration.

Procedure. During the task, the participants had to process 70 documents. Each document contained a question and four possible answers. The system marked a document as processed when the participant answered the contained question. Processed documents could not be re-opened and re-answered. The document remained unprocessed if the participant closed it without providing an answer. The system considered the task as accomplished if the participants processed all documents. There was no time constraint, and the task ended as soon as the participants answered all questions. The system notified the participants of task completion through a background color change. It was up to the participants how they approached the task (e.g., divide documents and process them individually, or process all questions mutually), as no constraints in this regard were set.

Visual representation. At the beginning of the task, the display contained 70 processed documents and 70 unprocessed documents. The folder symbols represented unprocessed documents ("document is in the folder"-metaphor). The document symbols with an ID represented processed documents ("I took the document out of the folder"-metaphor). The symbols varied in size and had fixed positions on the display.

Each display unit contained four symbols. The system placed the symbols in a way that no bezels occluded any symbol. Each display unit could contain only one opened document since it filled in the entire display unit. Figure 3.1 shows a visual representation of the focus task with an open document.

Interaction. Each participant had a virtual cursor. The participants controlled the cursors using the swipe gesture on the provided smartphones. The participant had to place the cursor over the document and execute the tap gesture to open a document. With an open document, the participant could not control the cursor. Instead, the participant could activate an option. Four options were answers to the question. The fifth option was to close the document without providing an answer. The participant had to highlight it using the swipe gesture to activate an option, subsequently executing the tap gesture.

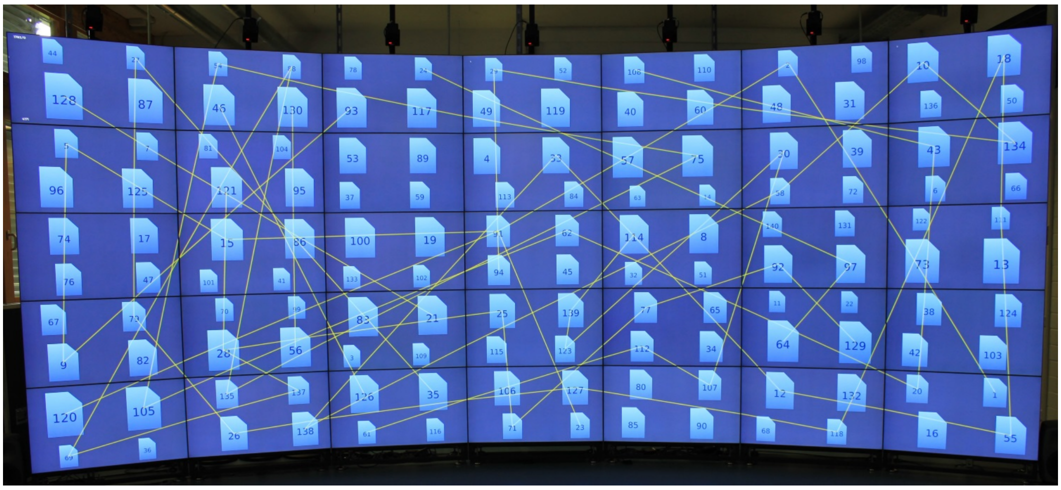

Figure 3.2: Overview Task: 140 document symbols connected by study participants, based on the documents' IDs.

Motivating user. Although the IDs on the document symbols were only relevant for the overview task, we decided to utilize them to motivate the participants not to guess too much. The participants got instructions that if they would provide a wrong answer to a question, the showed ID on the document would be wrong as well. As a result, the assessment of the overview task would be worse since the IDs serve as indicators for how the documents should be connected.

3.2.2 Overview Task

The overview task resembled a connecting facts activity. The activity is applicable, for instance, to connect visually similar home burglaries to visualize burglars' movements. If looking only at the interaction component of the activity, which is the subsequent execution of action at two different positions on a display, then the activity is directly comparable to any classification or sorting task (e.g., [67]). In the context of fixed-position data, this activity might be a part of a build a graph task, a backtrack a series of events task, or a route creation task.

Procedure. The participants had to connect all documents ensuing from the documents' IDs during the task, like with a Connect-the-Dots puzzle (Figure 3.2). For instance, the participant had to select (using the cursor) the document with the ID 3 and then connect it with the document that has the ID 4 or 2. In contrast to the focus task, however, the system did not notify the participants regarding task completion, so they had to decide whether they were finished. Similar to the focus task, there was no time constraint, and the participants did not receive any strategies prescriptions for task accomplishment. The participants could start with any ID and progress in different directions (e.g., connect 3 with 4, or 4 with 3).

Visual representation. The participants continued working on the data set from the focus task. Thus, at the beginning of the task, the display showed 140 document symbols. During the task, the participants added new connections between individual documents. The connections had a shape of thin yellow lines. The task's difficulty increased with the progress since each new connection cluttered the working area further. This design decision was made to see if increasing difficulty would affect the participants' chosen strategy. During the connection process, the system drew an additional line between a selected document and the virtual pointer.

Interaction. To connect two documents, the participant had to select them one after another using the swipe gesture to move the cursor and the tap gesture to select the document under the cursor. The connection could be aborted by putting the cursor in a space between documents and executing the tap gesture.

Motivating user. To force participants to work carefully, a feature for removing existing connections was omitted.

3.2.3 Design Justifications

The two different tasks were mainly designed to observe collaborative coupling and territorial behavior. This section reflects upon the design decisions and expected effects.

Collaborative Coupling. The focus task required good skills in mathematics and physics. Mathematical questions demanded a high level of concentration. In contrast, answers to physics questions were either known or not. The combination of these two types of questions should promote transitions between loosely and tightly coupled collaborative work. For example, lack of knowledge in the physics domain should push participants towards tightly coupled collaboration, while mental arithmetic should instead dissolve tightly coupled collaboration. The focus task should also allow for better subdivision of the task through spatial regions; for example, one can split documents based on display sides. Opposite to it, the overview task disabled this possibility. Thus, the expectation was that loosely coupled collaboration would dominate over tightly coupled collaboration during the focus task. In contrast, the overview task settings would rather result in converse user behavior. Additionally, there was an assumption that visual distractions caused by constant pointers' and lines' movement and increasing difficulty had to push participants even more towards close collaboration during the overview task.

Territoriality. The assumed decisions made to influence collaborative coupling should affect participants' territorial behavior as well. For example, the lack of possibility of dividing the task into sub-task based on display regions in the overview task should decrease the number of territory types drastically compared to the focus task. Since fixed-position data withdraws an important technique for territory creation, namely grouping, and the utilized interface implemented only one explicit territory (question window), there was a chance that these circumstances would mitigate territorial behavior. To counteract this, no visual elements of the interface (apart of pointers) were placed behind the bezels to provide a clear separation of display regions. Thus, it was expected to create some pseudo-grouping - using the gestalt principle of the common region [88] - and to increase territoriality sensation by participants. Additionally, the highest and the lowest row of the display were utilized to investigate participants' attitudes towards these critical regions and determine what types of territories are more suitable.

3.2.4 Participants

The experiment took place with 12 groups of two participants each, aged between 18 and 39 years (M = 25.08; SD = 4.90), with normal or corrected-to-normal vision. There were 11 female participants and 13 male participants. Random assignment of participants to groups yielded three types of group configurations: three male groups, two female groups, and seven mixed groups.

Seven groups contained participants that did not know each other and had never worked together. Four groups contained participants who did know each other and worked together on some projects in the past. Finally, one group contained participants who knew each other yet had never collaborated before.

With regards to language, seven groups contained participants with the same day-to-day language and five groups that contained participants with different day-to-day languages. All groups with different languages used the English language for communication.

The participants had rather an average level of computer games experience (M = 3.67; SD = 1.62) and mobile games experience (M = 3.08; SD = 1.35). Half of the participants had never seen LHRDs (12 participants 50%). Other participants had either already seen LHRDs (9 participants 37.5%) or even worked with them (3 participants 12.5%).

All participants had an academic background (students or research associates). Each participant got a payment for participating in the experiment and took part only once in the experiment.

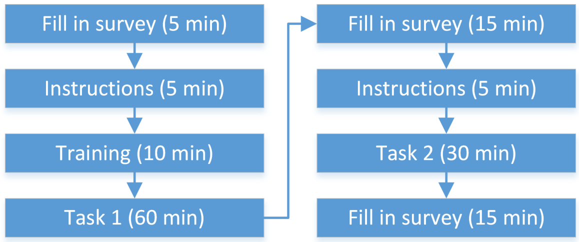

Figure 3.3: User study procedure: numbers in brackets show how much time in minutes participants required on average for individual phases.

3.2.5 Procedure and Data

The procedure comprised eight steps (Figure 3.3). First, the participants had to fill in a *personal survey* (see Appendix A.1) that encompassed questions regarding age, sex, first language, eyesight, wall-sized display experience, PC games experience, mobile game experience, height, and partner (co-user).

Next, the supervisor instructed the participants about the experiment procedure, explained the individual tasks, and how to interact with the application using the provided input device (*Instructions*). The supervisor also stressed the importance of teamwork, noted that it is up to participants how they will approach the tasks, and asked them to be as fast and as precise as possible. Finally, participants were instructed to stay in the tracking area that was bounded by the display in the front, by a thick white line on the floor in the back, and by the walls sideways.

The briefing was followed up by the training phase (*Training*). Participants were motivated to try out the interaction devices, solve some sample tasks, and ask questions. There was no time constraint for this stage. The transition to the focus task took place after both participants indicated their readiness.

After the completion of the focus task, the participants were asked to fill in a *questionnaire* (see Appendix A.2). The questionnaire encompassed multiple questions about different aspects of the study: interface, large display, the input device, and collaboration. The participants filled in the questionnaire twice, once after each task. We derived the questions from the NASA TLX questionnaire [47] (e.g., How mentally demanding was the task in general? How mentally demanding was it to work with such amount of data?). The participants answered the questions using a 7-point Likert scale.

Next, the overview task took place, followed by the questionnaire at the end.

During the study, quantitative and qualitative data were gathered. Quantitative data encompasses participants' position in front of the display (logged every 100 milliseconds), pointers' positions (logged on every position change), and task-related system events like opening a question and answering a question, and connection of documents. Qualitative data encompasses surveys, field notes, and video recordings. In total, we captured 877 minutes of video/audio data. Because of a defective camera, two experiment runs were recorded partially. That led to 65 minutes of lost video/audio data. Missing information could be acquired from field notes, however.

3.3 Results and Discussion

This section presents and discusses the results of the study. It starts with general information and feedback. Next, it looks at the participants' navigation patterns, different manifestations of collaborative coupling, and territorial behavior. For a better understanding of the results, groups with prior collaboration experience received the *pce = prior collaboration experience* subscript (e.g., group 7 is written as 7_{pce}).

3.3.1 General Feedback

The participants found the focus task more mentally demanding and more frustrating than the overview task (Table 3.1). Moreover, *questions answering* and *work with the given amount of data* were assessed as most mentally demanding and frustrating. In comparison, the *collaboration process* showed a rather low mental demand and did not frustrate the participants. Furthermore, the participants perceived it as successful.

Additionally, the participants assessed if the *interaction device and techniques were satisfying, easy to understand, and easy to master.* For both tasks, participants found the interaction device highly or rather satisfying (task 1: M = 6.08, SD = 0.70; task 2: M = 5.58, SD = 1.35), very comprehensible (task 1: M = 6.79, SD = 0.40; task 2: M = 6.67, SD = 0.55), and very easy to use (task 1: M = 6.79, SD = 0.40; task 2: M = 6.25, SD = 1.13). Although users appreciated the possibility to adjust pointer properties, they rarely made use of it. During the focus task only one user per group (in 8 of 12 groups) changed pointer properties.

3.3.2 Physical and Virtual Navigation Behavior

As expected, groups' behavior in terms of navigation behavior was different in the focus task condition than in the overview task condition. At the beginning of the focus task, 2 out of 12 groups decided to work tightly and process the documents mutually. Both groups started on a random display unit, switched, however, soon to the most left/right column, and proceeded the documents in a column by column manner. Figure 3.4 (bottom) exemplifies the behavior. Since the participants opened

	Mental Demand	Performance	Effort	Frustration
Task 1				
In general	M = 5.50 SD=1.15	M = 3.54 SD=0.81	M = 5.16 SD=0.98	M = 4.46 SD=1.44
Data amount	M = 4.25 SD=1.53	M = 3.33 SD=0.94	M = 4.20 SD=1.32	M = 3.75 SD=1.59
Collaboration	M = 2.29 SD=1.17	M = 2.79 SD=1.22	M = 3.12 SD=1.45	M = 2.12 SD=1.45
Questions	M = 5.33 SD=1.34	M = 4.00 SD=1.00	M = 5.04 SD=0.79	M = 4.54 SD=1.55
Task 2				
In general	M = 4.08 SD=1.91	M = 2.25 SD=1.30	M = 4.79 SD=1.38	M = 3.54 SD=1.8
Data amount	M = 4.67 SD=1.65	M = 2.25 SD=1.30	M = 4.79 SD=1.38	M = 3.58 SD=1.75
Collaboration	M = 2.58 SD=1.68	M = 2.16 SD=1.34	M = 3.46 SD=1.5	M = 2.42 SD=1.47

Table 3.1: Assessment of different aspects of the focus and overview tasks by the participants: Mental Demand (1 - low demand, 7 - high demand); Performance (1 - Perfect, 7 - Failure); Effort (1 - low, 7 - high); Frustration (1 - low, 7 - high). The questions were regarding the task *in general* (How mentally demanding was the task? How successful was the participant? How hard did the participant work? How frustrated was the participant?), *data amount* (e.g., How mentally demanding was it to work with that amount of data?), *collaboration* (e.g., How mentally demanding was collaboration?), and *questions* (e.g., How mentally demanding was answering of the questions?)

documents alternately, the pointer position-maps of individual users complement each other. The remaining 10 out of 12 groups went for the "divide and conquer" strategy and partitioned the display into the "left" and the "right" regions. Each participant oversaw one region depending on his spatial position relative to the display and the partner. No distinct boundaries between these two regions were observed. Within the region. Figure 3.4 (top) depicts the behavior.

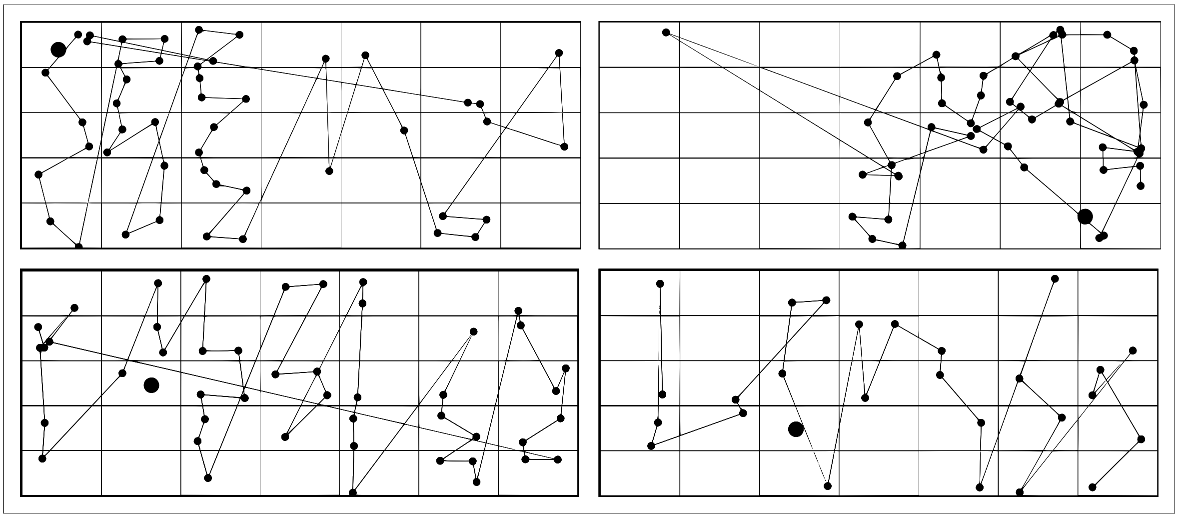

Figure 3.4: Logged pointers' positions during OpenTask-Events, each line connects two consecutive events: (top) participants A (left) and B (right) working loosely; (bottom) participants A (left) and B (right) working tightly.

While participants proceeded with solving questions, repetitive behavior could be recognized. Multiple participants tried to solve all questions inside one display unit before moving to the next one. Moreover, the movement between display units was column-oriented. For example, the participant started with the topmost display unit of the leftmost column, solved all the questions inside it, and moved the pointer to the display unit beneath the current one. The participant worked in this manner until the column was processed. Next, the participant moved the pointer to the column on the right and continued in the same manner, starting either again from the top or staying at the bottom and working upwards.

However, within the groups that worked loosely, the workflow did not last until the task's end. Instead, it took place until participants met in the middle of the display. After that, participants switched the sides to answer the questions left by their partner or started to work tightly-coupled and answered remained questions mutually.

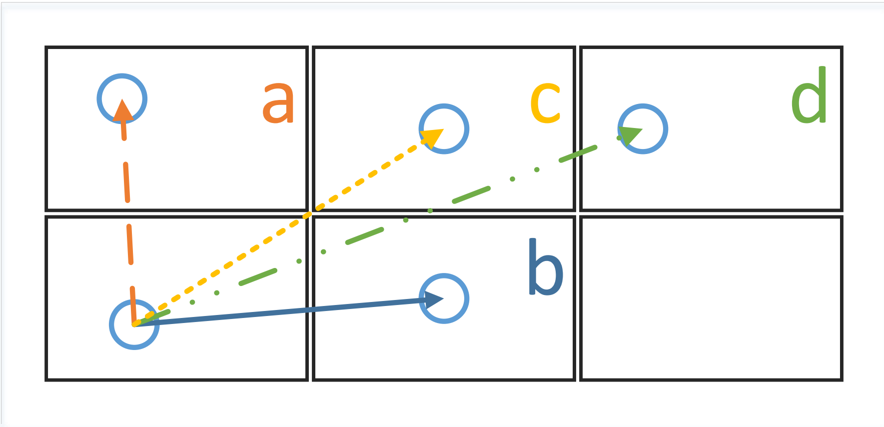

Figure 3.5: Transition types: (a) direct vertical neighbor; (b) direct horizontal neighbor; (c) indirect neighbor; (d) jump.

The logs of documents' positions on the display units and the timestamps of OpenDocument-Events helped to compare different virtual-navigation strategies. For that, all transition from one display unit to another were classified into four groups (see Figure 3.5):

- Direct vertical neighbor - the participant transitioned to a display unit directly above or beneath the current display unit.
- Direct horizontal neighbor - the participant transitioned to a display unit directly to the left or directly to the right of the current display unit.
- Indirect neighbor - the participant transitioned to a diagonally adjacent display unit.
- Jump - the participant transitioned to a non-adjacent display unit.

The Friedman test was carried out to examine any differences between the occurrences of individual virtual-navigation strategies. The result showed a significant difference, $\chi^2(3)$=40.269, $p < 0.001$. Dunn-Bonferroni post hoc tests were carried out and revealed significant differences between the types: indirect neighbor and jump (p = 0.026), indirect neighbor and direct vertical neighbor ($p < 0.001$), direct horizontal neighbor and direct vertical neighbor ($p < 0.001$), jump and direct vertical neighbor (p = 0.015). Thus, the participants navigated significantly more often using the direct vertical neighbor pattern than the other patterns. The tendency for the direct vertical neighbor pattern is also visible in the box plot diagram (see Figure 3.6). The participants were also questioned regarding interior bezels just after completing the task. Only one person stated the bezels were distracting since they hindered to perceive the display as a single continuous surface. The other 23 participants stated that the bezels were not distracting.

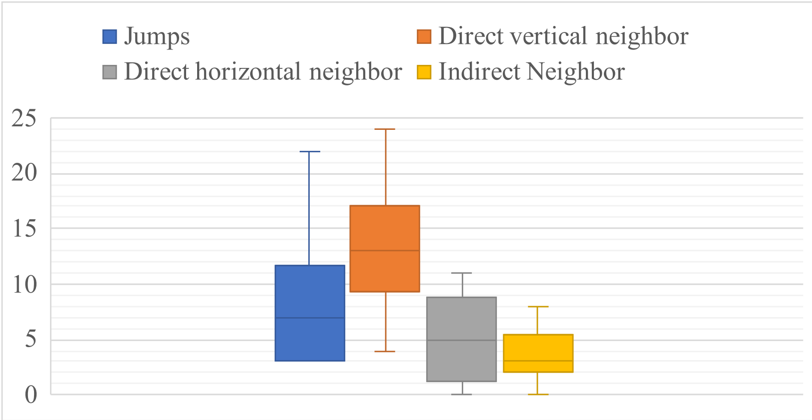

Figure 3.6: Occurrences of transition types: Y-axis represents number of transitions.

The workflow adopted by the participants during the focus task affected physical navigation. The participants walked a lot along the LHRD and switched sides. The participant's position in front of the display depended directly on what display (or displays' column) the participants worked.

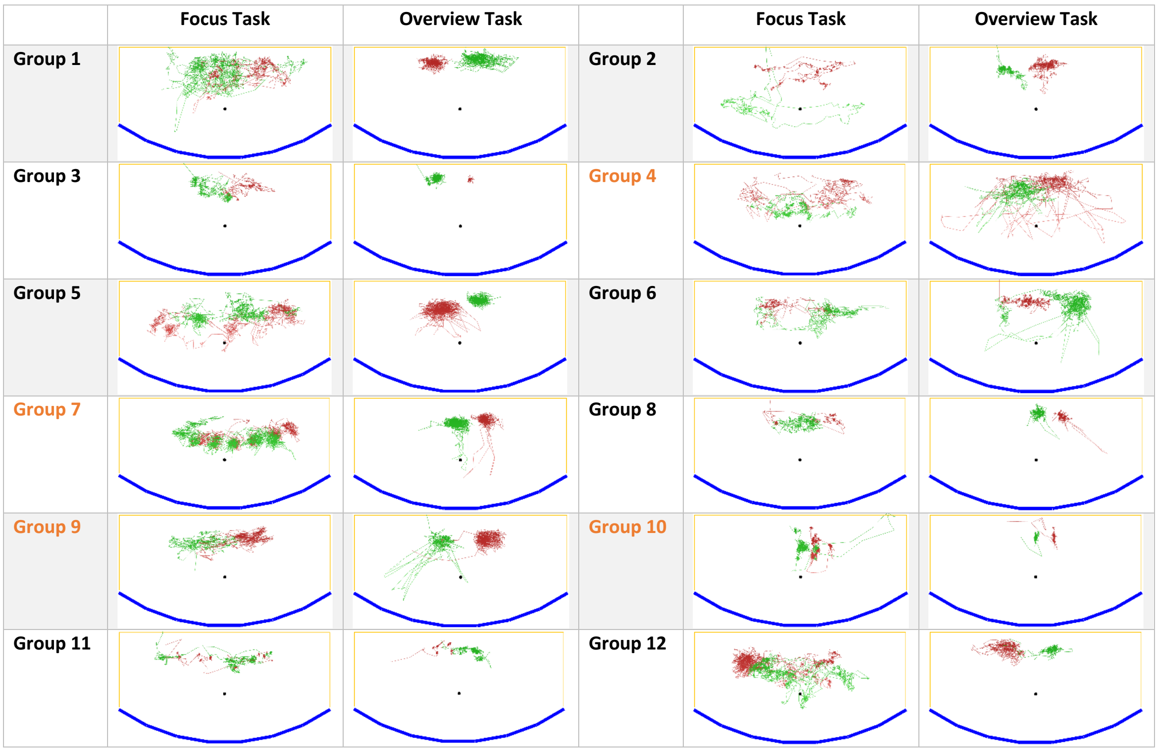

Figure 3.7: Participants' movements during the focus and overview tasks: blue – the wall-sized display, yellow – the boundaries of tracking/working area, green and red – participants' movements. Groups 4, 7, 9, 10 had prior collaboration experience.

During the overview task, the groups' navigation behavior was less thrilling. The participants mostly remained in place, preferring to use more subtle head movements instead of body movements for physical navigation. This behavior can be again ascribed to the specifics of the task condition. In the overview task, the participants could not apply the same strategy as in the focus task since the documents that must be connected could lie in the different areas of the LHRD. Therefore, the participants positioned themselves at the most comfortable spots for overviewing the entire LHRD. Of course, such behavior can be partly attributed to the curved display. However, considering the user's distance to the display and the display's dimension, it is to be expected that a similar behavior would also occur with a flat display of a similar size. Figure 3.7 visualized the differences in physical navigation during different task conditions.

The observation and data analysis revealed a virtual navigation pattern during the focus task condition. This pattern affected the physical navigation behavior of the participants. However, what are the reasons for such behavior? Considering psychological and physical factors, several explanations can be provided.

One possible explanation could be that visual boundaries of display regions formed by bezels induced a feeling of element grouping according to the gestalt principle of common region [88]. Thus, participants would like to finish work in "one" region before moving to the next one. A similar perception of the display area was observed by Andrews et al. [2], and Grudin [36]. Such workflow would also ease tracking of progress for users since the display could be used as external memory [2] in that case.

Column-oriented movements could be motivated by large display size in conjunction with a tendency to reduce physical navigation, as row-oriented workflow would require more walking. Like with display units, column-oriented movement allows easier tracking of progress for participants and reduces search activity. For example, the participant always knows that all questions left to the column she is currently working on are processed. Since the pattern was observed by tightly working groups as well as by loosely working groups, we can exclude the possibility of a second user presence affecting the pattern.

Although most participants barely perceived the interior bezels, they seemed to affect the participants' behavior vigorously. Thus, interior bezels could be exploited by user interface designers to support users better or direct them in the desired way. For instance, one can group elements of a graph using bezels to highlight their relationship. Moreover, knowing what effect the bezels and display size have on the users' behavior, designers become able to predict users' actions and build more intelligent interfaces. For instance, the system can pre-load complex data, pre-calculate a complex visualization, or do some other pre-procession for those elements which the user will open next.

3.3.3 Collaborative coupling

As mentioned above, the process of collaborative coupling can be expressed, among others, by collaboration tightness, coupling styles, user roles, and task subdivision strategies. This section looks into the effects of task conditions on different collaborative coupling manifestations.

Collaboration tightness

Overall, the participants spent equal amount of time working loosely coupled ($\Sigma = 14702sec; M = 1225.16; SD = 601.46$) and tightly coupled ($\Sigma = 1257sec; M = 1257.67; SD = 1350.67$) during the focus task. Groups 7_{pce} and 10_{pce} worked predominantly tightly coupled, while groups 1 and 2 worked predominantly loosely coupled. The other eight groups frequently switched between loosely and tightly coupled collaboration (see Figure 3.8), thus exposing a typical mixed-focus collaboration workflow. During the overview tasks, the participants made transitions less frequently (see Figures 3.8, 3.9), and spent more time working loosely coupled ($\Sigma = 13256sec; M = 1104.67; SD = 670.14$) than tightly coupled ($\Sigma = 7532sec; M = 627.67; SD = 647.29$).

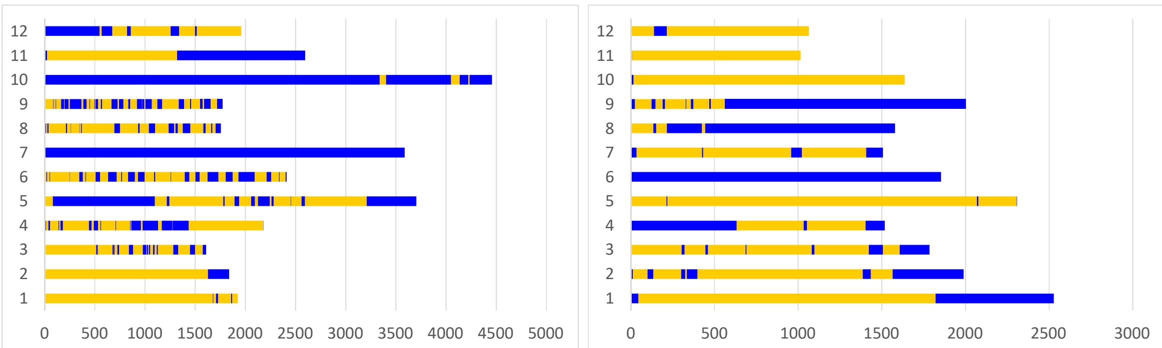

Figure 3.8: Periods of loosely coupled and tightly coupled work during the focus task (left) and the overview task (right): the Y-axis represents individual groups. TheX-axis shows durations of loosely (yellow) and tightly (blue) coupled work periods in seconds, as well as time points of transitions. Groups 4, 7, 9, 10 had prior collaboration experience.

Additionally, groups with and without previous mutual experience of cooperative work exposed a significant difference in collaboration tightness during the focus task. The groups with previous mutual experience discussed individual questions more frequently.

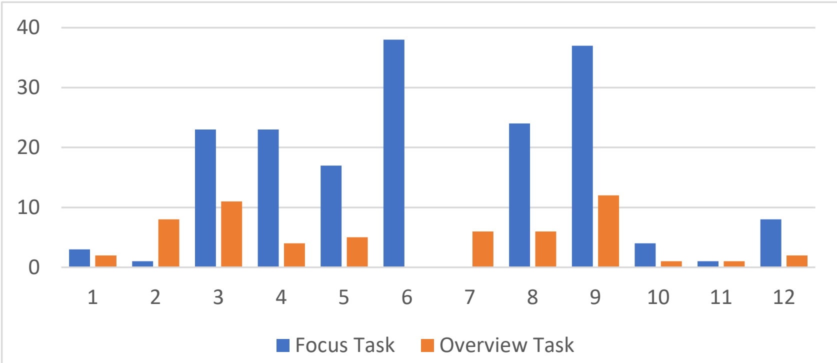

Figure 3.9: Number of transitions per group: the X-axis represents individual groups. The Y-axis shows the number of transitions (blue - focus task, orange - overview task). Groups 4, 7, 9, 10 had prior collaboration experience.

The observation was confirmed by quantitative data as well. For that, the CloseTask-Event was utilized as an indicator of intra-group behavior. The event was fired by the system each time the participant closed a document without answering a question. The result revealed that groups with previous mutual experience of cooperative work left significantly fewer questions for later (mean = 10.00 SD = 6,37) in comparison to the groups where participants have never worked together (mean = 39.71 SD = 17.75) (Mann-Whitney U test, p = 0.018). Figure 3.10 depicts the difference. Most CloseTask-Events (84) exposed the group where participants knew each other yet have never worked together.

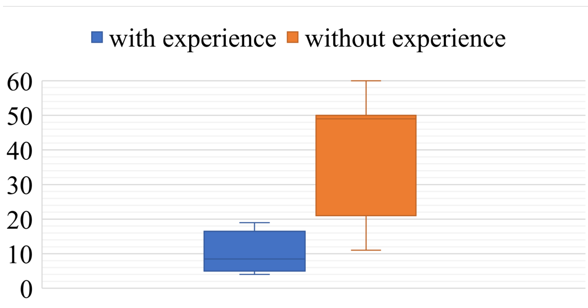

Figure 3.10: Number of CloseTask-events for groups with and without previous mutual collaboration experience.

The findings show that task conditions have a significant effect on collaborative tightness. On the one hand, during tasks that require an advanced level of expertise in a task-related domain (like in the focus task), users can experience a lack of knowledge or uncertainty. In this case, three possible reactions were possible: the participant would guess and answer; the participant would ask for help; the participant would close the question without answering it. As a result, a particular group type will expose firm mixed-focus collaboration behavior. On the other hand, tasks that do not require any particular knowledge, but diligence only, will instead proceed in a loosely coupled manner. That means that putting users in a collaborative environment does not automatically cause collaboration. For instance, observation revealed extreme cases where participants processed only a few last documents mutually.

Consequently, one must consider and support both collaborative coupling types when designing a groupware system for sensemaking or any other complex task. Considering the finding, designers could improve their systems, allowing for displaying the document content on the smartphone. That would reduce visual clutter on the shared display, causing less distraction for groups working loosely. Groups working tightly together could still open documents on the large display or share the smartphone display. A better solution is to utilize a system that can automatically recognize the current state of collaboration tightness and adjust interaction and visualization modalities appropriately.

Coupling Styles

During the study and while analyzing video recordings, collaborative coupling styles were analyzed. The coding schemes of coupling presented in [50, 136] and their combinations were utilized as templates for the observations. Since the schemata are problem-based, the tasks' problems were defined as follows: answer a question – for the focus task; find a match for document A – for the overview task. The employed interface did not allow for coupling style *"same problem, different areas"* [50] during the focus task, as well as *"same information, different views"* and *"same problem, different informations"* [50] during both tasks. Thus, we excluded these codes from the set.

At the beginning of each task, a short coordination phase took place (similar to *discussion* style in [50]), where participants discussed how they should approach the task. Only two groups in the focus task and one group in the overview task went for tightly coupled collaboration where participants processed questions or connected documents mutually ("same problem, same area" style [136, 50]).

The analysis yielded matches for each coupling style in the set (see Table 3.2). The most common style was "different problems" [136, 50]. Additionally, 6 of 12 groups exposed an interesting coupling style periodically during the overview task. It is, though, even for humans hard to detect. First, the participants were working loosely. Then at some point, one participant asked the partner for help (e.g., *"I am looking for X, if you see it, then tell me."*). That caused the transition to a new coupling. Starting from this point, participants worked both loosely- and tightly-coupled trying to solve their problem and their partner's problem as well. Liu et al. observed similar behavior [67].

Styles	Tang et. al [136]	Isenberg et. al [50]	Our Study Task 1	Our Study Task 2
Discussion		•	•	•
Same problem, same area	•	•	•	•
View engaged	•	•	•	•
Disengaged	•	•	•	•
Different problems	•	•	•	•
Same general problem		•	•	•
Same problem, different areas	•	•	ex	•
Same information, different views		•	ex	ex
Same problem, different informations		•	ex	ex
One working, another viewing	•		•	•
Multiple problems, different areas				•

Table 3.2: Collaborative coupling styles observed by Tang et. al [136], by Isenberg et. al [50], and in our study (• = observed, ex = excluded). The style *multiple problems, different areas* have not been observed in previous studies.

Our result, as well as results from previous research on collaborative coupling, e.g., [136, 50], shows that environment and task characteristics (e.g., fixed-position data) might affect what coupling styles users will (be able to) employ. In our study, however, the task conditions had a marginal effect on coupling styles since we could observe almost all of them in both conditions. However, we suggest investigating coupling styles for each specific task, task setting, and system type. For instance, what will happen if more than two persons collaborate? *Will new styles emerge or some known styles vanish? Will two discussing people distract the third one, who is currently working loosely? If so, should we incorporate mechanics for protection, or is the distraction level negligible?*

The analysis yielded that the schemes for coupling styles constructed through users' visual attention and level of verbal communication cannot express coupling in-depth. For instance, the view engaged coupling style described in [50] and [136] is typical for a partner-partner relationship. However, the study exposed the view engaged coupling in the context of a leader-assistant relationship as well. If the leader was the view-engaged user, the assistant was the one who interacted, and the leader commented/gave instructions. In case the roles were differently distributed, the leader was the one who interacted and commented/gave instructions. The assistant remained still view-engaged yet communicated rarely. Therefore, we suggest adding user roles to the coupling style classification.

User Roles

The observation analysis revealed five user roles for tightly coupled work. The leader and assistant roles were observed during the focus task only while the finder and executor roles were observed during the overview task only:

- *Partner*: both users have equal rights. This role was common for strategy discussions, situations where both participants did not know the right answer, and by opening the questions. "Do you agree?" and "Is it OK with you?" were phrases that often indicated the phases of partnership.
- *Leader*: the user who makes decisions and issues orders. We observed the role during the opening and answering the questions. The leader was usually the one who talked. Leaders decided what questions to open next and how to approach questions. Though often delegated this task to their assistant, leaders often interacted with the system by themselves.
- *Assistant*: the user who is the counterpart of the leader. They executed orders, helped if asked, and rarely made suggestions. Often, if the leader did not delegate any tasks to the assistant for a while, the assistant would part from the leader and started to work loosely coupled.
- *Executor*: the user who connects documents during the second task. Similar to partners, we did not observe any hierarchy by executor and finder.
- *Finder*: the user who searches for a match. We observed two cases. In the first case, there was a permanent finder, who looked for a match and actively indicated (verbal, using gestures and virtual pointer) to the executor, and continued looking for the next match. In the second case, there were two finders, and the executor role was assigned dynamically (the one who could perform connection faster became an executor, the other continued searching for the next match).

The observed user roles fit any analytics task (partner, leader, assistant), and any classification/sorting task (executor, finder). For instance, the leader-assistant roles are similar to sensemaker-forager roles described in [146], yet describe the relationship and user activities in a more general way. Previous research on user roles, e.g., [146], suggests fostering user roles in groupware, for instance, employing different interfaces, views, and filters. However, user interfaces should support the dynamic switch of user roles in this case. During the study, the participants exposed a frequent change of user roles. Partners became leader and assistant; leaders became assistants; executors became finders and vice versa. Groupware systems should ensure equal input possibilities for all users and the seamless transfer of territorial rights to support such dynamics. Equal input possibilities will allow users to undertake different activities without negotiating much. Coordination of actions can diminish in that case to verbal notification of intentions (e.g., "I will connect these documents" or "I will put this document in the bucket"). Settings that provide only one input device for all users will likely increase coordination costs, thus making the roles more rigid and impeding collaboration [101].

The seamless transfer of territorial rights is another important design factor. In our study, the participant who opened a document became its owner and acquired rights for interaction with it. In case the owner had the assistant role, the leader – being unable to control the document – had to instruct what answer to choose. However, such limitations might become an issue if a more sophisticated input is required. In this case, the possibility to hand over ownership rights for a document (or a territory, if talking in more general terms) will allow for a more flexible collaboration flow.

Task subdivision strategies

Most groups decided to subdivide the focus task into spatial regions since its design predestines to such a decision. Tse et al. detected similar behavior [143]. Opposite to the focus task, we assumed that the absence of the possibility for the spatial subdivision would force participants to work tightly coupled. The results, however, did not confirm the assumption. The participants split the documents by IDs (e.g., from 1 upwards to 70 and 140 downwards to 70). For both tasks, we extracted the following strategies:

- Different Documents Tightly (DDT) – The participants worked predominantly on different documents (focus task) or searched for different connections (overview task). During the focus task, the participants usually portioned the display into the left and right parts; and split the documents by ID during the overview task. However, they transitioned frequently to tightly coupled work for discussion or help. Compared with other strategies, the participants left fewer documents for later during the focus task.

- Different Documents Loosely (DDL) – Same as DDT, however, the participants transitioned rarely from loosely to tightly coupled work. Mostly, these transitions took place at the end of the task (e.g., discussion of a few remaining questions or connection of a few remaining documents).
- Same Document Tightly (SDT) – The participants worked together on one question at a time (focus task) or looked for the same connection (overview task). They interacted alternately with the system and exposed rarely or no transitions to loosely-coupled work.

Table 3.3 summarizes while Figures 3.11 and 3.12 exemplify based on log data different strategies for tasks subdivision the groups applied.

Strategy	# of occurrences (focus task / overview task)
DDT	3 / 1 + (3)
DDL	7 / 7 + (1)
SDT	2 / 1 + (2)

Table 3.3: Task processing strategies (the digit in the brackets indicates the number of groups that exposed the strategy, though did not use it as a dominant strategy): during the focus task three groups exposed the *Different Documents Tightly* strategy predominantly, seven the *Different Documents Loosely* strategy, and two the *Same Document Tightly* strategy. During the overview task, one group exposed the *Different Documents Tightly* strategy predominantly and three groups partially; seven groups exposed the *Different Documents Loosely* strategy predominantly and one group partially; and one group exposed the *Same Document Tightly* strategy predominantly and two groups partially.

The results differ from previous research, e.g., [136], where participants worked mostly in a tightly coupled manner. As discussed above, previous mutual collaboration experience seems to have an impact. However, the observations suggest that other factors might be in play as well. For instance, participants who worked predominantly loosely coupled at the beginning of tasks tended to work more tightly at the end of tasks. Since the tasks at the end were more challenging than at the beginning (e.g., it was more challenging to find remained connections because of visual clutter). Thus an assumption can be made that the easiness of the task should have an influence, as well as the size of the display in conjunction with fixed-position data.

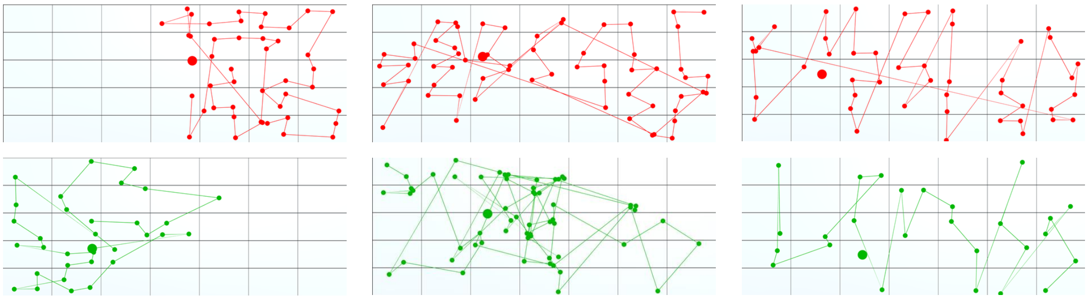

Figure 3.11: Task subdivision strategies during the focus task: (left) *Different Documents Tightly*, (middle) *Different Documents Loosely*, (right) *Single Document Tightly*. The dots visualize positions of the cursors (top – participant 1, bottom – participant 2) during OpenTask-Events. Each line connects two consecutive events. The participants who adopted the DDT strategy worked primarily in different display regions. Though they helped each other if needed and left fewer documents for later. As a result, we can see a clear cut between the two areas. The participants who adopted the DDL strategy started similarly in different display regions, communicated, however, not much and left many documents for later. Subsequently, after the participant met in the middle of the display, they switched sides and continued to work loosely-coupled. Finally, the participants who adopted the SDT strategy worked tightly-coupled and opened documents alternately. As a result, the visualizations of the OpenTask-Events of both participants complement each other.

This configuration drove apart many participants during the focus task because of their strategy to partition the task spatially (left and right side). In comparison, the displays used by Tang et al. did not allow for long distances between participants [136], and the setting utilized by Jakobsen et al. did not contain fixed-position data [53]. Moreover, the observation revealed that when participants stood close together, they tended to work more tightly.

Transitions

For a group of two users, transitions are defined as an *action* of the *user X* followed by a *reaction* of the *user Y*. Actions and reactions themselves are compound events that consist of one or more *detectable user activities*. Table 3.4 contains a set of the utilized user activities. Additionally, for each activity, the table suggests a sensor type for activity detection.

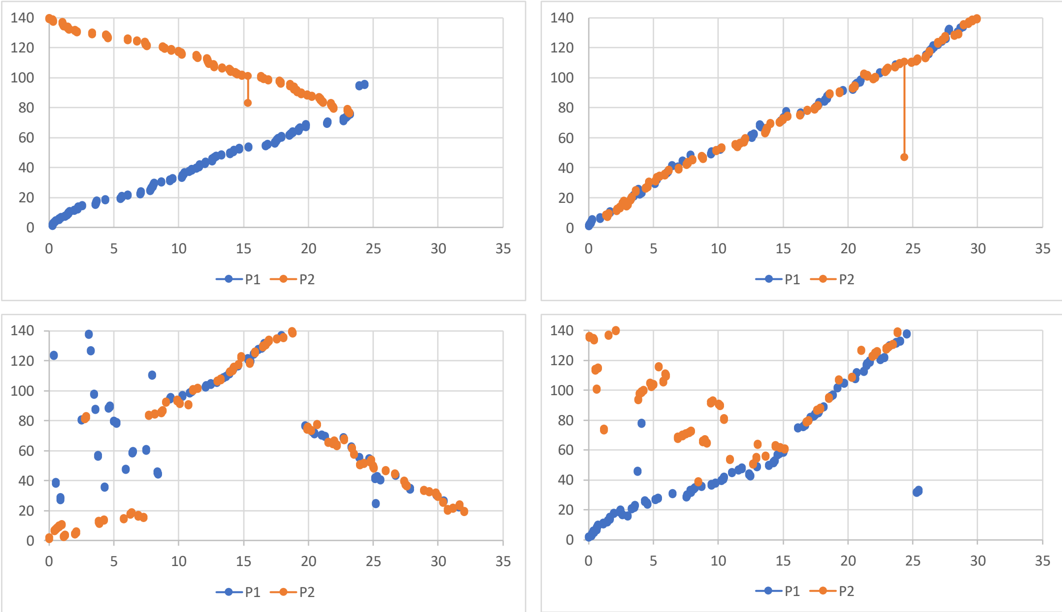

Figure 3.12: Task subdivision strategies during the overview task: (top-left) *Different Documents Loosely* – the participants started with two different IDs and worked loosely until the end; (top-right) *Single Document Tightly* – participants worked at one connection at a time; (bottom-left) *Different Documents Tightly* – although the plot is similar to one showing the *Single Document Tightly* strategy, the participants worked on two different connections at a time, yet very tightly; (bottom-right) participants started with the *Different Documents Loosely* strategy, switched, however, to the *Single Document Tightly* in the middle of the task. The Y-axis represents document IDs (from 1 to 140). The X-axis is a timeline (from 0 to 35 minutes). Every two dots with a line in between (blue – participant 1, orange – participant 2) visualize what documents the participants connected at what time. The more significant the difference between IDs of two connected documents, the longer is a line.

During the focus task, 90 transitions from loosely to tightly coupled work took place, and 83 transitions in the other direction. Figure 3.9 depicts a distribution of the transitions among individual groups. Most groups (8 of 12) performed significantly more transitions during the focus task; groups 1 and 11 performed an approximately equal number of transitions during both tasks. In comparison, groups 2 and 7_{pce} performed more transitions in the overview task. This circumstance could be the result of the task nature. While the overview task required diligence only and could be solved without any help, the focus task required domain knowledge that should be acquired from the partner in case of absence.

Table 3.4: Detectable user activities utilized for composition of actions and reactions. For each activity an appropriate sensor type for detection is proposed.

Activity	Shortcut	Sensor Type(s)
Reduce Distance	RD	Motion tracker
Increase Distance	ID	Motion tracker
Talk	T	Microphone
Fall Silent	FS	Microphone
Focus Partner	FP	Eye tracker, Motion tracker
Join View	JV	Eye tracker, Motion tracker
Disjoin View	DV	Eye tracker, Motion tracker
Make Gesture	MG	Motion tracker, RGB(D) Camera
Close View	CV	Detectable by an application

Please note that the following results are related to the focus task only. The reasons for that are addressed in the subsection (*Focus versus Overview*). Ten action types and eight reaction types for the transitions from loosely to tightly coupled work could be recognized. The reverse transitions, with four action types and four reaction types, were less manifold. Tables 3.6 and 3.7 present the transitions from loosely to tightly coupled work and vice versa respectively. The leftmost column contains observed actions, while the topmost row contains observed reactions. Each intersection shows how many times an action resulted in a particular reaction. The codes in brackets indicate from what initial state to what resulting state the action-reaction chain led, refer to the Table 3.5 for codes explanations. The results reveal (a) the most common constellations of action-reaction pairs that lead to tightly or loosely coupled work, (b) the importance weights of activities for actions and reactions.

Verbal Communication. As expected, verbal communication turned out to be a critical indicator of collaboration tightness. For instance, all action and reaction types of the transitions from tightly to loosely-coupled work included the *Fall Silent* activity. The most frequent reaction type (49 occurrences of 83) consisted solely of this activity.

In the case of the transitions from loosely to tightly coupled work, verbal communication played an important role, though for actions only. In total, 87 of 90 observed actions contained this activity. Interestingly enough, the most frequent action (34 occurrences of 90) consisted of the *Talking* activity only.

Table 3.5: Group states: initial (I_x) and resulting states (R_y) describe group states before and after, respectively, a transition took place.

States	Description
I_1	different views, silent, distance D_1
I_2	same view, talking, distance D_1
I_3	different views, talking, distance D_1
R_1	different views, talking, distance D_2 ($D_1 > D_2$)
R_2	same view, talking, distance D_1
R_3	same view, talking, distance D_2 ($D_1 > D_2$)
R_4	same view, silent, distance D_2 ($D_1 > D_2$)
R_5	different views, silent, distance D_2 ($D_1 < D_2$)
R_6	different views, silent, distance D_1

It seems that the participants perceived the *Talking* activity as the most efficient and effective approach for the attraction of their partners' attention. That showed, however, that in more than 30 percent of cases, the participants did not experience any urge to check their partners' current activity before interrupting them. Consequently, social protocols could not be considered a reliable work coordination instrument.

For the reactions, the *Talking* activity was less critical. In total, 34 of the 90 reactions contained the activity. Moreover, none of the most frequent reactions contained it.

Visual Attention. We coded changes in visual attention through three activities: *Join View*, *Disjoin View*, and *Focus Partner*. The *Join View* activity refers to a process of focusing on a display area the partner is looking at (e.g., a window containing a question). In contrast, the *Disjoin View* activity refers to a reverse process. The *Focus Partner* activity refers to a process of focusing on the partner himself instead of a display area. Please note that in cases when the *Focus Partner* activity was followed by the *Join View* activity, we did not include the latter in the code to keep the code simple.

For the transitions from loosely to tightly coupled work, the results indicated the significant importance of visual attention for the reactions. In total, 80 of 90 observed reactions contained either the *Join View* (72 occurrences) or the *Focus Partner* (8 occurrences) activity. In contrast, for the actions, changes in visual attention were marginal. In total, 21 occurrences of the *Focus Partner* activity and 13 occurrences of the *Join View* activity were observed.

Table 3.6: Transitions during the focus task: from loosely to tightly coupled work. The leftmost column contains action codes (AC). The topmost row contains reaction codes (RC). Each intersection shows how many times an action resulted in a particular reaction. The codes in brackets indicate from what initial state (I_x) to what resulting state (R_y) the action-reaction chain led.

AC \ RC	T	JV+T	RD+JV+T	JV	RD+JV	FP+T	RD+FP+T	FP	Sum
RD	1 (I_1R_1)	–	–	–	–	–	–	–	1
T	–	6 (I_1R_2)	10 (I_1R_3)	13 (I_1R_2)	5 (I_1R_3)	–	–	–	***34***
T+FP	–	–	–	2 (I_1R_3)	9 (I_1R_3)	–	–	–	11
RD+FP+T	–	–	–	1 (I_1R_1)	5 (I_1R_3)	2 (I_1R_1)	2 (I_1R_1)	–	10
RD+JV+T	3 (I_1R_3)	–	–	–	–	2 (I_1R_3)	–	–	5
RD+T	–	–	–	3 (I_1R_4)	6 (I_1R_4)	–	–	–	9
RD+JV	–	–	–	–	–	2 (I_1R_3)	–	–	2
RD+MG+T	–	–	2 (I_1R_3)	–	1 (I_1R_3)	–	–	–	3
MG+T	–	–	–	8 (I_1R_2)	1 (I_1R_3)	–	–	–	9
JV+T	4 (I_1R_2)	–	–	–	–	–	–	2 (I_1R_2)	6
Sum	8	6	12	***27***	***27***	6	2	2	90

Table 3.7: Transitions during the focus task: from tightly to loosely coupled work. Same layout and meaning as in the Table 3.6.

AC \ RC	ID+FS	FS	DV+ID+FS	DV+FS	Sum
DV+ID+FS	1 (I_2R_5)	25 (I_2R_5)	1 (I_2R_5)	–	***27***
FS	1 (I_3R_5)	1 (I_3R_6)	2 (I_2R_5)	4 (I_2R_6)	8
DV+FS	–	23 (I_2R_6)	–	1 (I_2R_6)	***24***
CV+FS	–	–	6 (I_2R_5)	18 (I_2R_6)	***24***
Sum	2	***49***	9	***23***	83

We can conclude that, during transitions from loosely to tightly coupled work, importance-weights of visual attention are distributed inversely to the importance-weights of verbal communication among actions and reactions.

The transitions from tightly to loosely-coupled work expressed more visual attention activities (*Disjoin View*) for the actions (51 occurrences of 83) than for the reactions (32 occurrences of 83). That was caused mainly by switching of the roles: reacting users, who joined their partners' views, became acting users and had to return to their views. Therefore, visual anchors in the form of working areas are essential for the detection of transitions between collaborative states. They increase the importance-weight of visual attention-related activities.

Proximity. Researchers observed correlations between changes in users' proximity and changes in collaboration tightness [53, 153]. They detected that users reduce the distance to each other while switching from loosely to tightly coupled work. However, other researchers showed that tightly coupled collaboration could occur at more remote distances, too [67]. Indeed, the focus task exposed the phenomena of proximity change (*Increase Distance*, and *Reduce Distance* activities). During the transitions from loosely to tightly coupled work (30 of 90 actions and 41 of 90 reactions contained the *Reduce Distance* activity) and vice versa (27 of 83 actions and 11 of 83 reactions contained the *Increase Distance* activity). The amplitude of the individual activities depended on the initial distance between the participants (during transitions from loosely to tightly coupled work). It also depends on the distance between the disjoining participant and his view (during transitions from tightly to loosely-coupled work).

Proximity change served, on the one hand, as an indicator of increased attention towards the partner. On the other hand, the participants utilized it to take a more favorable position relative to a visual view. That shows again how critical visual anchors are for transition detection. Visual anchors promote physical navigation, and as a result, increase the importance-weights of the proximity-related activities.

Gestures. The participants primarily employed one gesture type, namely a pointing gesture towards an opened question window. This gesture was utilized as the *Make Gesture* activity. In total, 12 occurrences of this activity were detected. All occurrences were parts of the actions that took place during the transitions from loosely to tightly coupled work. In the scenario where each participant could open only one window at a time, the activity had low importance weight and was often unnecessary. However, the importance-weight can increase in the case of cluttered displays (e.g., similar to studies in [2, 49]).

System events. During the study, application events related to user activities were logged, e.g., CloseView-events, OpenView-events. No event type except for the *CloseView*-event affected participants' collaboration states. Thus, we utilized the event as an activity and looked for occurrences. Moreover, the activity appeared only by the transitions from tightly- to loosely-coupled work within the actions only. In total, we observed 24 actions (out of 83) containing it. The activity signalized the attainment of a problem's solution. After that, a disjoining activity was triggered. In general, virtual activities seemed to have a low importance weight.

Focus versus Overview. So far, discussed results relate to the focus task only. The overview task revealed completely different group behavior. First of all, significantly fewer transitions (58 transitions) took place compared to the focus task (179 transitions). More critical, however, was the lack of the most indicators/activities. With rare exceptions, the participants did not express any significant changes during the transitions. The observed actions and reactions contained activities that were related to verbal communication only.

Moreover, these were often ambiguous. As a result, not every detected verbal communication led to a transition. Thus, without a mature speech recognition component that can provide the system with a meaning of communication, it will be barely possible to detect if users are working tightly or just chatting.

Consequently, the conclusion can be made that to enable the detection of collaborative states and transitions between states, a comprehensive group behavior model and a well designed (visual) interface that promotes the emergence of detectable activities are required. Visual anchors are one example of such improvement. For tasks with a high amount of visual search activity, e.g., sorting tasks, special interaction techniques that force tightly coupled work can be used, e.g., shared interaction techniques [67]. Another possibility is to allow only one user to interact with the system. That will ensure a fixed distribution of user roles, thus compelling tightly coupled work. However, forcing a particular work style might lead to discrepancies between users' expectations regarding the interface and the existing interface. That could be perceived as awkward and result in negative experience [101].

3.3.4 Territoriality

The participants expressed territorial behavior both on and in front of the display during both tasks. It was more salient during the focus task than during the overview task, probably because of the possibility for better task subdivision in spatial regions. The observations revealed as well that participants made excessive use of bezels to define territories. Andrews et al. observed similar behavior [2].

Territories

In total, eight types of territories emerged during the focus task. The following list describes these types concerning visual elements and spatial positions on or in front of the display:

- *Personal* (similar to [119]) and *Personal-Shared*: represented by a question window. One instance of this territory type occupied exactly one display unit. The system reserved this area for the participant who opened the question. Therefore no attempts were made by co-workers to operate in this area. The territory expressed multiple semantics during the task. In the case of loosely-coupled work, it was a *personal territory*. In the case of tightly-coupled work, it was a *personal-shared territory*. We do not call it *group territory* since only one participant had control over it. In contrast to personal territories on tabletops [119], and multi-touch vertical displays [53], personal territories in our study were not always in direct proximity to their owner.

- *Personal-Reserved*: a display unit with a pointer inside. In the case of loosely-coupled work, the participants perceived this real estate of the display unit with a pointer inside as personal territory. Co-workers made no attempts to open a question on that display unit. Participants, however, felt free to trespass this territory with their pointer.

- *Personal-Surrounding*: a column in which the participant is working. We observed that participants did not work in this territory if they could work elsewhere. Participants were more respectful of this territory if the owner stood directly in front of it.

- *Temporary Abandoned*: sometimes, due to a transition from loosely-coupled to a tightly-coupled work style, personal territories became abandoned for a while. Such territories do not provide any drawbacks in the case of two collaborators. However, it might negatively affect if more than two users work together.
- *Group* (similar to [119]): the entire display represented a group territory during the overview task. The participants worked loosely and tightly coupled within this territory. In the case of tightly coupled work, the territory had region masters. Regions had a fuzzy vertical border somewhere in the middle of the display. Region masters looked for documents in their regions first.
- *Storage* (similar to [119]): storage territories were represented by display units that do not contain participants' pointers and do contain unprocessed questions.
- *In-between*: physical space between the participant and the area on the display the participant was working. The participants were very respectful of this territory and tried not to overstep it. Often the participants indicated their intention to trespass the territory through body signals, like starting a moving movement but not moving. If the participant saw that the partner received the signal (and showed no objections / or even approved the intention), the participant trespassed the territory.

Although the territorial behavior was not particularly salient – probably due to the employed indirect interaction technique [45] – It could be observed that the participants were susceptible to three territory types: *personal territory*, *personal-reserved*, and *in-between territory*. Since the interface did not allow for interaction on a display unit occupied by a question window, the participants did not even try to work on display units on those their partners were working. Such display units were indicated either by a question window (*personal territory*) or by a pointer (*personal-reserved territory*). Thus, we conclude that explicit territories - territories implemented within a system - are less sensitive to interaction devices and techniques and possess the potential to lessen coordination workload.

Fixed-position data affected territoriality and user interaction as well. It encouraged significantly physical navigation (see Figure 3.7) in the form of full-body movements (prevailed in the focus task) or head movements (prevailed in the overview task) since the participants had to process data in all display regions. Moreover, participants could not set up a permanent territorial environment since they could not move data assets. Instead, they roamed in front of the display and used its physical features to define territories. Thus, territoriality was extremely dynamic compared to studies with floating data items, e.g., [119, 53].

Critical regions

One unique aspect of spatial data applications is that users must work on every display region that contains data. That circumstance might raise an issue of critical regions. For instance, Azad et al. and Jakobsen et al. observed that users avoid lower regions of the display, probably because it was uncomfortable to interact with them [5, 53]. In our setup, a wall-display was utilized that includes very high display regions (over 3.0 meters) and low display regions (20 centimeters from the ground). Therefore, it offers a possibility to determine the participants' attitudes towards these regions, so data was placed in the highest and the lowest row to force participants' activities within these regions.

At the end of each task, the participants answered if it was comfortable to work in these regions. Only four participants (after the focus task) and two participants (after the overview task) found the lowest row uncomfortable. The participants named decreased legibility as the reason. Significantly more participants felt uncomfortable towards the highest row: 12 participants out of 24 (after the focus task) and 8 participants (after the overview task). The reason was the high physical demand as participants must hold their head in an abnormal position for a while. Some participants stated in the end that physical demand decreased in the overview task since they only had to glance at the highest row and not gaze at it for a long time. Hence, it is advisable to use high display regions for explicit territories that do not require users' attention for a long time, e.g., storage territories.

3.4 Guidelines

This section derives guidelines for groupware designers from the results and discusses the results in the previous section.

- **Consider navigation patterns** – The results revealed a virtual-navigation pattern of how users process spatially fixed items. The analysis showed that users navigated significantly more often column-wise compared to row-wise or erratic navigation. The combination of three factors could cause the observed behavior: display size, bezels, and fixed-position data items that did not expose any relations to each other. Knowing how task and system parameters affect users' virtual and physical navigation, groupware designers can implement better intelligent interfaces. Such interfaces will predict users' behavior and consequently activate mechanisms that, for instance, mitigate interferences or pre-load and pre-process data.

- **Choose a proper display design** – The participants' physical navigational behavior during the overview task emphasized the importance of the display's configuration. In the overview condition, the participants were forced to work with the entire display. To reduce their efforts, the participants positioned themselves strategically wise in the middle of the workspace. This constellation allowed for a quick overview of the display real estate employing subtle head movements. However, considering the size of the LHRD, one must admit that such behavior was not possible if the LHRD had a flat surface. The display's curvature enabled the participants to see clearly and without distortions information placed near the left and right edges. Therefore, groupware designers must ponder what display's configuration will best suit the task and the groups' configuration.

- **Consider users' background** – The study revealed that groups with the previous mutual experience of cooperative work behave differently compared to other groups. The barrier on the way from loosely-coupled to tightly-coupled work was significantly less perceivable, and participants frequently discussed individual questions. Therefore, it is essential to understand who will use the groupware to provide an adequate interface. Additionally, designers must bear in mind that putting users in a collaborative environment will not automatically start the collaboration. Thus, designers have to implement and apply techniques that will enforce more tightly-coupled work if required.

- **Design for both loosely and tightly-coupled work** – The results showed that phases of loosely-coupled work are as frequent as phases of tightly-coupled work. In some cases, the total duration of loosely-coupled work even prevails compared to the tightly-coupled work. Therefore, groupware designers must consider both types of work and design not only for groups but also for individuals. For that, the system has to recognize collaboration states to ensure proper adjustment of coordination strategy. User interfaces should provide enough intelligence to recognize current group behavior or change in it to support multiple coordination strategies and ensure proper switch between them. Adaptive interfaces [86] can help significantly at this point. This kind of interface automatically decides how to modify the presentation and behavior of interactive elements based on utilized knowledge, for instance, in the form of a user model [14, 103, 132].

- **Keep coupling ambiguity in mind** – As mentioned in the previous point, adaptive interfaces have the potential to foster mixed-focus collaboration. However, for that, the system must be able to recognize different collaboration states. Previous research showed that collaboration states could be identified using coupling styles. However, the study presented in this chapter revealed that coupling styles might be ambiguous and do not always provide enough information regarding the current collaboration state. On the other hand, the study showed that information about transitions could provide the system with valuable data about user activities. Extending the system with a transitions' detection mechanism can help to disambiguate coupling styles.

- **Consider user roles** – Previous research and this study showed that user roles are an integral part of the collaboration process. The concept of user roles can be utilized to design specialized user interfaces that best support the user's current role. However, the study showed as well that the distribution of the user roles is exceptionally dynamic. Therefore, the acceptance of fixed user roles must be investigated. Additionally, the study revealed that if the roles are not well balanced in terms of workload, the users will likely switch to a loosely-coupled work.

- **Consider tendency for task subdivision** – Users tend to subdivide the task to process it more efficiently. Thus, groupware designers should consider providing tools that will support such a strategy. On the other hand, this strategy leads to a more loosely-coupled work. If designers aim to ensure more tightly collaboration, they should integrate constraints instead to prevent the subdivision. However, that will likely disagree with users' expectations resulting in low acceptance of the system.

- **Beware of abandoned territories** – The study showed that fixed-position data could cause the emergence of a new territory type, namely, abandoned territory. These territories remain on screen, clutter it, and occlude information, although their owners do not use them actively and are located elsewhere. During the study, this territory type emerged when participants switched from loosely- to tightly-coupled work. In the case of two users, these territories are harmless. However, in the case of more than two users, they can become a distracting factor. Groupware designers should consider this territory type and provide techniques that will mitigate these territories' adverse effects, for instance, hide them while the owner is absent.

- **Consider bezels** – The surveys revealed that the participants did not perceive the presence of the bezels. However, the bezels seem to affect both navigation and territorial behavior. Therefore, designers can use the bezels' grid to visualize data in a more meaningful and intuitive way for users. Eventually, designers can even push users towards desired behavior if they utilize bezels properly.

- **Consider critical regions** – The study showed that although mobile devices solve the problem of object reaching in distant display regions, they do not solve the problem of critical display regions entirely. Thus, being able to interact with the highest region of the LHRD, the participants perceived this region as critical in terms of ergonomics. Considering such regions in applications with fixed-position data is especially vital since fixed-position data can force users to work in critical regions. Therefore, designers should either forgo these areas or reserve them for territories that do not require a long stay of the user, for instance, storage territory.

3.5 Revisiting hypotheses

This section applies the results yielded by the experiment to the hypotheses H1, H2, H3, H4, H5, and H8 defined in Chapter 1 to see if they can be confirmed or rejected.

H1: Collaborative coupling behavior during focus phases of work will differ from collaborative coupling behavior during overview phases of work

The experiment confirmed the assumption of the hypothesis. Indeed, The results showed that users' coupling behavior during the focus and the overview conditions in the context of an analytical task were different. During the focus condition, the participants spent an equal amount of time working loosely- and tightly-coupled and frequently switched between these two working modes. In contrast, the participants switched less frequently between loosely- and tightly-coupled modes during the overview condition and worked predominantly loosely-coupled. Additionally, although users changed roles dynamically during both conditions, the focus conditions revealed the roles where one user took over leadership. In contrast, the overview condition exposed only the user roles with no distinct leader.

H2: During creative tasks, participants will expose more tightly-coupled work in comparison to analytical tasks

The experiment partially investigated the hypothesis for the analytical task. Yet, insights for a creative task are needed to confirm or disapprove the hypothesis. The next chapter will provide such insights.

H3: Transitions between loosely-coupled and tightly-coupled work contain distinct cues that allow their detection

The experiment partially confirmed the hypothesis. In the experiment, the hypothesis was valid for the focus condition only. The overview condition lacked the most indicators. The observed indicators were predominantly verbal and required speech analysis. Probably, a sophisticated speech recognition system will allow detection of transitions better during such indicator-poor conditions. However, such systems will require an immense amount of data for training. Yet, the experiment also revealed that through a thorough design of a visual interface and interaction flow, the transitions could be brought to light and, therefore, can be made more detectable.

H4: Territoriality will play a significant role during work with fixed-position data in analytical and creative tasks

The experiment confirmed the hypothesis for analytical tasks. Territoriality appeared to be an essential element of the collaborative process. The participants exposed the territorial behavior distinctly. Although it was more salient during the focus condition, it could also be observed during the overview condition. Fixed-position data also promoted the emergence of territories. However, although territories had a significant role during the collaboration process, the participants did not need any explicit tools for the management of the territories. They could handle them through a social protocol.

H5: Territoriality will not take place during overview phases of work

The experiment contradicted the hypothesis. The results showed the presence of territorial behavior and the emergence of territories during the overview condition.

H8: Physical navigation during focus phases of work will differ from physical navigation during overview phases of work

The experiment confirmed the hypothesis. Physical navigation during the focus phases differed distinctly from physical navigation during the overview phases. During the focus condition, the participants used predominantly translational movements to reposition themselves in front of the display. On the other hand, during the overview condition, the participants used more rotational movements remaining in the overview position.

Chapter 4

Experiment: 2D Level Design - Effects of User Roles on Socio-Physiological Phenomena

The study in Chapter 3 investigated socio-physiological phenomena in the context of analytical tasks. These tasks contain planning and intellectual activities. The experiment in this chapter adds to the picture insights regarding the creative activity. Additionally, the experiment investigated the impact of fixed roles on the collaborative process as well as the acceptance of fixed roles by users.

Parts of this chapter were previously published in in the following papers:

Sigitov, A., Hinkenjann, A., and Staadt, O. Effect of User Roles on the Process of Collaborative 2D Level Design on Large, High-resolution Displays. In *Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications* (2020), SCITEPRESS - Science and Technology Publications, pp. 118–129

4.1 Research Objective

The study's analysis presented in chapter 3 revealed multiple insight regarding socio-physiological phenomena in the context of an analytical task. Among others, the insights revealed that collaborative environments do not lead automatically to a tightly-coupled workflow. On the contrary, the results showed that many groups preferred to work loosely-coupled. It is likely that this behavior was a result of the task conditions themselves. The task allowed for a clear subdivision, and the result did not depend on how users will work loosely- or tightly-coupled. On the other hand, creative tasks provide a different condition since the result does not exist and must be created. This circumstance requires coordination of co-workers and, therefore, might lead to a more tightly-coupled workflow.

The research objective of the experiment presented in this section was twofold. First, the experiment aimed to extend the study's findings described in chapter 3 by findings in the context of a creative task. Like the previous study, the experiment utilized fixed-position spatial data; however, employing a creative task instead of a non-creative task. Therefore, the experiment pursued the following goals:

- Detect socio-physiological behavior of participants during a creative, collaborative task
- Observe if the creative task where a mutual creative result must be produced will force participants to work rather tightly-coupled

Additionally, the experiment investigated the effect of user roles' explicit distribution on the collaboration process. Twelve groups (two participants each) participated in the study. All groups had the same task. The participants of the first six groups had the interface, which allowed them to create tiles and place tiles on the LHRD. Thus, the participants could decide on their own who will undertake what role in case they decided to distribute the roles. The participants of the other six groups had different interfaces that either allowed them to create assets or to place them. Thus, the participants had to undertake a specific role. Therefore, additionally to the mentioned goals, the results of the experiment should provide answers to the following questions:

- Will the explicit distribution of user roles affect the collaboration process?
- Will the participants accept such rigid distribution of the user roles?

4.2 Study

The experiment aimed to investigate the collaboration process in the context of creative tasks. An additional goal was to identify how a user interface that forces users to adopt a specific role within the team will affect the collaboration process. Groupware described in chapter 6 and the apparatus describe in section 1.7 was used to execute the experiment. This groupware allows for collaborative prototyping of 2D game levels on LHRDs. Twelve participant dyads designed levels for 30 minutes in two different conditions. The process of 2d level design incorporated the following activities:

- **creation of assets** – the participants must create a prototype of a 2d game level. However, no predefined assets were provided. This circumstance should animate the team members to a more tightly-coupled work and stimulate their creativity. Having nothing apart from tools, the participants had to coordinate themselves to decide what kind of game they would create and what kind of assets they would need.
- **placement of assets (fixed-position data)** – to create a layout of a 2d game level, the participants had to place created assets on the screen. They had to decide where on the screen they want to set what asset. An assumption was that participants would coordinate this activity to provide a consistent result.
- **coordination** – this activity should synchronize two previous activities resulting in a more tightly-coupled and consistent work.

Apart from the time constraint, no other constraints were set.

4.2.1 Conditions

The study had a between-groups design. The independent variable was *Condition* with two levels, namely *Equal Roles* and *Different Roles*. In the *Equal Roles* condition, participants were provided with identical interfaces. Thus both group members could perform the same set of manipulations. In that case, the participants could ignore the concept of user roles entirely or dynamically (re-)assign roles.

In the *Different Roles* condition, the participants were provided with two different interfaces. One interface only allowed for the creation of visual assets, while the other interface only allowed for the placement of visual assets. Therefore, the participants had either undertake the role of a 2D artist (creation of visual assets) or a level designer (placement of visual assets). As in the *Equal Roles* condition, the same mobile client application was utilized. However, for 2D artists, we deactivated modules responsible for interaction with the LHRD, while for level designers, we disabled the *Craft* panel.

4.2.2 Interface

As mentioned earlier, the apparatus described in section 1.7 and groupware described in chapter 6 were employed to conduct the experiment. The resulted system consisted of the shared LHRD, two mobile devices (one for each team member), and an additional PC that runs a server to enable communication between individual devices.

This system allowed for the following activities: (a) create tiles on mobile devices, (b) delete tiles on mobile devices, (c) automatically synchronize tiles libraries across devices, (d) move a fine and a coarse pointer on the LHRD using mobile devices, (f) place tiles on the LHRD using mobile devices.

To create a tile, participants had to open the *Craft* panel on a mobile device. That panel contained a canvas to draw on and a color palette to switch colors. The participant had to select a color and draw on the canvas using a finger. After the participant finished drawing, she could give the tile a name and confirm creation to put the tile into the library.

To place the tile on the LHRD, the participant had to activate the *Controller* panel first. Then, using the swipe-gesture, the participant had to move the fine pointer to a place where she wants to put the tile. Subsequently, the participant had to drag and drop the tile on a particular area inside the *Controller* panel on the mobile device. The tile would then appear under the fine pointer.

To differ between pointers, participants could change the color and the opacity of their pointers in the *Settings* panel.

More information on the utilized groupware can be found in chapter 6.

4.2.3 Participants

Twelve groups of two participants participated in the study. Six groups must accomplish the task under *Equal Roles* condition while the other six groups accomplished the task under *Different Roles* condition. The participants of the *Equal Roles* condition were aged between 21 and 41 years (M = 27.58; SD = 6.05). The participants of the *Different Roles* condition were aged between 20 and 35 years (M = 24.67; SD = 4.23). All participants had a normal or corrected-to-normal vision. There were four female and eight male participants in both conditions. Each participant took part only once in the study. All participants had an academic background (students or research associates). Each participant received 10 Euros for taking part in the study.

4.2.4 Procedure and Data

A supervisor guided participants through the entire study. First, the supervisor asked the participants to fill in a consent form and a demographics questionnaire (see Appendix A.4). Next, the supervisor explained the task, the study's procedure, what equipment the participants will wear, and how and what data the system will gather.

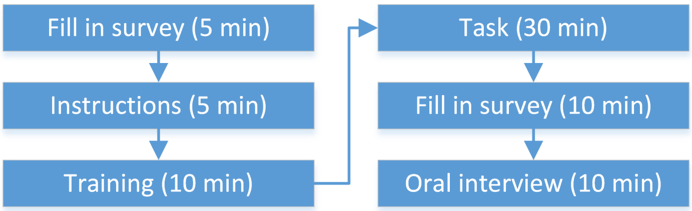

Figure 4.1: Level Design - Study procedure

In the case of *Different Roles* condition, the supervisor also asked the participants to decide who will undertake which role. If participants could not decide, the roles were assigned randomly. Afterward, the supervisor demonstrated how the groupware works and invited the participants to try it. The participants had as much time as they needed to get to know with the system. Finally, the supervisor equipped the participants with helmets used for position tracking and let them build a 2D game level for 30 minutes. During the study, the supervisor observed the process and made field notes. After the time expired, the participants filled in the questionnaires (see Appendix A.5), and the supervisor conducted a short oral interview. Figure 4.1 depicts the study's procedure.

During the experiment, qualitative data was gathered. The data included surveys, field notes, and video recordings. In total, there were 368 minutes of video/audio data. Moreover, the system logged quantitative data that encompassed the participants' position, pointer positions, and task-related system events.

4.3 Results

This section presents and discusses the results of the experiment. It provides insights regarding physical navigation, collaborative coupling, territoriality, and workspace awareness in the context of a collaborative creative task.

4.3.1 Physical navigation

During the experiment, participants did not frequently change their location in front of the display (see Figure 4.2). Most of the time, the participants positioned themselves in an overview position, and physical navigation was reduced to head and body rotations.

During the *Different Roles* condition, there were two groups (see groups 1 and 4 in Figure 4.2) that worked from up close with the display and therefore had to change their location a lot to reach different display areas. Altogether, physical navigation did not expose any complex patterns.

Only two groups (group 2 in the *Equal Roles* condition and group 2 in the *Different*

Roles condition) performed a crossover. The participants of the other groups remained on a side (left or right) they chose at the beginning of the experiment.

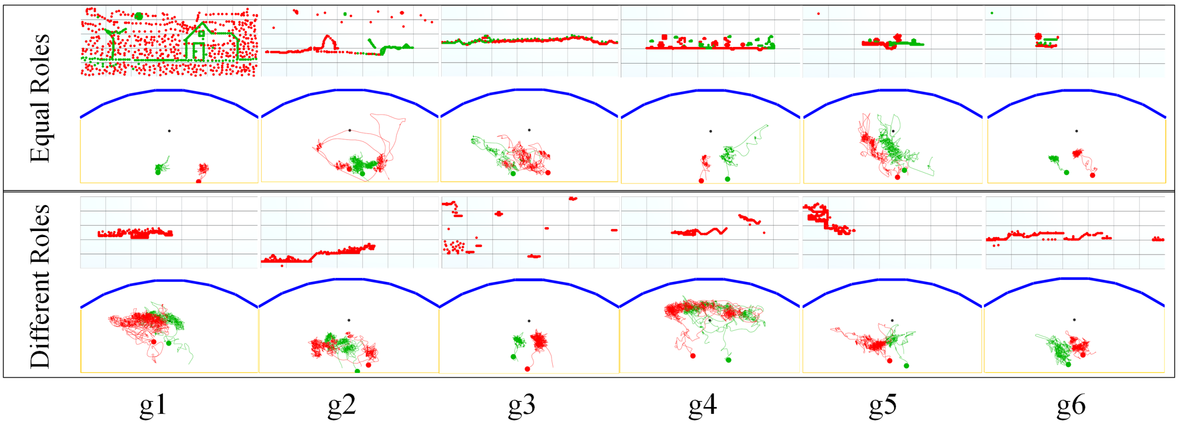

Figure 4.2: Visualization of display usage [front view] and user movements [top view] in Equal Roles [ER] and Different Roles [DR] condition. Gray grid represents the LHRD from the front. The green and red dots on the grid depict the position of the tiles. The blue curved line represents the LHRD from the top. The yellow lines outline the tracking area in front of the LHRD. The green and red lines inside the tracking area depict the movements of the users during the study.

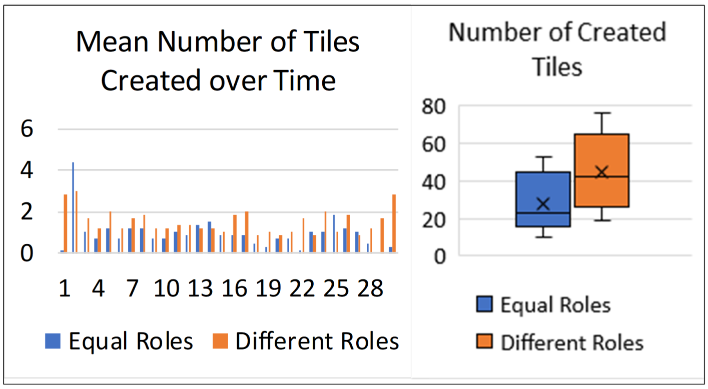

Figure 4.3: Number of created tiles in different conditions: (left) number of tiles created over time. The Y-axis represents the number of tiles. The X-axis represents a point in time n minutes between the start and the end of the experiment. (right) Box plot diagram shows the number of created tiles for different conditions.

The observed behavior can be ascribed to two factors: the curvature of display and tiles' size. Although we made tiles relatively small (45px x 45px), the participants could work well with that size from a distance. Additionally, the display's curvature allowed the participants to work comfortably on practically all display regions remaining in the middle of the working area. Thus, the participants did not depend on location changes and could switch between working display regions display by merely rotating their heads or bodies.

Overall, the impact of physical navigation was marginal in both conditions.

4.3.2 Collaborative coupling

Creation of assets. Figure 4.3 depicts the finding regarding tiles creation. The system logs analysis showed that the creation of assets took place over the entire session. All groups in both conditions demonstrated this behavior. The supervisor who made field notes also detected the behavior. The behavior can be ascribed to the fact that the participants repeatedly received new ideas during the design process, thus returning to the *draw tile* sub-task.

The analysis also showed that the groups in the *Different Roles* condition created, on average, more tiles in comparison to the groups in the *Equal Roles* condition. Assumably, the distribution of roles created a feeling of responsibility for the assigned task, thus leading to more focused work, which, in turn, results in better productivity. However, the statistical analysis using independent-samples t-test revealed that the difference was insignificant.

Perception of Collaboration. The participants ***felt working rather cooperatively*** ($Mean_{ER}$ = 4.33, SD_{ER} = 1.23; $Mean_{DR}$ = 5.67, SD_{DR} = 1.07) and agreed that it was ***fun to work collaboratively*** ($Mean_{ER}$ = 6.0, SD_{ER} = 1.13; $Mean_{DR}$ = 6.58, SD_{DR} = 0.67). They also ***did not feel distracted by the partner*** ($Mean_{ER}$ = 1.75, SD_{ER} = 0.62; $Mean_{DR}$ = 1.33, SD_{DR} = 0.65). Only 3 out of 24 participants stated that they would prefer to work alone and perform better if working alone. All three participants belonged to the *Equal Roles* condition.

Collaborative coupling. The video recordings were analyzed multiple times to identify collaborative coupling behavior. First, periods of loosely and tightly coupled work were identified, the length of those periods was measured, and the overall time of loosely and tightly coupled work was calculated for each group. Figures 4.4 and 4.5 show the analysis results.

The visualization exposed noticeable difference between the *Equal Roles* and *Different Roles* conditions. In the *Equal Roles* condition, the participants seemed to work more in a loosely-coupled manner. Thus, an independent-samples t-test was conducted to compare the time the participants spent working loosely-coupled in different conditions.

The analysis revealed a ***significant difference*** in the scores for the *Equal Roles* condition ($Mean$ = 1331.21, SD = 290.17) and the *Different Roles* condition ($Mean$ = 908.48, SD = 174.75); $t(10) = -3.06, p = 0.012$. The detected significant difference indicates that utilized interfaces can greatly affect how users approach a common task

Figure 4.4: Level design process for different conditions: (left) periods of loosely and tightly coupled work; (right) total time for loosely and tightly coupled work

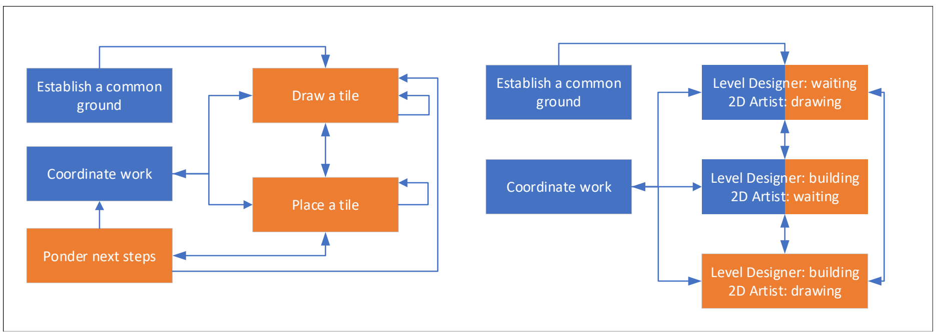

Figure 4.5: Level design process for different conditions: (left) state diagram for the Equal Roles condition; (right) state diagram for the Different Roles condition

and how they shape their collaboration. Especially in teams that contain users who do not know each other well (or not at all), interfaces that force tightly-coupled work might be advantageous, resulting in a more coordinated workflow and more consistent results.

Next, the analysis detected what sub-tasks the participants approached during the identified periods. Based on the gained information, state diagrams were created that describe the collaboration processes for the *Equal Roles* and *Different Roles* conditions. Figure 4.5 depicts the state diagrams. The results show that the participants of the *Equal Roles* condition shaped the collaboration process differently compared to the *Different Roles* condition.

In the *Equal Roles* condition, the participants started with establishment of a *Common Ground*. They discussed what kind of level they want to build, what tiles are necessary, who will create which tiles, where the ground will be, and where they should start to place tiles. Next, they moved on to the *Draw a Tile* state working loosely-coupled. After the participants created the first tiles, they could move on to the states *Place a Tile* or *Ponder Next Steps*. In both states, the participants worked in a loosely coupled manner. They could also switch to the tightly coupled step *Coordinate Work*, for instance, to share new ideas, ask for advice, or propose new tiles.

Although according to questionnaires, the participants felt like working cooperatively, the work was shaped rather loosely coupled. The work was divided into three different ways: same task different place (territoriality), same task different sub-task (e.g., placement of different assets, drawing of different tiles), different tasks (one draws a tile, other places the tile).

In the *Different Roles* condition, the participants started similarly with a discussion over general parameters. Subsequently, they moved on to the next state. In this state, the 2D artist was drawing while the level designer was waiting for the tiles. After they created the first tiles, the participants would switch over to a state where the level designer was placing the tiles, and the 2D artist was waiting for new requests; or to the state where the level designer was building, and the 2D artist was continuing to draw more tiles. Additionally, participants could also switch over to the coordination state to discuss the next steps. Overall, the participants worked more coordinated and more tightly in the *Different Roles* condition. Notably, the participants playing the 2D artist role were more deeply involved in the level designer's work. It did not always work the other way around. Some 2D artists produced many assets without being asked for them. That sometimes required additional coordination, since the level designer could not decipher the tiles' meaning.

The participants of the *Different Roles* condition were also asked if the idea of role distribution does make sense. Most participants (10 out of 12) found the idea sensible because they could focus on his/her sub-task and therefore provide more qualitative results. They also stated that they did not miss the functionality the co-participant had.

Groupware developers can utilize the concept of *User Roles* to direct the collaboration process during creative work and push it towards more tightly work. The roles must be balanced to ensure that all team members have enough work for the entire session. Otherwise, users might become a feeling of being expendable, and the work process might become less satisfying. The study revealed such a situation in one group where the participant who was playing the 2D artist role experienced periods of idleness.

4.3.3 Territoriality

Most participants preferred to work in a comfortable display region. However, the study has shown that they utilized other display regions as well. The observed behavior is not unexpected. Since the participants had only 30 minutes to complete the task, there was no expectation that they would build a level that takes the entire display. Nevertheless, the participants were asked to work as if they would have enough time to do so. Additionally, there were no prescriptions regarding where the participants should start and in what direction the level should expand. As Figure 4.2 depicts, most groups (groups 2,3,4,5,6 in the *Equal Roles* condition, and groups 1, 4, 6 in the *Different Roles* condition) worked predominantly in the middle row of the display. Two groups (group 1 in the *Equal Roles* condition and group 3 in the *Different Roles* condition) tried to utilize the entire display. One group started in the top left corner of the display and the other in the bottom left corner.

The *Different Roles* condition did not allow for territorial behavior on the shared display. In the *Equal Roles* condition, however, the study revealed distinct territorial behavior in the early stages of the experiment. Four out of six groups decided to split the task by area after establishing a common ground and agreed on what kind of level they wanted to build. The participants divided then the display into the left and right side and started to work loosely from the outer display edges to the center. Figure 4.2 depicts this behavior that was exposed by groups 2,3,4, and 5 during the *Equal Roles* condition. After the participants met, the territorial behavior diminished. The participants split the task mostly by a sub-task (e.g., one participant drew and placed coins, while the other drew and placed plants).

All in all, there was no need to support territoriality or provide special tools for territory management. Since the participants perceived the collaboration as tight, they did not feel threatened or disturbed by the partner's actions. One possible improvement could be an overview territory on the shared display to show all created tiles at once. That will ensure a better workspace awareness and create a new ground for more tightly coupled work.

4.3.4 Workspace awareness

Finally, the study also provided pieces of evidence of workspace awareness. Two sources could potentially increase workspace awareness of the participants: the large display and the mobile devices. The mobile devices were synchronized, which means that if one participant created a tile, it would appear in the library panel on the co-participant's tablet. Additionally, the panel will automatically scroll down, so the tile becomes visible.

The supervisor could multiple times observe that the participants laughed or smiled when a new tile, created by the co-participant, appeared in their library panel. In some cases, however, we could detect that this also leads to interferences. For instance, in the *Different Roles* condition, one 2D artist always waited until the level designer was done with tile placement before he submitted a new tile. Otherwise, the level designer must navigate the tiles library to the tile he was currently using due to the auto-scroll function.

During the oral interviews, the participants were also asked if they occasionally observed what the partner was doing and if that affected them by any means. All participants answered in the affirmative. Most participants (22 out of 24) stated that they were ***inspired*** by what the partner was doing and received new ideas. Two participants also stated that they observed the partner actions to **avoid interferences**. One participant stated that he was in no way affected by what the partner was doing.

4.4 Guidelines

This section derives guidelines for groupware designers from the results and discusses the previous section's results.

- **Design for both focus and overview conditions** – Similar to the study described in chapter 3, the participants worked either in the focus or overview condition. However, in this experiment, the conditions were not controlled, so the participants could choose what condition better suits them. Most groups decided to work in the overview condition. Only two groups (see groups 1 and 4 in Figure 4.2 chose to work from up close. This observation reveals two insights. First, the conditions we described in the study with an analytical task also exist in creative tasks. Therefore groupware designers should consider and design for both conditions (overview and focus). Second, users prefer to employ subtle physical navigation if it is possible. For that, however, a proper display design is essential. Providing a flat LHRD will enforce less ergonomic physical navigation that will require users to walk to regions near display edges in order to be able to work comfortably there. That, however, applies mostly to wall-sized displays. With smaller displays, the problem would likely be less significant.

- **Provide tools for better coordination** – The results did not confirm the assumption that participants will coordinate themselves to provide consistent results. In the *Equal Roles* condition, the participants preferred to split the work and design parts of the level individually. Therefore, the results were less uniform than the results from the *Different Roles* condition. In the oral interviews, the participants stated that tools, which, for instance, will allow for a very rough sketch of the level, would significantly increase coordination possibilities and, therefore, consistency of the results. Thus, groupware designers should analyze tasks and identify and implement features that allow for better coordination.

- **Use fixed user roles to enforce tightly-coupled work** – The experiment revealed that fixed user roles could be a useful tool for enforcing tightly-coupled collaboration. Although previous research [101] delivered pieces of evidence that fixed distribution of roles might be perceived negatively by users, this experiment did not confirm that observation. The participants of the experiment exposed a positive attitude towards such constellation. Moreover, the observations revealed that the results were more consistent and that the participants were more productive in the *Different Roles* condition compared to the *Equal Roles* condition. Therefore, groupware designers should at least consider the possibility of distribution of user roles. However, the defined roles should be well balanced in terms of workload. As the study in chapter 3 showed, users tend to dissolve the existing distribution of roles if one user did not feel like contributing enough to the task.

- **Rely on social protocols in respect of territories** – The experiment confirmed again that users tend to expose territorial behavior even if no tools are provided to support such behavior. However, the experiment shows that if no artificial territories exist (territories created and managed by the system), then social protocols are enough to manage territoriality. The experiment showed as well that the participants did not miss any particular territories during the task. Therefore, groupware designers can, with a high probability, ignore this phenomenon for creative tasks with fixed-position data.

- **Consider critical display regions** – The observations showed that most participants avoided regions that were less comfortable for work. Groupware designers have at least three possibilities to mitigate the critical regions' issue. First, design LHRDs that did not contain such regions. This approach will save money during the production and usage of the LHRD. However, it will make the LHRD less universal as well. Second, groupware designers can utilize critical display regions to visualize contextual or task-related information. That will provide more value to users. The third possibility is to utilize interaction and visualization techniques to allow for more comfortable work in these regions.
- **Do not break interaction flow** – The developed groupware employed a mechanism for synchronization of created assets across mobile devices. To make changes visible and therefore extend workspace awareness of participants, another mechanism was utilized that scrolled the library view to a just added asset. The observations showed that this mechanic resulted from time to time in an interrupted workflow. Some participants even tried to counteract if working tightly-coupled. Although the goal was achieved and workspace awareness could be extended, the negative effect prevailed. Thus, groupware designers should carefully weigh what mechanics they employ and their effect on users' workflow.
- **Support extended workspace awareness in creative tasks** – In contrast to the previous point, extended through the characteristics of the LHRD workspace awareness had a positive effect on the participants. Most participants stated that they were inspired and received new ideas through the awareness of the co-user's activities. During the experiment, workspace awareness ensured continuous input of small task-related information chunks. That information chunks could be easily acquired through brief head movements, making the acquisition cost extremely low. Thus, groupware designers should consider LHRDs as a possibility of extending workspace awareness for creative tasks.

4.5 Revisiting hypotheses

The experiment presented in this chapter delivers additional insights for the hypotheses H2, H4, H5, and H8.

H2: During creative tasks, participants will expose more tightly-coupled work in comparison to analytical tasks

The expectation that a creative task, where users will have to generate a mutual artifact, will expose more tightly-coupled work compared to an analytical task was not met. The experiment revealed that depending on the condition, the participants worked either predominantly loosely-coupled or spent an equal amount of time for loosely- and tightly-coupled work. The results are similar to the analytical task. Thus, the hypothesis could not be confirmed, meaning that task nature does not affect collaboration tightness.

H4: Territoriality will play a significant role during work with fixed-position data in analytical and creative tasks

While *Different Roles* condition did not allow for territorial behavior, territoriality could be observed during the *Equal Roles* condition, especially during the early stages of the experiment. Similar to the analytical task, the participants divided the display into left and right areas. Again the hypothesis could be confirmed, showing that territoriality is an integral part of the collaborative process. However, similar to the previous experiment, no needs for territoriality management were detected. The participants could easily handle it using social protocols.

H5: Territoriality will not take place during overview phases of work

The experiment rejected the hypothesis. The territories were even more salient during the overview phases of work as in the previous experiment.

H8: Physical navigation during focus phases of work will differ from physical navigation during overview phases of work

Compared to the previous experiment, the participants were not forced into a particular task condition and could freely choose how to approach the task. As a result, most groups preferred to work in the overview mode, while only two groups worked in a focus condition. Thus, the conclusion regarding the hypothesis is not so meaningful as in the previous experiment. Nevertheless, the observed behavior was identical to the participants' behavior from the experiment described in Chapter 3. During the focus condition, the participants executed more translational movements, while during the overview condition, more rotational movements were exposed. Thus, the hypothesis can be confirmed.

Extended workspace awareness (Hypotheses H6 and H7)

Although no statements can be made regarding hypotheses H6 and H7 yet, the study results revealed some positive effects of the extended workspace awareness. So, most participants said that the possibility of observing what their co-workers were doing helped them generate new ideas and foster their creativity. Additionally, some participants used extended workspace awareness to coordinate work. Thus, a conclusion can be made that extended workspace awareness might positively affect the collaborative process. However, the experiments presented in the next chapter will show that there is a negative effect as well.

Chapter 5

Workspace Awareness Experiment: Effects of Visual Distractors in Peripheral Vision on User Performance

Previous studies described in this thesis did not focus on the workspace awareness phenomenon. However, they provided pieces of evidence that workspace awareness can have a positive as well as a negative effect on users. This chapter presents two experiments aimed to investigate possible adverse effects of workspace awareness during collaborative work on LHRDs.

Parts of this chapter were previously published in in the following papers:

SIGITOV, A., KRUIJFF, E., TREPKOWSKI, C., STAADT, O., AND HINKENJANN, A. The Effect of Visual Distractors in Peripheral Vision on User Performance in Large Display Wall Systems. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces - ISS '16* (New York, New York, USA, 2016), ACM Press, pp. 241–249

5.1 Research Objective

Collaborative work on LHRDS raises the necessity for rendering visual feedback for each user independently. Due to the inherent characteristics of LHRDs, it will often occur that the co-user's visual feedback will appear in the other user's peripheral vision. That is because users are frequently aware of most parts of the visual display other than their active working area as it often falls within the human visual field. Feedback for other users will be perceived and processed by the user's brain, as peripheral vision is sensitive to motion and visual changes [77, 87, 142, 160]. There is no drawback if collaborators are working tightly-coupled. It has been even shown that such workspace awareness is apt to facilitate groups' task performance [42].

However, previous studies described in this thesis have shown that users frequently choose to work-loosely coupled. On the other hand, collaborative frameworks often only consider tightly-coupled interaction, while ignoring individual work phases is seen as a trade-off in favor of workspace awareness. Moreover, CSCW researchers often consider only the user's focus/working area as critical. For instance, users can cause interference when invading a co-user's working area [162]. The peripheral area, on the other hand, was considered safe. There is, however, no empirical evidence that confirms this assumption. For instance, previous work in the psychology domain indicates that distractors can negatively affect human performance and efficiency [96, 151]. Also, Gutwin et al. [42] argued that increased workspace awareness would likely decrease the effectiveness of individual users. Such tendency might be ascribed to distractors' impact as well.

Forster et al. [32] conducted several experiments on a 15" screen and showed that task-irrelevant stimuli could distract the user. As a result, a decrease in effectiveness could be observed. Task-relevant peripheral stimuli can also decrease task performance. Chewar et al. [24] investigated secondary task display attributes (e.g., position, color) aiming to lessen interference of peripheral task-relevant stimuli with the primary task. The conducted experiments showed that users' primary task performance decreased due to peripheral stimuli. In contrast, Mori et al. [79] showed the effect of windows in the peripheral visual field on user task performance. They found that peripheral windows impair users' efficiency the stronger, the closer peripheral windows are to foveal vision. It was also shown that dynamic stimuli have a more negative impact than static stimuli.

The above-described experiments were conducted on standard desktop displays. Thus they investigated effects in very near peripheral vision area only. Moreover, the experiments did not consider high load tasks that make heavy use of humans' memory (particularly short-term memory) and attention resources.

The experiments presented in this chapter investigated the impact of visual distractors in the peripheral vision on users' effectiveness and efficiency in tasks with a high-load and low-load mental demands. The experiments' goal was to better understand requirements on workspace awareness during loosely-coupled work phases.

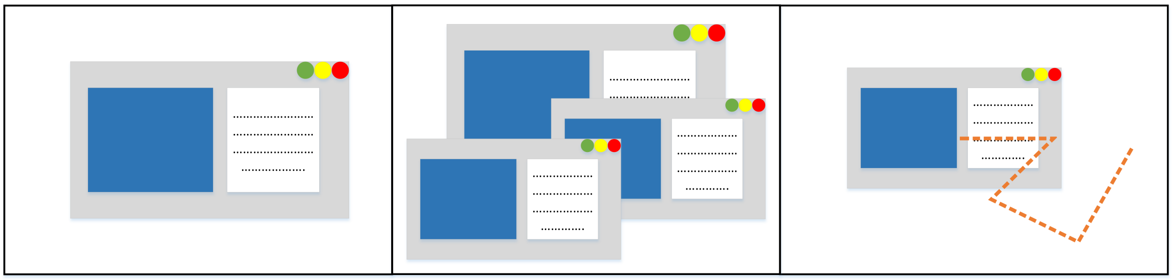

Figure 5.1: Stimuli: (left) pop-up window, (middle) multiple pop-up windows, (right) pop-up and moving window

5.2 Experiments with a High-Load Mental Demand (Short-Term Memory and Attention)

In the context of analytical tasks, some sub-tasks heavily depend on memory capabilities. There are two possibilities of how distractors may impact users' efficiency if considering these sub-tasks. Either through attention capturing [56] (start of the memorization process is delayed because attention was driven away). Or through memorization impairment (memorization process is interrupted) [90, 163]. In the latter case, a distractor interferes with storing information in short term memory, affecting immediate recall of the information.

Two interrelated user experiments were conducted to address the gap in understanding the effect of visual distractors in the context of co-located collaboration during an analytical task. In these experiments, the effects of visual task-irrelevant events such as those caused by visual feedback to co-workers in peripheral vision were investigated. The experiments specifically targeted display area location effects, learning issues, distractor awareness, and workload issues to address the various dimensions of how distractors can affect user performance. The experiments were performed by contrasting **short-term memory** and **attention**-driven distractors. The underlying assumption was that information stored in short-term memory might get lost while being distracted, resulting in decreased effectiveness by complex tasks, which require the memorization of intermediate results. On the other hand, since the humans' peripheral vision system is movement-oriented [77], dynamic visual events have an increased potential to attract user attention at an unconscious level, thus become distractors that can affect performance.

Figure 5.2: Schematic depiction of a background image as shown at a single display

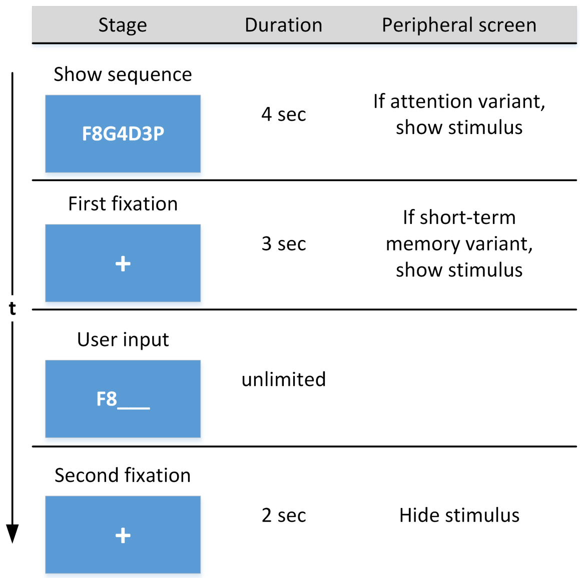

Figure 5.3: Trial loop, with insertion of distractors in the first fixation (short-term memory experiment 1) or during the show of the sequence (attention experiment 2)

5.2.1 Procedure and design

Both experiments had a within-subject design. They employed a 3 x 4 factorial design, consisting of the factorial combination of three peripheral areas and four different event types (pop-up, multiple pop-ups, move, and no stimulus, Figure 5.1). These stimuli (except for "no stimulus") would appear in one of the 34 displays ordered in one of the three different areas (Figure 5.4). Each window contained an image field and a text field. Each stimulus was shown precisely one time on each peripheral screen during the experiment.

The 34 locations were associated with each screen that makes up the tiled display wall, except the center screen, which served for the memory task itself. Screens were clustered in three areas to analyze the effect of cues in the near, middle, and far peripheral visual field (Figure 5.4).

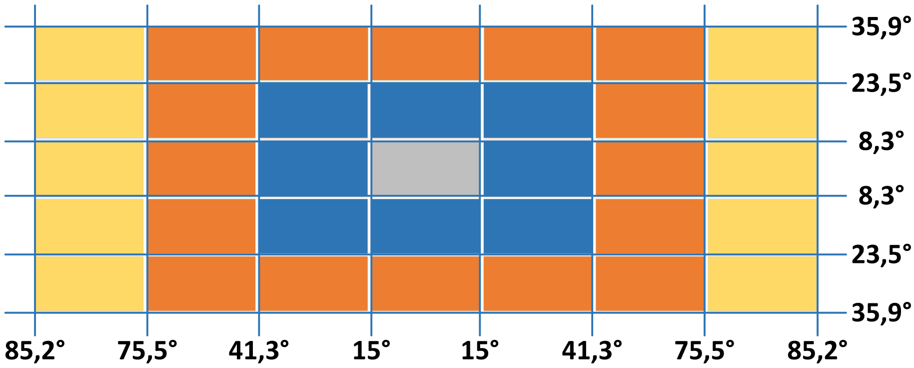

Figure 5.4: The near (blue), middle (orange) and far (yellow) peripheral visual field areas defined through angular distances.

Each area lays inside a defined angular distance range with some tolerance due to apparatus geometry. As a result, each participant produced 136 sample records. The order of trials was fully randomized. All screens showed 1 of 15 static background images (see Figure 5.2), representing a news feed. The background images were different, though very similar in structure and usage of color and text, containing several news notes as text with a corresponding image. The design of background images and used stimuli was akin on purpose to lower contrast between them.

The difference between the two experiments was the point of time at which a specific distractor appeared. As described in Figure 5.3, each trial spans four stages. First, a character sequence was shown to the user in the middle of the focal screen for 4 seconds. The main task encompassed the activities of remembering this particular sequence and recalling it from memory afterward. Next, the sequence disappeared, and a fixation point in the form of a small cross appeared for 3 seconds. Directly afterward, the screen contents blanked, and the participant had to recall and enter the sequence using the provided keyboard. During the input, the participant could observe the sequence she is entering on the center screen, and correct it if needed. This stage did not provide any time limits. However, users were requested to start input directly after the screen blanked to avoid memory decay differences. The participant finalized the input stage by pressing the Enter key and followed by a second fixation point stage, which lasted for 2 seconds, after which a new trial began. Users were requested to focus on the center screen or the keyboard during the full experiment, explicitly avoiding the direct focus of attention on the distractors.

In the first experiment (labeled **short-term memory** or STM), a distractor was shown during the first fixation point stage, which means that the participant had 4 seconds to remember a sequence. After it becomes hidden, the system tries to clear short-term memory content using a distractor. In the second experiment, called the **attention** experiment, a stimulus appeared simultaneously with the sequence. The goal was to distract participants while participants were trying to remember a sequence, thus drawing their attention away and reducing the task's time. Regardless of the experiment variant, shown stimuli remained static on the screen after animation until the second fixation point stage and disappeared at the beginning of it.

Each sequence had a length of 7 tokens with the pattern *LDLDLDL*, where L stands for letter token, and D stands for digit token. All letters were upper case. For clarity, we omitted the digits 0, 1, 5, and characters O, L, and S during the process of sequence generation. We also rejected the digit 7 and the letters W and Y since their words have more than one syllable.

The participants received instructions to look only at the focus screen in the center of the display wall and ignore other screens. Each participant could practice the memorization task for up to 20 trials and ask questions beforehand. No stimuli appeared during the practice stage.

At the beginning of the experiment, each participant filled in a survey that contained questions regarding age, gender, eyesight, color blindness, LHRDs experience, and computer games experience (see Appendix A.6). The question about LHRDs experience was a single choice question with the following options: have never seen before; have seen a couple of times; have worked with them. The question about computer game experience was a Likert scale question with a 7-point scale from 1 (novice) to 7 (professional). During the experiment, users were asked two questions after each block of 34 trials (see also Appendix A.7):

1. How mentally demanding was the last series of the trials?

2. How well could you concentrate during the last series of the trials?

The participants had to answer the questions using a 7-point Likert scale from 1 to 7, with seven being very high or very good, using the provided trackpad. At the end of the experiment, each participant had to fill in a standard NASA TLX [47] survey (see Appendix A.9) and a questionnaire regarding stimuli awareness and the application static background (see Appendix A.8). The question about stimuli awareness was a Likert scale question with three Likert items (one for each stimulus type). Each Likert item had a 7-point scale from 1 (low level of awareness) and 7 (high level of awareness). Besides, an oral interview took place. These questions addressed issues related to mental demand, stimuli, background (level of distraction), and their strategy of remembering the sequences. Furthermore, the supervisor observed the participants during the experiment, looking specifically at concentration and distraction indications.

The rationale behind the experiment is as follows. First, to investigate the effect of particular stimuli in particular areas of LHRDs, a single-user, controlled experiment was chosen as a design. Such an investigation with multiple users would be barely possible, as the presence of additional users would result in uncontrollable variables: co-users might make sounds or motions in a peripheral area that affect the user, thus distorting the results. Therefore, the experiment focused on visual distractors caused by system feedback instead of focusing on other visual distractors that can be caused by users. Second, a high-load task was chosen to explore distractors' effect in cognitively demanding applications, an area in which LHRDs often find an application. The task seems to be very specific; however, remembering and recalling small information chunks underlies multiple general tasks such as comparing, searching, or determining relationships. Third, an information-saturated background was chosen for two reasons: to reduce the contrast between stimuli and background and emulate an information-rich environment typical for LHRD applications. Fourth, during the experiment design, the fact was considered that curved displays have a higher potential to increase visual distraction than flat displays. However, in this experiment, the curved LHRD allowed covering most of the human FOV. Though likely covering a smaller FOV, similar adverse effects can be expected at flat wall displays as well, since the results notably showed that distractors in the near peripheral field had the highest negative impact.

5.2.2 Participants

The *stm* experiment was performed with 8 participants (2 females) aged between 22 and 33 years ($M = 27.00, SD = 4.10$), with normal or corrected-to-normal vision. The participants had rather a high-level of computer games experience ($M = 5.00, SD = 1.41$), and most participants had seen LHRDS a couple of times before or worked with them (7 participants 87.5%). Similarly, the *attention* experiment comprised 8 participants (1 female) aged between 22 and 40 years ($M = 27.75, SD = 5.52$), with normal or corrected-to-normal vision. The participants also had rather a high-level of computer games experience ($M = 4.50, SD = 2.00$). Most participants had seen LHRDs a couple of times before or have worked with them (6 participants 75%). All participants had an academic background (students or research associates). The participants received a cash payment for taking part in the experiment. Each participant took part only in one experiment (either *stm* or *attention*).

5.2.3 Results

Data of 816 trials per experiment (102 trials per participant, totaling 1632 trials) was analyzed using two-way repeated measures ANOVA. Data were analyzed separately for each experiment with within-factors display area (near peripheral, mid-peripheral, far peripheral) and stimulus type (pop-up window, multiple pop-up windows, pop-up, and move window). The "no stimulus" was not associated with a display area, and as such corresponding trials were not included in this ANOVA. Levenshtein distance [65] was used to calculate the difference between the correct sequence and the sequence provided by the user. As explanation, for sequences A and B Levenshtein distance is defined as $LD(A, B) = min(a(i) + b(i) + c(i))$. Here B is obtained from A by the minimal number of $a(i)$ replacements, $b(i)$ insertions and $c(i)$ deletions of characters. For example, the Levenshtein distance between "ocean" and "means" is 3, since the following three edits change one into the other, and there is no way to do it with fewer than three edits: Deleting "o", replacing "c" by "m" and inserting "s". Finally, as we noted, displays were clustered in areas (Figure 5.4) to analyze the effect of distractors in specific areas of the peripheral vision, ranging from near (1) to the far (3) peripheral field. While the display areas contain different amount of displays, the number of trials per area was high enough to warrant no negative effects. The mean values for each participant for each display area were finally included in the analysis. The population mean values for each display area can be estimated through the sample mean values. The mean value is more precise if it is based on many trials. As many trials were used for each display area to calculate the mean values, differences in the number of trials should not affect the results since representative values for each display area can be assumed. The Šidák correction was used to counteract the problem of multiple comparisons. Within the following, we compare the results of both *stm* and *attention* experiments, identifying the differences in the cue effects.

General performance. A surprising result was found by analyzing the general performance based on Levenshtein distance. There was only a marginal difference between the "no stimuli" conditions, and the stimuli conditions in the *attention* and *stm* groups (see Table 5.1). This result is not in line with previous findings and needs further research. However, a between-subjects analysis over ANOVA revealed a significant difference between the *attention* and *stm* group: the *attention* group produced significantly more errors than the *stm* group ($F(1, 1630) = 21.58, p < .001$).

Display area. There was no main effect of the display area or stimulus type (pop-up, multiple pop-ups, pop-up, and move) on recall time, the number of correct tokens from position 0 till the first error, and Levenshtein distance in both experiments. Display area, but not stimulus type showed marginal influence on the number of correct tokens at proper position ($F(2, 14) = 3.606, p = .055, \eta_p^2 = .34$) only in the attention experiment. With respect to the different areas in peripheral vision, for this experiment, posthoc pairwise comparisons show a greater number of correct tokens at proper po-

	STM		ATT	
Condition	Mean	SD	Mean	SD
Stimuli				
Display Area 1	0,88	1,19	1,33	1,59
Display Area 2	0,83	1,26	1,15	1,47
Display Area 3	0,87	1,34	1,09	1,40
No Stimuli	0,82	1,21	1,16	1,35

Table 5.1: Stimuli vs. No-Stimuli condition for Levenshtein distance

sition for display area 3 ($M = 5.21, SD = .2.22$) than 1 ($M = 4.84, SD = 2.40$) than, $p < .001$ (Šidák corrected). These results indicate that distractors in far peripheral vision did affect performance less than distractors in near peripheral vision.

Interestingly enough, the stimulus "pop-up and move window" had almost the same effect in areas 1 and 3 in both experiments. However, in the display area 2, the effect was lesser in the attention experiment and stronger in the short-term memory experiment. Overall, and in the reflection of the errors produced by non-stimuli conditions, the display area's effect can be disregarded.

Learning. To gain better insights in learning effects, data from 136 trials was categorized in 4 equal time periods of 34 trials. To compare both experiments, we performed repeated measures ANOVA for each experiment with the within factor time period, which showed a significant effect on Levenshtein Distance in the *stm* group, $F(3, 21) = 12.11, p < .001, \eta_p^2 = .634$. Mean Levenshtein Distance decreased from $M = 1.24(SD = 0.88)$ for the first 34 trails to $M = 0.59(SD = 0.56)$ for the last time period (see Figure 5.5). Posthoc pairwise comparisons of time periods (Šidák adjusted) showed a significant difference of Levenshtein Distance between period 1 and 3 $(M = 0.64, SD = 0.67), p = .024$ and period 1 and 4, $p = .033$. As can be seen clearly in Figure 5.5, performance increased over time, showing a strong learning effect. Additionally, a comparison of learning curves has yielded that the overall distraction level was higher in the *attention* experiment. This is in line with the results of ANOVA between-subjects analysis.

Awareness. A repeated measures ANOVA was conducted for both experiments to assess the effect of stimulus type on the level of awareness rating. Stimulus type affected awareness ratings only in the *attention* group ($F(2, 14) = 4.688, p = .028, \eta_p^2 = .401$) as awareness seemed to differ between windows: Moving windows showed rather high awareness ($M = 5.63, SD = 1.30$) followed by multiple windows ($M = 3.63, SD = 2.2$) and single windows ($M = 3.38, SD = 2.33$). However, adjusted posthoc comparisons

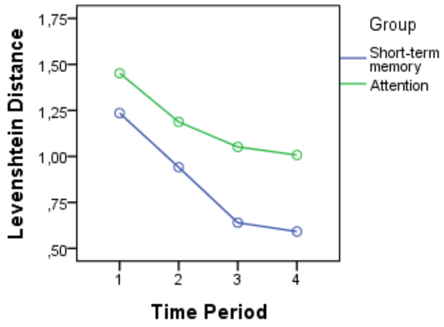

Figure 5.5: Mean Levensthein Distance over time

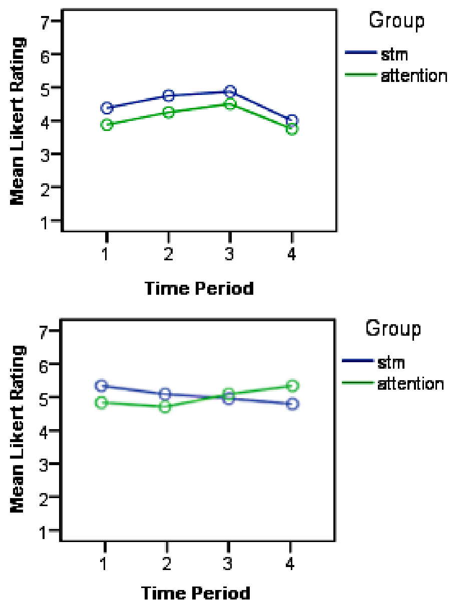

Figure 5.6: Mean Likert rating for frustration (top) and mental demand (bottom) for different time periods

were not significant here. In the *stm* group, the awareness of stimuli seemed to be similar for different distractor types.

Workload. Overall workload as depicted by NASA TLX (all subscales) was located in the center on a 21-point scale ($M = 11.56, SD = 3.26$). Mental demand, temporal demand, and effort showed above-average mean values and seemed to be more relevant to the task than the other subscales (see Table 5.2). Standard deviations of all subscales are remarkable and vary from 4.07 (Mental Demand) to 5.29 (Frustration). The NASA TLX ratings show that the memory task was quite demanding and can be rated as moderately high-load.

Repeated measures ANOVA showed no significant influence of time on mental demand or mental frustration in both groups (see Figure 5.6). Mean mental demand was consistently high over time ranging from 4.83 to 5.83 in the *stm* group and from 4.75 to 5.38 in the *attention* group with standard deviations between 0.75 and 1.55. Mean mental frustration showed similar values ranging from 4 to 4.83 in the *stm* group and from 3.75 to 4.5 in the *attention* group with standard deviations from 1.17 to 1.94.

In oral interviews, participants were asked about different aspects of the experiment. Most participants found the experiment mentally demanding: 75% of participants in the *attention* group and 87.5% in the *stm* group said that the experiment was either "demanding from the start" or "became demanding throughout the experiment". Only a few participants were distracted by the static background, as 37.5% and 25% of participants in the *attention* and *stm* group respectively gave a positive answer. On the other hand, all participants agreed that the dynamic distractors did indeed distract them. The answers to the question "Which area of distraction was most distracting?" were entirely in line with their performance: 100% of participants of the attention group indicated the near peripheral area.

In contrast, in the *stm* group, 75% of the participants indicated the near peripheral area, 12.5% indicated all three areas, and 12.5% said that "stimuli were not distracting". Finally, participants were asked if they recognized the disappearance of the stimuli during the second fixation phase and if it was distracting. Most participants (75% in the *attention* group and 62.5% in the *stm* group) did not recognize the disappearance. The remaining participants stated that they recognized it. However, it was not distracting.

5.2.4 Discussion

As a result, the study showed that distractors similar to those in mixed-focus collaborative scenarios could affect performance negatively. Even though no further person was in view, the distractor design was chosen so that similar effects can be expected in actual multi-user scenarios. Still, the optical flow produced by a nearby user while interacting can also potentially cause further distraction, which is an interesting issue for further research. Tunneling effects could counteract these distractions, but also this warrants further research.

While assuming that task-irrelevant distractors would affect short-term memory and attention, some effects of stimuli on user performance could be detected during experiments.

Short-term memory. The mental load of the task was high. By design, character sequences were constructed to make it harder to apply chunking as a memory aid, while the number of elements the participant had to keep in mind was rather high [**?**].

	stm group		attention group	
	Mean	SD	Mean	SD
How mentally demanding was the task? (Very low 1 – 21 Very high)	15.87	1.88	14.12	5.49
How physically demanding was the task? (Very low 1 – 21 Very high)	4.75	3.84	9.62	6.88
How hurried or rushed was the pace of the task? (Very low 1 – 21 Very high)	13.75	3.24	11.50	6.14
How successful were you in accomplishing what you were asked to do? (Perfect 1 – 21 Failure)	10.50	3.46	8.75	4.62
How hard did you have to work to accomplish your level of performance? (Very low 1 – 21 Very high)	15.62	3.62	14.37	5.29
How insecure, discouraged, irritated, stressed, and annoyed were you? (Very low 1 – 21 Very high)	10.12	5.03	9.75	5.87

Table 5.2: NASA Task Load Index Survey results: the participants assessed the system using a 21-point Likert scale with 1 = very low / perfect to 21 = very high / Failure

The level of task load was supported by the feedback acquired through questioning during and directly after the experiment, as users noted (moderately) high cognitive demands. Another indication of high mental demand was gained through observation, as participants exhibited clear lip movement throughout the experiment. The results of the *stm* group revealed that the stimuli effect remained more or less constant regardless of the area in peripheral vision it was. As such, the conclusion can be made that the provided stimuli did not impair short-term memory.

Attention. In contrast to the *stm* experiment, the results obtained in the *attention* experiment only endorsed the anticipated negative effect when comparing to the *stm* group, but not to the conditions excluding a distractor.

The results are surprising: concerning previously performed studies, these experiments did not show that task-irrelevant stimuli always affect performance in our moderately high-load tasks, as shown by Forster et al. [32], even though a higher task load was confirmed. However, it should be noted that Forster et al. noted that especially low-load tasks were affected. Interestingly, the oral interviews showed that stimuli in the near periphery distracted most, while in the far periphery were barely perceived consciously, which would be in line with results achieved by [79]. However, performance results did not confirm the latter. These results can be explained by looking more closely at both the cue (distractor) and task design.

Distractor design. The perception and effect of far-off stimuli could be amplified through an increased contrast between stimuli and background. Concerning stimulus type, the stimulus pop-up and move window distracted most as expected, as it exhibits the highest level of visual change. Interestingly enough, it is followed not by the stimulus multiple pop-up windows but by a single pop-up window. However, the distractors' effect was not significant enough, as we showed while comparing our results to the no stimuli conditions. The question remains if other types of distractors (e.g., more salient distractors) will produce different results. While literature only provides limited indications, the peripheral visual field is more receptive to, for example, to blue colors [87]. Furthermore, issues such as transparency and the size of cues can also have a more significant effect. At least large size cues would produce more optical flow in the peripheral visual field to which it is receptive.

Task design. One possible explanation for the results is that high cognitive load has been shown to produce attention tunneling that makes humans less receptive to events outside the central visual area. Mental workload is known to reduce the area of one's visual field (perceptual tunneling [141, 159]), but little is known about its effects on the shape of the visual field. Initial studies seem to indicate the expected limits of the visual field, and a potential shape distortion [97]. Hence, due to the high-cognitive load, attention may have been tunneled, as such that distractors could have a lower impact than if a low cognitive load task would have been deployed. If tunneling had occurred, distractors in areas 2 and 3 would have less effect than distractors in area 1, which is in line with Mori's experiment [79] and which users noted orally. However, the performance was not affected significantly by the display area as we showed. Hence, it would be appropriate to perform the same experiment, yet with a lower cognitive load task, to confirm this assumption.

5.3 Experiments with a Low-Load Mental Demand (Attention)

The experiments described in the previous section showed that extended workspace awareness could negatively affect users' performance during tasks with high-load mental demand. The considered memorization task is an integral part of the sensemaking process. During sensemaking, users must often compare multiple pieces of evidence. Although the experiments revealed that visual distractors would likely not corrupt the short-term memory content, they can disturb the memorization process, preventing data placement in memory.

Creative tasks are usually less mentally demanding. The experiment described in chapter 4 provided initial insights regarding the effects of workspace awareness in such tasks. Another similar experiment, as in the previous section, was conducted to extend these insights. However, the mental demand of the utilized task was significantly low, thus being closer to the domain of creative tasks. Additionally, only the *attention* case was investigated since the previous experiments did not reveal any significant effects on short-term memory.

5.3.1 Procedure and Design

The complete experiment's procedure was as follows. First, the participants filled in a personal survey. Next, the supervisor explained the task, the apparatus, and which actions the participants must do. Like in the previous experiments, the participants received the instruction to look only at the focus screen and ignore other screens. Subsequently, the supervisor invited the participants to practice the task. The participant had to accomplish ten samples. Afterward, the supervisor asked the participants if they understood the task and answered questions. Following this, the supervisor started the experiment. At the end of the experiment, the participants filled in the NASA TLX survey [47] (see Appendix A.9) and a survey regarding stimuli awareness and background (see Appendix A.8). Figure 5.8 visualizes the procedure.

The experiment employed a task introduced by Forster et al. [32]. In that task, a set of six symbols arranged circularly appeared on display. The symbols were either dots or arrows. The participants had to detect if the current set contains a left-arrow or a right-arrow and press an appropriate key on the keyboard. Therefore, the task's mental demand was significantly low compared to the memorization task described previously.

The experiment described had a between-subject 2 x 3 factorial design. The first factor was the *difficulty level* of the task. It had two levels *without noise* and *with noise*. The *without noise* level represented the condition where displayed symbol-sets contained only one arrow (left or right), and the other five symbols were dots (see figure 5.7). In that condition, the participant could instantly see the arrow. The *with noise* level represented the condition where all six symbols were arrows. However, there was only one correct arrow (left or right). Other arrows were incorrect and pointed, for instance, top-right, bottom, left-bottom (see figure 5.7). Therefore, the participant must find the correct arrow first and only then press the correct key. That condition was more difficult and time-consuming.

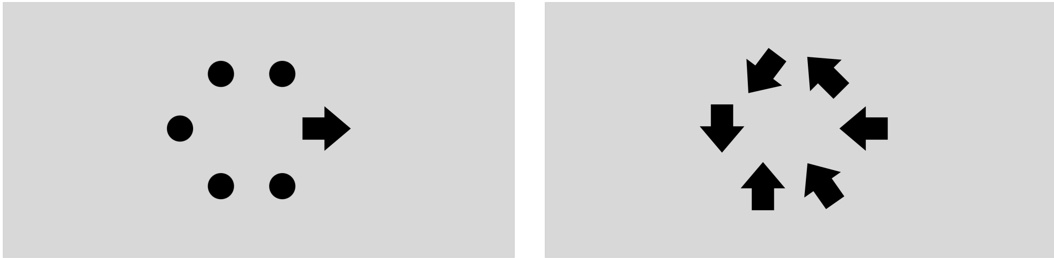

Figure 5.7: Difficulty levels: (left) *without noise* condition, (right) *with noise* condition

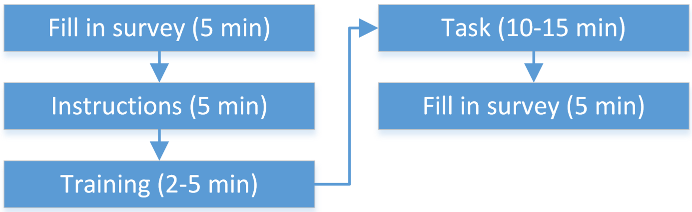

Figure 5.8: Procedure of the experiment with a Low-Load Mental Demand (Attention)

The second factor was the peripheral area of the display. Like the previous experiments in this chapter, there were three areas: near-, middle-, and far- peripheral (see figure 5.4).

The experiment employed two groups *control group*, and *stimuli group*. The participants of both groups worked on the display unit in the middle of the LHRD. The surrounding displays showed static images with news snippets that contained images and text. The participants of the *control group* underwent a condition where no stimuli were shown on the surrounding display, and the *difficulty level* changed randomly. In contrast, the participants of the *stimuli group* underwent a condition where a *pop-up window* stimulus was shown for each sample. Similarly to the *control group* the *difficulty level* switched randomly.

5.3.2 Participants

Sixteen experimentees participated in the experiment. There were two groups: *control group*, and *stimuli group*. Each group contained eight participants. The control group contained 2 females and 6 males aged between 29 and 51 years ($M = 37.80, SD = 8.28$), with normal or corrected-to-normal vision. The participants had rather a high level of computer games experience ($M = 4.37, SD = 1.50$), and all participants had seen large, high-resolution displays a couple of times before or worked with them. The stimuli group contained 3 females and 5 males aged between 20 and 31 years ($M = 25.60, SD = 4.03$), with normal or corrected-to-normal vision. Similarly, the participants of the stimuli group had rather a high level of computer games experience ($M = 4.00, SD = 1.60$). Most participants of the stimuli group had never seen large, high-resolution displays (5 participants 62.5%). All participants had an academic background (students or research associates). The participants received a cash reward for taking part in the experiment. Each participant was assigned only to one group, either control or stimuli.

5.3.3 Results

Each participant processed 10 training samples, 102 *with noise* samples, and 102 *without noise* samples. In total, the apparatus recorded 214 samples per participant, resulting in 3424 samples. For each sample, the system recorded the following data: the unique id of the participant, the id of the sample, time the participant required to process the sample, the unique id of the display that displayed the stimulus, a value of the flag that indicated if stimuli were present, a value of the flag that indicated the difficulty level, the unique id of the peripheral area that contained the stimulus. Additionally, after the participants processed all samples, they filled in the NASA TLX survey.

This section presents the results of the analysis of the gathered data.

NASA TLX. The evaluation of the NASA TLX survey revealed that the participants of both *control* and *stimuli* groups had a similar perception of the task. They assessed the mental demand of the task as *rather low* (*control group* ($M = 7.75, SD = 5.52$); *stimuli group* ($M = 7.12, SD = 4.40$)), and the physiucal demand as *very low* (*control group* ($M = 3.87, SD = 4.37$); *stimuli group* ($M = 3.25, SD = 1.85$)). The participants *did not feel rushed* (*control group* ($M = 9.75, SD = 3.27$); *stimuli group* ($M = 10.37, SD = 4.61$)), *did not feel to work very hard* (*control group* ($M = 9.00, SD = 6.82$); *stimuli group* ($M = 10.75, SD = 5.04$)), and *were rather relaxed* (*control group* ($M = 4.37, SD = 3.77$); *stimuli group* ($M = 4.62, SD = 2.69$)). Moreover, they *were sure of their effectiveness* (*control group* ($M = 3.62, SD = 1.32$); *stimuli group* ($M = 3.62, SD = 1.32$)). Table 5.3 summarizes the results of the surveys.

As mentioned at the beginning of the section, the experiment aimed to lower the task's mental demand compared to the task described in section 5.2. A comparison of the NASA TLX surveys for both experiments (see Table 5.4) showed the achievement of this objective. The participants of the *low-load mental demand experiment* perceived their task as significantly less mental and physically demanding. They were also more sure of their effectiveness, felt more relaxed, and felt to work less hard. Only the temporal demand was similar for both experiments.

Difficulty Levels. The results revealed a significant effect of the difficulty levels on time the participants needed to process a sample. For samples with noise, the participants needed, on average, twice as much time as for samples without noise. That

	Control group		Stimuli group	
	Mean	SD	Mean	SD
How mentally demanding was the task? (Very low 1 – 21 Very high)	7.75	5.52	7.12	4.40
How physically demanding was the task? (Very low 1 – 21 Very high)	3.87	4.37	3.25	1.85
How hurried or rushed was the pace of the task? (Very low 1 – 21 Very high)	9.75	3.27	10.37	4.61
How successful were you in accomplishing what you were asked to do? (Perfect 1 – 21 Failure)	3.62	1.32	3.62	1.32
How hard did you have to work to accomplish your level of performance? (Very low 1 – 21 Very high)	9.00	6.82	10.75	5.04
How insecure, discouraged, irritated, stressed, and annoyed were you? (Very low 1 – 21 Very high)	4.37	3.77	4.62	2.69

Table 5.3: NASA Task Load Index Survey results: the participants assessed the system using a 21-point Likert scale with 1 = very low / perfect to 21 = very high / Failure

difference was measured for both groups *control* and *stimuli* (see Figure 5.9). Since the Shapiro-Wilk's test showed that the recorded data is nonparametric, a paired samples Wilcoxon test was conducted to detect if the difference between difficulty levels was significant. The test was executed for each group separately. For the *control* group, the test indicated that the processing time of samples with difficulty level *with noise* was significantly higher than the processing time of samples with difficulty level *without noise* $p < 2.2e - 16$. For the *stimuli* group, the test indicated the same results. This finding was expected and lay in line with the finding of Forster et al. [32].

Performance. As the evaluation of NASA TLX surveys revealed, the participants felt confident regarding their effectiveness (see Table 5.3). This feeling corresponded indeed the real results. As Figure 5.10 depicts, in each condition, that encompassed 102 samples, there were no more than five wrong answers. Interestingly enough, the participants of the *control* group performed on average even better on samples with noise. A Mann-Whitney-U test was conducted to investigate if there were any significant differences between difficulty levels of the *control* group and *stimuli* group. However, the test did not reveal any significant differences.

	high-load experiment		low-load experiment	
	Mean	SD	Mean	SD
How mentally demanding was the task? (Very low 1 – 21 Very high)	**15.00**	4.07	**7.44**	5.16
How physically demanding was the task? (Very low 1 – 21 Very high)	**7.19**	5.95	**3.56**	3.48
How hurried or rushed was the pace of the task? (Very low 1 – 21 Very high)	12.62	4.88	10.06	4.14
How successful were you in accomplishing what you were asked to do? (Perfect 1 – 21 Failure)	**9.62**	4.05	**3.62**	1.36
How hard did you have to work to accomplish your level of performance? (Very low 1 – 21 Very high)	**15.00**	4.43	**9.87**	6.26
How insecure, discouraged, irritated, stressed, and annoyed were you? (Very low 1 – 21 Very high)	**9.94**	5.28	**4.50**	3.39

Table 5.4: NASA Task Load Index Survey - High-load experiment versus Low-load experiment: the participants assessed the system using a 21-point Likert scale with 1 = very low / perfect to 21 = very high / Failure

Effect of the Stimuli. Although the participants of the *stimuli* group processed incorrectly slightly more samples than the *control* group, statistical analysis could not detect any significant difference between the groups. Therefore, the stimuli did not have any effect on the effectiveness of the participants.

To investigate the effect of the stimuli on the participants' efficiency that can be defined as the time needed to process a sample, a Mann-Whitney-U test was conducted. For that, the samples of *control* and *stimuli* groups were first split into two groups depending on the difficulty level. Next, the samples of the *stimuli* group were divided into three categories based on the peripheral area where the stimuli appeared. Therefore, there were six conditions to test.

Figure 5.11 visualizes the efficiency of the participants for the difficulty level *without noise* and Figure 5.12 for the difficulty level *with noise*. The box plot diagram for the difficulty level *without noise* indicates that participants of the *stimuli* group were less efficient irrespective of the peripheral area compared to the *control* group (see Figure 5.11). For the difficulty level *with noise*, the difference is less clear(see Figure 5.12).

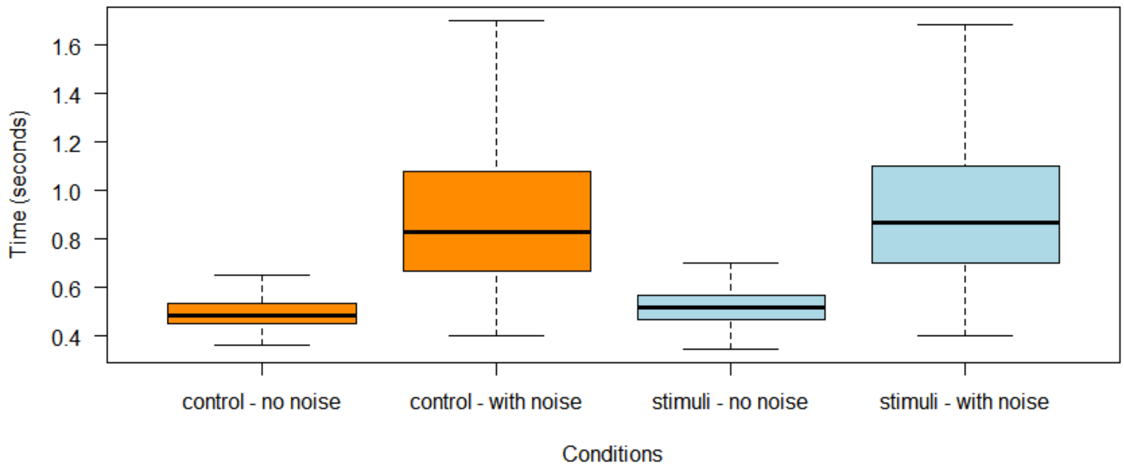

Figure 5.9: Low-Load Experiment: Time the participants needed to process a sample in different conditions: (control - no noise) time of the control group for samples without noise; (control - with noise) time of the control group for samples with noise; (stimuli - no noise) time of the stimuli group for samples without noise; (stimuli - with noise) time of the stimuli group for samples with noise.

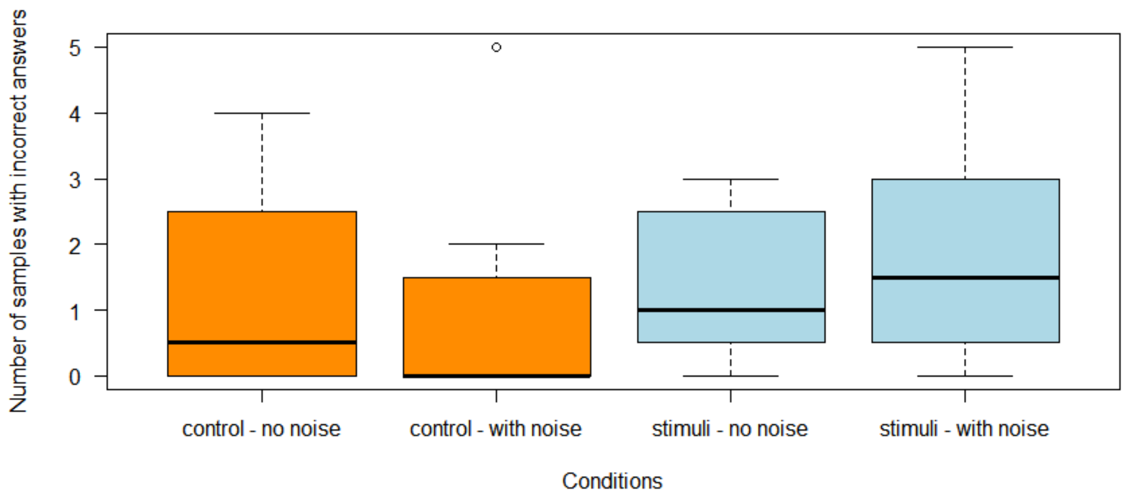

Figure 5.10: Low-Load Experiment: Number of samples with incorrect answers for different conditions: (control - no noise) number of incorrect answers of the control group for samples without noise; (control - with noise) number of incorrect answers of the control group for samples with noise; (stimuli - no noise) number of incorrect answers of the stimuli group for samples without noise; (stimuli - with noise) number of incorrect answers of the stimuli group for samples with noise.

To examine if the differences were significant a Mann-Whitney-U test was executed.

Table 5.5 presents the results of the test. Indeed the results revealed significant differences for each condition with difficulty level *without noise*. For the difficulty level *with noise*, a significant difference was detected only for the condition where the stimuli were shown in the near peripheral area.

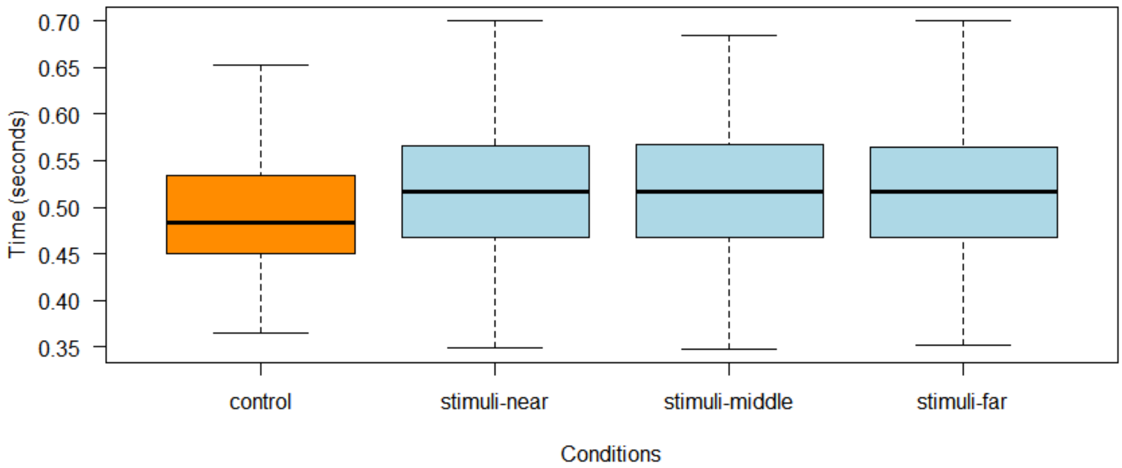

Figure 5.11: Low-Load Experiment: Time needed to process a sample for the difficulty level *without noise*; (control) time of the control group for samples without noise; (stimuli - near) time of the stimuli group for samples without noise and stimuli in the near peripheral area; (stimuli - middle) time of the stimuli group for samples without noise and stimuli in the middle peripheral area; (stimuli - far) time of the stimuli group for samples without noise and stimuli in the far peripheral area.

	p-Value	
Condition	without noise	with noise
control VS stimuli-near	**4.565e-05**	**0.006527**
control VS stimuli-middle	**1.156e-08**	0.05312
control VS stimuli-far	**3.442e-05**	0.4824

Table 5.5: Low-load experiment: results of the Mann-Whitney-U test. The test compared the time the control group needed to process samples with the time of the stimuli group. The samples of the stimuli group were divided into three buckets depending on the peripheral area where the stimuli was shown. Additionally, the samples of the control group and the stimuli group were split into two buckets depending on the difficulty level. The matrix shows the p-Values for each tested condition. The values in bold indicate the conditions where the test determined a significant difference.

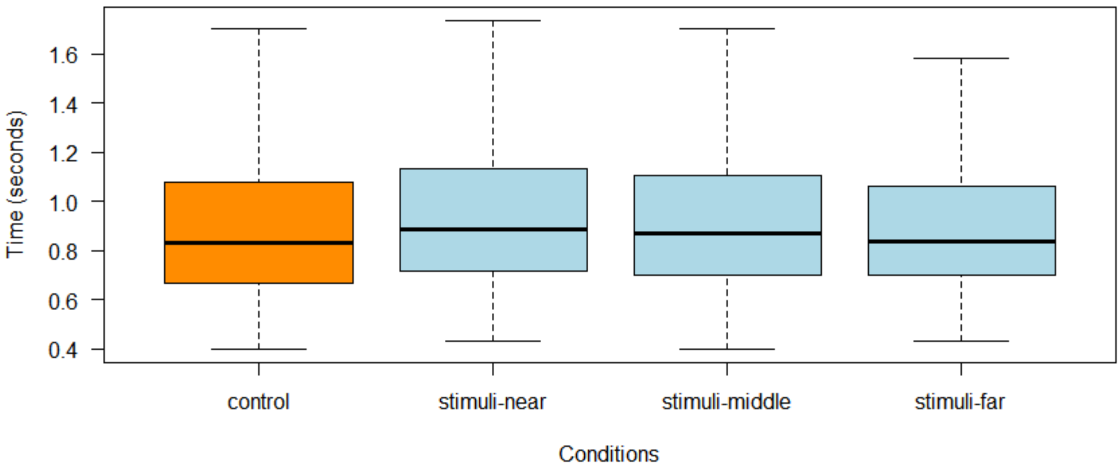

Figure 5.12: Low-Load Experiment: Time needed to process a sample for the difficulty level *with noise*; (control) time of the control group for samples without noise; (stimuli - near) time of the stimuli group for samples without noise and stimuli in the near peripheral area; (stimuli - middle) time of the stimuli group for samples without noise and stimuli in the middle peripheral area; (stimuli - far) time of the stimuli group for samples without noise and stimuli in the far peripheral area.

5.3.4 Discussion

The experiment results revealed significant differences between the *control* group and the *stimuli* group. This finding means that users can perceive visual stimuli in all parts of the peripheral vision. To process perceived visual stimuli and decide if these are relevant for the task brain needs to allocate mental resources. Thus, it will have fewer resources for the main task and have to process multiple tasks in parallel. As a result, an apparent effect of task-irrelevant stimuli was observable during the experiment. The efficiency of the participants declined significantly compared to the condition without stimuli. On the one hand, for individual samples, the effect might be considered negligibly; however, it will likely accumulate during longer sessions leading to mental fatigue. Subsequently, not only efficiency but effectiveness as well might decline.

On the other hand, the experiment revealed that users' awareness reduces with increasing task's mental demand, which means that artificial noise can counteract the negative effect of task-irrelevant stimuli in the peripheral vision. The peripheral area where users can perceive such stimuli will shrink significantly. Multiple researchers already observed such perceptual tunneling (e.g., [141, 159]). However, the noise makes the task more mentally demanding, leading again to a decreased performance. Moreover, the results showed that noise had a more negative effect on the efficiency than task-irrelevant stimuli and almost doubled the time needed to process a sample. Therefore, a conclusion can be made that task-irrelevant stimuli are more preferable over the noise in the task itself for short tasks. The effect the noise and task-irrelevant stimuli will have during more extended periods and what effect different amounts of noise will have compared to task-irrelevant stimuli remain exciting questions for future investigations.

5.4 Guidelines

This section provides some guidelines based on the presented experiments' findings.

- **Avoid noise in focus vision area** - the experiments described in section 5.3 showed the negative effect of noise in the focus vision area on users' performance. The efficiency decreased significantly, and the time needed to accomplish the task almost doubled. The effect might become even worth with increased task duration through mental fatigue. Therefore, groupware designers have to mitigate task-irrelevant visual artifacts and provide tools that will allow users to highlight task-relevant visual artifacts that will ease the recurrent retrieving of information.

- **Estimate the mental load of the task** - mental load of the task impacts the size of the peripheral vision area clearly where users can perceive visual stimuli. The experiments showed that low-mental demand tasks do not affect users' awareness while mentally demanding tasks shrink the area distinctly. Subsequently, groupware designers have to understand the task's mental load to handle task-irrelevant visual stimuli accordingly.

- **Protect near peripheral area** - no matter how mentally demanding the task is, the near peripheral area seems to be always affected by visual task-irrelevant stimuli. The experiments showed that stimuli in that area might negatively affect users' effectiveness or efficiency if placed timely. Therefore, groupware designers should provide techniques and mechanics that will protect the near peripheral vision area, reducing the effect of visual stimuli. For instance, buffer territories can be introduced that will surround the user's focus area. This territory will then either prohibit other users from operating in it or slow down the speed of dynamic visual stimuli and make them more transparent to decrease awareness.

- **Mitigate the awareness of visual stimuli during loosely-coupled work** - The experiments demonstrated apparent adverse effects of visual stimuli in the peripheral vision on user performance. Therefore it is recommended to mitigate the users' awareness of these stimuli during the phases of loosely-coupled work. Groupware designers can experiment with such parameters of visual artifacts as colors, sizes, and speed to reduce awareness. Additionally, the user's relative position to different display areas can play a role.

- **Increase the awareness of visual stimuli during tightly-coupled work** - While visual stimuli can distract during the loosely-coupled work, they also can be useful during tightly-coupled work. When working tightly-coupled, users need to be aware of co-users' location (virtual and physical), activities, and intentions, so they can better coordinate their actions. Rendering visual stimuli more noticeable in that case can provide additional cues that allow users to acquire the required information faster, making the interaction workflow smoother.

5.5 Revisiting hypotheses

The experiment described in this chapter investigated if extended workspace awareness can harm users' performance and therefore addressed the hypotheses H6 and H7.

H6: Visual events in peripheral vision might affect the performance of individual users

The experiment presented in Section 5.2 indeed confirms the hypothesis. The results revealed that visual distractors in peripheral vision might negatively affect the performance of individual users if placed timely.

H7: Visual events in peripheral vision will not affect low mental load tasks

The experiment presented in Section 5.3 investigated if the adverse effect remains for tasks with lower mental demand. It was expected that the effect would diminish since the user will have more free mental resources available. However, the experiment disapproved the hypothesis and showed that users might suffer from the visual distractors in peripheral vision even during tasks with low mental demand.

Chapter 6

Rapid Prototyping Tools

Several rapid prototyping tools - implemented on the Unity game engine base - emerged during preparation for the execution of studies. Rapid prototyping tools are of substantial value for researchers since they significantly lower the hypothesis/concept evaluation overhead. Unfortunately, a choice of the rapid prototyping tools for LHRDs at the time of the experiments' execution was scarce. To address this issue and boost the research's progress, a lean, easy to use extension for the Unity game engine was developed. Subsequently, groupware for 2D level design on LHRDs was developed based on that extension. However, the groupware is not limited to the level design task only and can serve as a framework for different creative tasks. This section provides an overview of the extension and groupware and presents both tools' evaluation results.

Parts of this chapter were previously published in in the following papers:

Sigitov, A., Scherfgen, D., Hinkenjann, A., and Staadt, O. Adopting a Game Engine for Large, High-Resolution Displays. *Procedia Computer Science 75* (2015), 257–266

Sigitov, A., Staadt, O., and Hinkenjann, A. Distributed unity applications evaluation of approaches. In *Communications in Computer and Information Science*, C. Stephanidis, Ed., vol. 617. Springer International Publishing, Cham, 2016, pp. 138–143

Sigitov, A., Hinkenjann, A., and Staadt, O. Effect of User Roles on the Process of Collaborative 2D Level Design on Large, High-resolution Displays. In *Proceedings of the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications* (2020), SCITEPRESS - Science and Technology Publications, pp. 118–129

6.1 Unity Engine Extension

The developed extension allows – with a small overhead – to implement applications that are apt to run on both single-display and multi-display systems. It takes care of the most common issues in the areas of the distributed and multi-display rendering like frame, camera, and animation synchronization. In conjunction with Unity, which significantly simplifies creating different kinds of virtual environments, the extension affords to build mock-up virtual reality applications for large, high-resolution displays and implement and evaluate new interaction techniques and metaphors, and visualization concepts. The extension pursues three goals:

- Ease the application configuration process in terms of distributing application instances among compute-units and displays.

- Ease the process of camera configuration in terms of distributing view frustum fragments among application instances.

- Solve or at least ease the task of synchronizing application instances.

The extension consists of two general components: a software module in the form of Unity scripts and a guidance component that provides hints for adapting applications for LHRDs. The software module itself consists of the editor and run-time modules.

6.1.1 Editor Module

The editor module provides a tool for creating a camera system that reflects the geometrical arrangement of displays in an LHRD. To configure it, the user has to fill in the displays' dimensions and their positions and orientations in space relative to a defined coordinate system. The configuration process is aided by visual feedback that provides the user with a graphical representation of the camera system. Figure 6.1 depicts the visual components of the editor extension. Moreover, the editor module allows for the configuration of the distribution of application instances among display units. For that purpose, the developer has to assign appropriately so-called MPI ranks to the display units. Based on that information, a new MPI configuration file will be generated and evaluated by the MPI environment when the application starts. Additionally, to instances' distribution, a manager instance should be defined. The manager instance is a process that receives user input, runs simulations, e.g., animation or physics, and conveys the results to the other instances, which we refer to as worker instances.

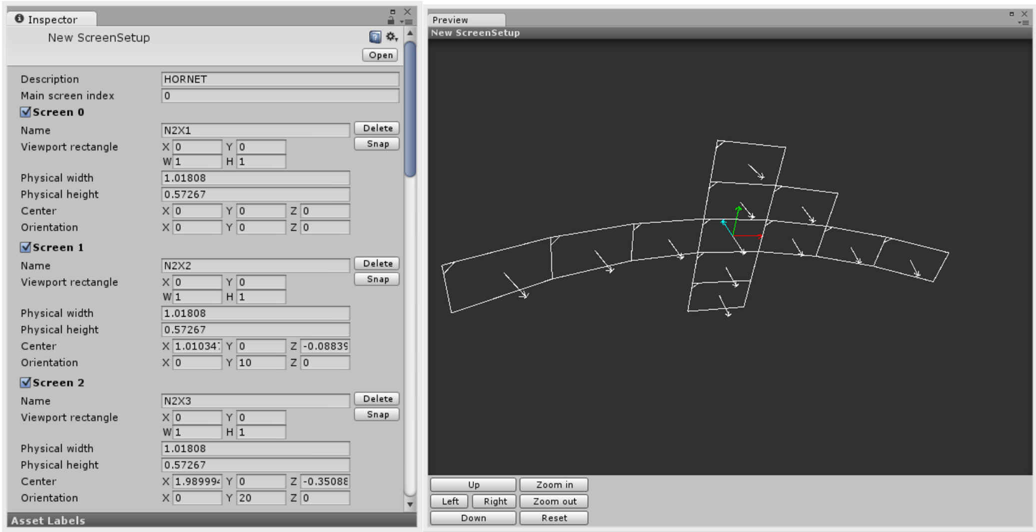

Figure 6.1: Unity Camera Configuration Tool – Configuring a curved LHRD: (left) custom editor for displays, (right) graphical representation of the camera system

6.1.2 Run-Time Module

The run-time software module consists of multiple Unity scripts. The primary purpose of that module is the synchronization of application instances. In the given context, we distinguish between four synchronization types: frame synchronization, camera state synchronization, transform state synchronization, and event synchronization.

The application instances are frame-synchronized if the sequence numbers of frames they process are equal at every point in time. However, this ideal case is hard to ensure. The application instances must contain a locking mechanism to achieve visual output synchronization. This locking mechanism has to be added right before the function call that swaps the back and front buffers, making the previously rendered image visible. There are two fundamental types of such locks: hardware-based and software-based. Hardware-based locks like NVIDIA's Swap Sync require costly professional graphics cards. It is the best way of synchronizing buffer swapping, however. A software-based lock is less precise than a hardware-based lock but free. They are usually implemented on the application layer and might incorporate different strategies for that purpose. The developed extension uses the MPI barrier mechanism from the OpenMPI library.

A barrier is usually placed right before a buffer swapping function call. Since no process can pass through the barrier before all other processes have reached it, it serves as a synchronization point, thus ensuring that all processes display their frames roughly at the same time and run at equal speeds. In order to introduce such a barrier, the programmer needs access to the source code of the framework to manipulate it. However, there is no such possibility in Unity, since its source code is closed. While it would be possible to use DLL hooking techniques, we implemented a different workaround based on the concept of coroutines available in Unity. A coroutine is a type of function with the unique ability to interrupt its execution and return control to Unity actively. The engine saves all local variables and the instruction pointer when this occurs. It restores them later when the coroutine resumes, similarly to a thread when it is interrupted by the operating system. By default, active coroutines are called every frame. Some functions allow for the transformation of that behavior, however. They are WaitForSeconds, WaitForFixedUpdate, and WaitForEndOfFrame. According to the Unity manual, the latter will stop executing a coroutine and activate it again just before displaying the frame on the screen. Thus, a barrier placed right after this function yields workable results. The described extension provides a script with a coroutine that implements this approach.

Another script, called CameraSyncer, provides functionality for camera synchronization. Camera state synchronization takes place in two stages: First, the camera-specific values are collected by the manager instance and conveyed to all worker instances. These values could be: position, rotation, frustum parameters, projection mode, culling mode, and background color, to name a few. During the second stage, the script applies the received values. Additionally, the script calculates a new camera frustum following the created display configuration to match the user's perspective if head tracking is enabled. Camera state synchronization proceeds in a broadcast manner. It means that all worker instances will receive the values since they all need them to produce the correct output.

Transform state synchronization has its name from the Unity component called Transform. That component manages three properties of a game object: position, rotation, and scale. Transform state synchronization is implemented in a script called TransformSyncer and is responsible for synchronizing the mentioned properties. Oppositely to camera state synchronization, it incorporates a publisher-subscriber communication pattern. The description of the synchronization procedure is as follows:

1. All application instances share the same object.

2. One manager instance runs all simulations on the object, e.g., animation and physics, which usually affect the Transform component's properties. The manager instance determines which camera can see the object and submits the values to the respective worker instances based on the camera system configuration.

3. The worker instances manage only the visual representation of the object. They do not simulate physics or animations; neither react to user input. Their main task is rendering. Right before a buffer swap synchronization barrier, they go into a listening mode and wait for updates from the manager instance.

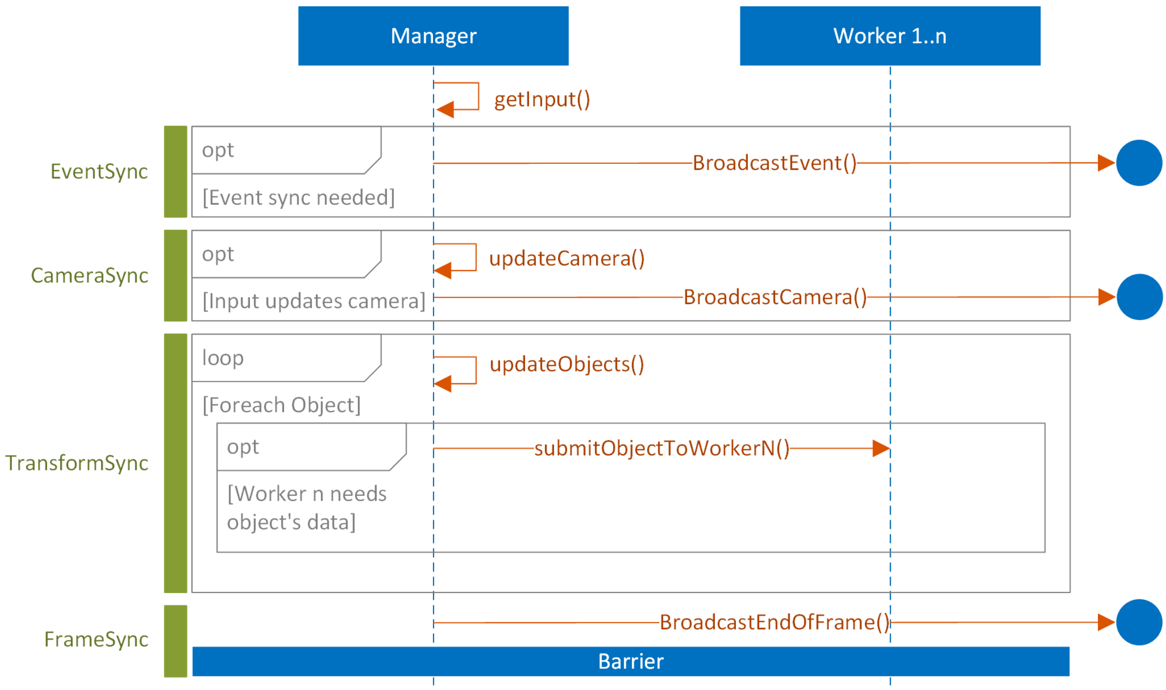

Figure 6.2: Overview of the four different types of synchronization used in our approach

4. After the manager instance has distributed all updates, it broadcasts the EndOfFrame message and then paces to the synchronization barrier. The EndOfFrame message forces the worker instances to leave the listening mode and approach the synchronization barrier as well.

5. All application instances pass through the barrier, starting a new frame.

From the statements made in points 2 and 3, we can see that the same objects have to differ in terms of components they contain: only the manager instance can have components relevant to simulation. In order to make the transition of an application from a single display to a multiple display environment easier for the developer, the TransformSyncer script provides an array field that can take in references to several arbitrary object components. When running in the multi-display environment, the script will use these references to remove from the object the specified components within the worker instances.

Event synchronization usually has to occur if an object has to be created, removed, or modified in response to user input or another event. That is because only the manager instance may acquire user input and compute simulations. The extension uses the publish-subscribe pattern to synchronize events. Each worker instances register for an event using the *SubscribeToEvent* method of the *MPIReceiver* class. The method takes two arguments: an id of the event and a reference to the callback that will process the event data. In its turn, the manager instance serves as a publisher that observes the user input and fires an appropriate event. The event is then distributed to all workers.

Figure 6.3: Sample applications: (top left) custom 2D arcade game; (top right) custom static 3D scene; (bottom left) modified *2D Platformer* application from the Unity Asset store; (bottom right) modified *Unity Labs* application from the Unity Asset store

Figure 6.2 provides an overview of all synchronization types.

6.1.3 Proof of Concept

The extension was evaluated on the system described in section 1.7. We used scenes of different types and complexity. Two applications were taken from the Unity Asset store: one 2D application called *2D Platformer*, and one 3D application called *Unity Labs*. Another two applications were internal implementations: one 2D arcade game and one static 3D scene. All applications were instantiated 35 times. All instances ran in parallel and had the following distribution on the system: one manager instance and eleven worker instances on display node 1, twelve worker instances on display node 2, and eleven worker instances on display node 3. The instances' synchronization took place using the OpenMPI library and the provided routines described in section 6.1.2. Figure 6.3 visualize the visual outputs of the applications. The borders of the display were cropped in the images for better representation. The Unity quality settings were set to the default *Good* preset. Vertical synchronization (VSync Count) was set to *Every VBlank* and Anti-Aliasing to *4x Multi Sampling*. For interaction purposes, a conventional keyboard was utilized. All four applications ran at stable frame rates of least 30 frames per second.

6.1.4 World-State Synchronization

Three specific approaches for world state synchronization in distributed Unity applications were developed: *Naïve*, *AdaptiveF* (Frustum-based), and *AdaptiveC* (Camera-based). The approaches handle virtual objects that own an MPIView component. This component tags an object as distributable and encapsulates a unique object ID that ensures a proper object match across individual application instances.

Naïve. The Naïve approach broadcasts state information of all distributable objects. It does not matter if a particular application instance requires this information for a current frame. The approach provides the highest integrity level for applications, as all instances have the same world state. For instance, that allows correct shadow calculation (for objects that lay outside the instance's partial frustum, but their shadows within) on output instances. However, Naïve causes high network overhead, which depends on both the number of virtual objects and the number of application instances.

AdaptiveF. The AdaptiveF approach tests distributable objects against each virtual camera's frustum. It conveys state information of an object to an application instance only if the object lies within a frustum of the instance's camera. AdaptiveF lowers network overhead. Dependences on the number of virtual objects and number of application instances remain, though, since each object undergoes the frustum check for each virtual camera. That, in turn, increases the computational overhead on the manager instance. The approach does not ensure proper shadow calculation, as it cannot detect shadows within a frustum.

AdaptiveC. The AdaptiveC approach enforces the manager instance to create and maintain all virtual cameras' replicas. Each camera replica will raise the Unity callback OnWillRenderObject for each virtual object it will render in a current frame. In this way, AdaptiveC determines object visibility for a particular camera. Hence, application instances receive state information of only visible distributable objects. AdaptiveC abolishes dependence on the number of virtual objects. Dependence on the number of application instances remains due to virtual camera replicas. Also, overhead on the manager instance rises since each camera replica renders an image. AdaptiveC and AdaptiveF have equal network overhead. Similar to AdaptiveF, AdaptiveC does not safeguard correct shadow generation.

At the heart of the extension lies the centralized control model [23]. The entire world simulation process takes place only on the manager instance that distributes a new world state across output instances at the end of each frame. The output instance is responsible for state receiving, state applying, rendering, and output to a connected display unit.

6.1.5 Evaluation Scenarios

Two types of 3D evaluation scenarios were implemented (static (s) and dynamic (d)) with three conditions (standard (1), shadow (2), and multiple lights (3)) each. There was only one light (directional) in the standard condition, which had a random position in a virtual scene and cast no shadows. That was the only difference to the shadow condition, where the directional light cast shadows. In the multiple lights condition, there were nine lights in total: one light was directional, and eight lights were point lights. Neither of them cast shadows.

There were five stages in all type-condition combinations. There were 64 distributable virtual objects at the beginning of the first stage. The number of objects doubled with each subsequent stage. The lowest frame time, highest frame time, average frame time, and total stage time were logged for every stage. The stage preparation frames were not considered to avoid administrative overhead interference. Also, the dynamic batching and occlusion culling methods were turned off to mitigate Unity's internal routines' impact on the evaluation results.

The static scenarios comprised static, not synchronized virtual cameras. The cameras shared the same origin and orientation. Each camera's frustum made up a part of a large mutual frustum. Distributable virtual objects (cubes of the same size and different colors) appeared at a random position and with random orientation within the bounds of the mutual frustum. Each object revolved one degree per frame around its local Y-axis.

The dynamic scenarios had a camera setup comparable to one in the static scenarios. However, the cameras were dynamic and synchronized. The mutual cameras' origin lay at the local center of a ring-shaped volume. Distributable virtual objects emerged within the ring-shaped volume. Each object had a random position and orientation. The objects and the cameras rotated one degree per frame around their local Y-axis. Hence, only a subset of the objects lay within the cameras' mutual frustum at a time.

For a 2D case, we implemented only one type-condition combination, namely static-standard. The 2D scenario incorporated a set of cameras with an orthogonal projection instead of perspective projection, like in the 3D scenarios. It also made use of Unity Sprites instead of 3D cubes.

Two baselines were determined for every type-condition variation. The baseline (B1) reflects the application's performance at the standard condition with frame synchronization only. Additionally, MPIView components were disabled in order to prevent Unity from making any calls on them. The baseline (B2) shows the performance at a specific condition with frame synchronization and enabled MPIView components. Although MPIView components were active, no world state synchronization took place, as class methods contained no logic.

6.1.6 Evaluation Results

Figure 6.4 depicts the evaluation results. At every condition, the Naïve approach was less efficient than AdaptiveF and AdaptiveC. The average frame time increased linearly with the number of distributable objects. With 1024 distributable objects, it performed with four frames per second. However, it is the only approach that ensures proper shadow visualization currently. Moreover, it adds no computational overhead to the manager instance.

Likewise, AdaptiveF depends on the number of distributable objects strongly. It performed at least twice as fast as the Naïve approach, however. That ascribes to lower visibility computation overhead in comparison to synchronization overhead. By small numbers of distributable objects, it outperformed the AdaptiveC approach too. However, the approach is incongruous if shadow visualization is desirable.

AdaptiveC performed less efficiently with fewer distributable objects than the Naïve and the AdaptiveF approaches due to rendering overhead caused by virtual camera replicas. The effect is well observable at the shadow conditions (s2) and (d2). However, it is more resistant to the number of distributable objects in a virtual scene. As a result, with an increased number of objects, AdaptiveC performed significantly better than the other two approaches. In the variations (s2) and (s3), the transcendence is less apparent. However, the inspection of logged data for both variations disclosed that the average frame time of the AdaptiveF approach had been increasing at a faster pace. Similar to AdaptiveF, AdaptiveC ensures no proper shadows.

6.2 2D Level Design Groupware

Another software artifact that was developed within the scope of the thesis is 2D level design groupware. The groupware consists of four main software components (see Figure 6.5): server, mobile client, display client, and a level editor. Mobile clients can run on a mobile device, laptop, or a conventional desktop computer. It provides an interactive interface to users and allows them to create visual artifacts in the form of map tiles. Display clients take commands and messages from the server and pass them to the level editor. The level editor application encapsulates the display client component for communication purposes. The server is a connecting link between clients; therefore, clients communicate only with the server or through the server, and no client does know anything about other clients.

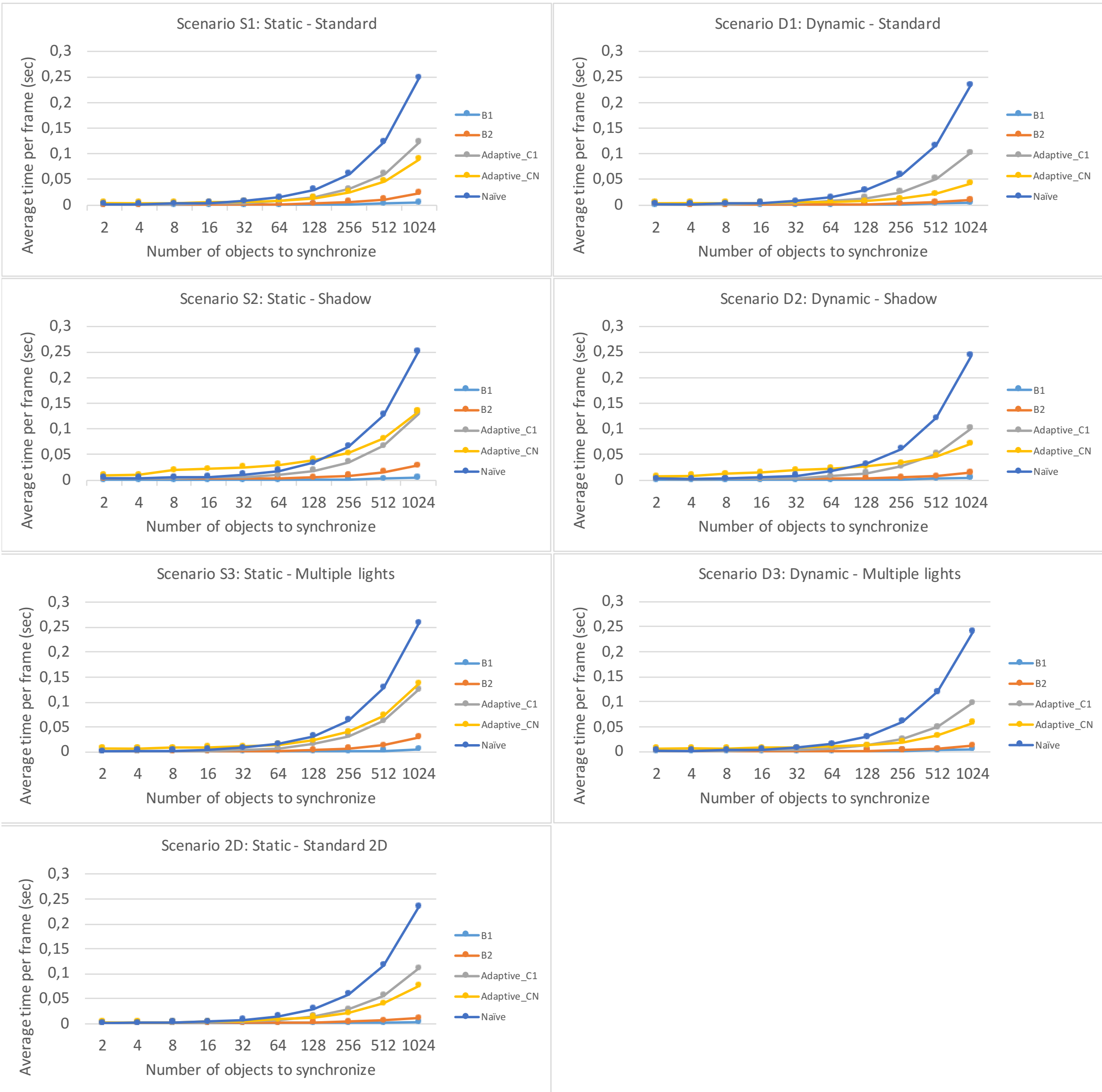

Figure 6.4: Evaluation results: (s1) static - standard; (s2) static - shadow; (s3) static - multiple lights; (d1) dynamic - standard; (d2) dynamic - shadow; (d3) dynamic - multiple lights; (2D) static - standard - 2D. The X-Axis shows number of distributable virtual objects. The Y-Axis shows the average frame time in seconds

The groupware uses the following protocol to register clients on the server. On each new connection, the server puts the client into the waiting pool first. Next, it asks the client to identify itself; after that, the client responds with its type and name. Depending on the client's type, the server chooses a communication protocol and allocates appropriate data structures for the client. Subsequently, the server responds and conveys a session-id to the client. That means that the server registered the client. Finally, the client can send data.

Together with the apparatus described in section 1.7, it formed a system. That system served as a platform during the execution of the study described in section 4. However, the groupware can be deployed to any LHRD system with mobile clients for interaction.

The next subsections describe the defined requirements on the groupware, software components of the groupware in detail and provide the evaluation results of the groupware and the system in general.

6.2.1 Requirements Analysis

To extract requirements on groupware for 2d level prototyping on LHRDs, we analyzed the prototyping task in terms of activities and settings. Activities describe actions the user has to execute to achieve task completion, while settings describe special environment features and conditions. It is worth noting that LHRDs vary significantly in form, size, shape, and functionality. Thus, we have to consider all possible configurations during requirements analysis.

Activities

To identify the common activities, we took a closer look at the Unity game engine, which is currently one of the most popular game engines that supports the creation of 2d games. The Unity game engine supports two workflows for 2d game creation: tile-based and sprite-based. By the tile-based workflow, sprites can be placed only at specific locations within a tilemap's cells. In comparison, sprites can be placed in any position by the sprite-based workflow. For both workflows, the following activities could be identified: (A1) *create asset* (e.g. pictograms, annotations, sketches), (A2) *place asset* on the level map, and (A3) *delete asset* from the assets library or the map.

For the ***create asset*** activity (A1), we defined the following system requirements:

- (A1.R1) The system must allow for the rapid creation of assets on the fly since the prototyping task belongs to the category of fast-paced brainstorming tasks.
- (A1.R2) The system has to provide an ergonomic and precise input device that allows for the efficient creation of asset sketches.
- (A1.R3) The system has to provide a mechanism for the storing and management of assets.

The requirement A1.R3 is a straightforward engineering task that can be solved using a dictionary data structure. Additionally, some management functions can be implemented, for instance, to resolve naming conflicts automatically.

The requirements A1.R1 and A1.R2 expose a more challenging question: what interaction device is more appropriate for the system. Considering the related work regarding interaction devices presented in Chapter 2 a conclusion can be made that there is a choice between touch-capable display walls and mobile device with touch displays. For the final decision, however, other requirements have to be discussed.

The ***place asset*** activity (A2) resulted in the following requirements:

- (A2.R1) The system has to provide an interaction technique for rapid and precise pointer positioning.
- (A2.R2) The system has to visually indicate the position for asset placement.
- (A2.R3) The system has to provide a mechanism for the selection of assets.

While touch-capable LHRDs make it easy to satisfy all three requirements, interaction using mobile devices require careful design considerations. Multiple researchers [82, 12, 26] already investigated precise pointing positioning on LHRDs. One possibility is to utilize the already mentioned LOP cursor. While in the coarse mode, the LOP cursor occupies a relatively large display area. It allows to change the working area rapidly on display, yet does not allow selection or manipulation of objects. For that, the user has to switch to the precise mode. Thus, the user has to work with two precision levels to operate efficiently on the entire display.

Finally, the ***delete asset*** activity (A3) requires the following functionalities:

- (A3.R1) The system has to allow for asset selection on the map providing visual feedback.
- (A3.R2) The system has to provide a mechanism for the deletion of assets from the map.
- (A3.R3) The system has to provide functionality for the selection and deletion of assets from the storage.

This activity's requirements touch on the same questions as the requirements of the activity (A2). Thus, no further discussion is required.

Settings

The settings of the task expose two special characteristics: (S1) *large shared display* and (S2) *synchronous co-located collaboration.*

For the ***large shared display*** setting (S1) we could identify the following requirements:

- (S1.R1) The system has to implement an appropriate communication protocol to ensure information transport between input-related and output-related devices.
- (S1.R2) Since LHRDs are usually driven by multiple compute nodes, the system has to implement a mechanism for synchronization of and data exchange between individual application instances.
- (S1.R3) The system has to provide an interaction device that allows the user to work in different display areas from different distances.
- (S1.R4) The system has to provide an interaction technique that ensures access to remote display areas.

The requirements expose two challenges: the development of distributed applications for LHRDs, and interaction with LHRDs. As stated in the requirement (S1.R2), applications for LHRDs usually must run on multiple computer nodes to utilize the entire display. Distributed applications consist of multiple synchronized instances. The main challenges here are the synchronization of the virtual world's internal state and the implementation of simultaneous back buffer swap to ensure a consistent image on display. The Unity extension presented in the previous section was employed to achieve this.

The (A1) activity already touched the challenge of interaction with LHRDs. The setting (S1), however, brings additional requirements (S1.R3) and (S1.R4) that require consideration. So far, direct interaction techniques for touch-capable LHRDs had the upper hand compared to the mobile device based techniques. These techniques can only partly satisfy the mentioned requirements. For instance, they do not tether the user like stationary devices do. However, they tether the user to particular areas during the interaction, and no interaction is possible from a distance.

Moreover, the user can have difficulty trying to access remote areas without any further actions. Although there are techniques that allow interaction with remote areas (e.g., Frisbee technique [59]), it can be still problematically to target the desired area. Thus, mobile device techniques seem to fit better into the defined setting.

The ***synchronous co-located collaboration*** setting (S2) resulted in the following requirements:

- (S2.R1)The system has to ensure multi-user collaboration allowing for simultaneous interaction with the display.
- (S2.R2)The system has to provide interaction techniques that do not lead to occlusion of LHRD regions by the user so that each user could overview the content.
- (S2.R3) The system has to ensure integrity, which means that users have to have access to the same data (e.g., assets in the storage).
- (S2.R4) The system has to provide a visualization technique that allows distinguishing between users within the virtual workspace.

The setting (S2) touches again on an interaction technique's choice. It is clear that the requirement can be better satisfied using touch-capable LHRDs. In that case, visualization is expendable since users interact directly with the display. It is obvious who is working where, while utilizing indirect interaction results in the need to visualize the users in the virtual workspace. However, this issue is easy to solve. For instance, each user can have a customizable pointer to make herself distinguishable from others.

On the other hand, indirect techniques satisfy the requirement (S2.R2) better. Direct interaction with the display from up-close leads inevitably to the occlusion of LHRD areas through the user's body. In comparison, indirect techniques allow interaction from a distance, thus avoiding the occlusion issue.

Both interaction modalities have to provide a solution for user identification to fulfill the requirement (S2.R1). In case of indirect interaction, a mobile device (or, to be more precise, an application running on the mobile device) can serve as an identification token. The implementation of such an approach is straightforward. In the case of direct interaction, a more sophisticated and complex solution has to be found (e.g., using tracking systems).

The requirement (S2.R3) demands integrity in terms of data, which means that if two or more users access some data from different places simultaneously, they have to be presented with the same data. For instance, if users can access asset storage in different display areas or own mobile devices, then the assets showed in the storage must the same for all users. A manager can be implemented to manage the data in some central place to satisfy this requirement.

6.2.2 Mobile Client

The mobile client (Figure 6.5) represents an interaction interface between the user and the system. Using a device with the mobile client application running, the user can log in on the server, move her pointer on display, create map tiles, and put or delete tiles on the map. Additionally, the mobile client application performs data transformation of the user input. The data transformation is necessary since the application can run on different devices, e.g., tablet-PC or laptop.

The mobile client application consists of three panels. The user can switch between *Controller*, *Craft*, and *Settings*. The Settings panel allows the user to adjust her pointer's color and speed on the LHRD. The *Craft* panel allows the user to create new tiles. The panel contains the palette with different colors, a slider for brush size adjustment, canvas to draw, a text field to name the tile, and two buttons save and reset. The *Controller* panel contains the menu bar, tiles bar, interaction field, recycle bin, and drop area. The menu bar allows the user to hide and show the *Settings* and *Craft* panels, quit the application, or delete a tile on a map. The tiles bar contains all the tiles created by the user or her co-workers. The user can drag a tile from the tiles bar into the recycling bin to delete it or into the drop area to put it onto the map.

The system implements the discrete coarse-and-precise pointer interaction technique similar to [82]. The precise pointer has the form and the size of a single tile, so it marks the area on the map a tile will occupy. On the other hand, the coarse pointer has the size of a display unit, thus providing a possibility for fast navigation between remote areas on display. The precise pointer always remains within the coarse pointer, thus moving the coarse pointer will also move the precise pointer.

The interaction field in the mobile client application allows the controlling of both pointers. The user can move the precise pointer by making the swipe gesture with one finger, while with two fingers, the user can move the coarse pointer.

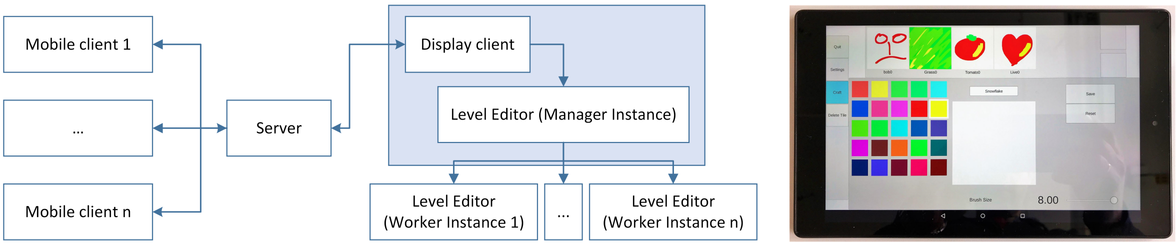

Figure 6.5: (left) System overview; (right) the mobile client application running on the tablet-PC

6.2.3 Server

The server application is responsible for multiple tasks. It creates logs in a database for every piece of information received or sent by it, allowing for an in-depth analysis of client interactions. It also backups the current state of the system and distributes it to the newly connected clients, thus ensuring the system's integrity and reliability.

Additionally, the server manages the tiles created by the users. Every time the user creates a tile, the client conveys the tile to the server first. The server saves the tile and resolves name conflicts if any (same name for multiple tiles). Next, the server distributes the tile among all clients.

The server also manages communication between clients. Every time the server receives a data package, it decides first what clients are affected by this new information. For instance, if the server receives a tile, all clients in the environment must be updated. However, if a mobile client reports on movement in the interaction area, only the display clients receive the notification. It can also perform data transformation, transforming data from a client into an appropriate form for other clients. For instance, the mobile client application can report on a one-finger swipe gesture passing a relative delta since the last frame. In that case, the server must accumulate the values and command the display client to move the precise pointer of the user one tile left if the accumulated value exceeded a given threshold. Thus, the mobile client's continuous values become a discrete value that can be understood by the display client.

6.2.4 Level Editor and Display Client

The level editor application was implemented using the Unity extension for LHRDs described in section 6.1. The level editor contains a simple 2D tilemap shown on display and can be edited by users using mobile clients. To configure the editor, the developer must provide the following values: the size of the tiles (which is also the size of the precise pointer); the size of the display units (which is also the size of the coarse pointer); width and height of the map.

Using the Unity extension for LHRDs, a set of virtual cameras that mimic the display's physical configuration is defined. Each virtual camera becomes assigned to an individual display unit. The level editor application consists therefore of n instances with n equals the number of display units. All instances are synchronized using mechanisms provided by the extension.

One instance of the level editor application (called manager) encapsulates the display client. The display client is responsible for receiving commands from the server and triggering the appropriate command in the level editor (e.g., show/hide coarse/fine pointer, place/delete tile). The commands are triggered only on the manager. In turn, it performs the desired action, subsequently changing the internal state of the virtual world, and finally distributes the new internal state, among other instances.

6.2.5 System evaluation

The groupware was evaluated within the study's scope described in Chapter 4. In total, 24 participants provided their feedback regarding the system in general and the groupware. Since the study had the between-subjects design, gathered feedback is subdivided into two groups based on the study's conditions. Therefore, the results are split into two portions and tagged with *ER* (Equal Roles) and *DR* Different Roles subscripts.

The results presented in this section are based on the evaluation of questionnaires used for feedback on the developed groupware (see Appendix A.5). Most questions provided a 7-point Likert scale for the answer (from 1 = bad / strongly disagree to 7 = good / strongly agree). There were also three questions with free text answers. Participants could explain what groupware functionality they missed, what interaction device they would prefer to use instead of the provided one, and leave some free comments. The questionnaire consisted of six sections: *Overall Assessment of the System*, *Assessment of the Large, High-Resolution Display as Output Device*, *Assessment of the Mobile Device as Interaction Device*, *Assessment of the Collaboration Aspects of the Level Prototyping Task*, *Assessment of the Groupware*, and *Open Questions*.

The *Overall Assessment of the System* section of the questionnaire contained questions from USE [70], Nielsen's Attributes of Usability [85], and UTAUT [144] questionnaires. Therefore, some questions were redundant. Table 6.1 eliminates the redundancy for the sake of space. Additionally, it merges the sections *Overall Assessment of the System* and *Assessment of the Groupware*. Appendix A.5 contains the entire questionnaire.

Overall system and groupware. The participants found the system rather ***easy to use*** ($Mean_{ER}$ = 5.33, SD_{ER} = 1.30; $Mean_{DR}$ = 5.66, SD_{DR} = 1.37). They acknowledged that the system is ***easy to learn*** ($Mean_{ER}$ = 6.41, SD_{ER} = 0.67; $Mean_{DR}$ = 6.67, SD_{DR} = 0.65) and that ***one can quickly become skillful with it*** ($Mean_{ER}$ = 5.58, SD_{ER} = 1.31; $Mean_{DR}$ = 5.83, SD_{DR} = 1.19).

Most participants stated that ***it was fun to use the system*** ($Mean_{ER}$ = 5.58, SD_{ER} = 0.99; $Mean_{DR}$ = 5.58, SD_{DR} = 1.73); that the ***system makes the work more interesting*** ($Mean_{ER}$ = 5.58, SD_{ER} = 1.24; $Mean_{DR}$ = 6.08, SD_{DR} = 1.24); and that they found that the ***system is suitable for the provided task*** ($Mean_{ER}$ = 5.25, SD_{ER} = 1.13; $Mean_{DR}$ = 6.08, SD_{DR} = 1.08).

The participants, however, stated that they were only ***partially satisfied with the system*** ($Mean_{ER}$ = 4.08, SD_{ER} = 0.99; $Mean_{DR}$ = 4.83, SD_{DR} = 1.33) and that it only ***partially worked the way they wanted*** ($Mean_{ER}$ = 4.92, SD_{ER} = 1.37; $Mean_{DR}$ = 4.83, SD_{DR} = 1.85). The oral interviews revealed that it was due to some missing functionality the participants would prefer to have in the system. The results also revealed that the participants of the *Different Roles* condition felt ***more comfortable working with the system*** ($Mean_{ER}$ = 5.41, SD_{ER} = 1.08; $Mean_{DR}$ = 6.00, SD_{DR} = 0.60), and that the participants of the *Equal Roles* condition would rather ***prefer to have a sitting accommodation*** ($Mean_{ER}$ = 5.25, SD_{ER} = 1.65) while the participants of the *Different Roles* condition could rather spare it ($Mean_{DR}$ = 3.16, SD_{DR} = 1.75).

The results suggest the provided groupware as a solid basis for future development. It can be extended to provide more sophisticated tools for users in terms of drawing and asset placement. So, for instance, the participants wished to replace the field with the predefined colors with the RGB-wheel, to allow cloning and editing of created tiles, the possibility to set multiple at once, and a *eye-free technique* for setting tiles. Additionally, the groupware can be modified to support other creative tasks, like interior design. It is also a good idea to provide sitting accommodation for longer sessions. Overall, the participants expressed a positive attitude towards the system, and the system suitability for the design task.

Large, high-resolution display. The participants stated that the ***display is suitable for the provided task*** ($Mean_{ER}$ = 5.83, SD_{ER} = 0.83; $Mean_{DR}$ = 5.75, SD_{DR} = 1.14) and for the ***co-located collaboration*** ($Mean_{ER}$ = 6.08, SD_{ER} = 0.51; $Mean_{DR}$ = 6.25, SD_{DR} = 0.62). Yet, the participants of the *Equal Roles* condition ***were not sure if a standard desktop display would be more suitable for the task*** ($Mean_{ER}$ = 3.75, SD_{ER} = 1.28). However, the participants of *Different Roles* condition somewhat disagreed that a standard display would be a better choice ($Mean_{DR}$ = 2.75, SD_{DR} = 1.42).

The participants felt in general ***comfortable working with the display*** ($Mean_{ER}$ = 5.41, SD_{ER} = 1.08; $Mean_{DR}$ = 6.00, SD_{DR} = 0.60). Yet, some participants ***felt physical discomfort*** during the task ($Mean_{ER}$ = 3.25, SD_{ER} = 2.05; $Mean_{DR}$ = 2.42, SD_{DR} = 1.16). Additionally, 11 out of total 24 participants found the ***display rather too large for the task*** ($Mean_{ER}$ = 3.83, SD_{ER} = 1.94; $Mean_{DR}$ = 3.08, SD_{DR} = 2.02).

Overall, the results showed that users consider LHRDs as an acceptable visual interface for co-located collaborative work and could imagine working with such devices in the future. The participants were satisfied with the display, its size, and its curvature. Although some participants felt physical discomfort while working with the display, we could detect during the oral interviews that it was due to frequent switches from the tablet display to the large display and vice versa. This problem is solvable through an eye-free technique for asset placement. Generally, we can conclude that if a system provides a secondary display in addition to an LHRD, designers must ensure an interaction process that keeps the number of switches between two displays as low as possible.

During the oral interviews, the participants also explained that in the given 30 minutes, it was practically impossible to utilize the entire display real estate. Thus the display could be smaller, in their opinion. However, if they would have enough time, then the size would be acceptable. Additionally, the participants stated that it would be worse to have a flat display instead of a curved one.

Interaction device. Most participants agreed that the provided ***mobile device is suitable for the task*** ($Mean_{ER}$ = 5.40, SD_{ER} = 1.07; $Mean_{DR}$ = 5.08, SD_{DR} = 1.38) and that it is ***easy to master***. ($Mean_{ER}$ = 6.25, SD_{ER} = 0.75; $Mean_{DR}$ = 5.50, SD_{DR} = 1.17) Most participants ***felt rather comfortable working with the mobile device*** ($Mean_{ER}$ = 4.83, SD_{ER} = 1.19; $Mean_{DR}$ = 5.33, SD_{DR} = 1.56). Yet, ***some participants felt physical discomfort*** ($Mean_{ER}$ = 3.66, SD_{ER} = 1.72; $Mean_{DR}$ = 3.58, SD_{DR} = 1.83). Fifteen out of total 24 participants ***were satisfied with the provided mobile device*** and would stick to it; 5 out 24 participants would prefer to work with a ***more lightweight tablet device or have a stylus*** for better drawing; 4 out 24 participants would prefer to have ***another interaction device/interface***, e.g., laser pointer, game controller, or touch-capable LHRDs.

The results showed that most users were satisfied with the tablet PC as an interaction device. Better acceptance could be achieved using more lightweight and more qualitative devices with support for pen input. In contrast to large displays with direct touch input, mobile devices provide better support for LHRDs in terms of reachability of remote display areas and objects. Moreover, they allow for interaction from a distance and mitigate occlusion situations. Since user acceptance is high, we would recommend designing interaction around that kind of devices and, as mentioned above, set focus on eye-free interaction techniques.

	Equal Roles		Different Roles	
	Mean	SD	Mean	SD
Overall system and groupware				
easy to use	5.33	1.30	5.66	1.37
easy to learn	6.41	0.67	6.67	0.65
I quickly become skillful with the system	5.58	1.31	5.83	1.19
The system is fun to use	5.58	0.99	5.58	1.73
The system makes the work more interesting	5.58	1.24	6.08	1.24
The system is suitable for the provided task	5.25	1.13	6.08	1.08
I am satisfied with the system	4.08	0.99	4.83	1.33
I felt comfortable working with the system	5.41	1.08	6.00	0.60
I would prefer to have a sitting accommodation	5.25	1.65	3.16	1.75
Large, high-resolution display				
The display is suitable for the provided task	5.83	0.83	5.75	1.14
The display is suitable for co-located collaboration	6.08	0.51	6.25	0.62
A common desktop display would be more suitable	3.75	1.28	2.75	1.42
I felt comfortable working with the display	5.41	1.08	6.00	0.60
I felt physical discomfort while working with the display	3.25	2.05	2.42	1.16
I think the display is too large for the task	3.83	1.94	3.08	2.02
Interaction device				
The interaction device is suitable for the task	5.4	1.07	5.08	1.38
It was easy to master the interaction device	6.25	0.75	5.50	1.17
I felt comfortable working with the interaction device	4.83	1.19	5.33	1.56
I felt physical discomfort while working with the interaction device	3.66	1.72	3.58	1.83
Perception of collaboration				
I and my partner worked entirely cooperative	4.33	1.23	5.67	1.07
It was fun to work collaboratively	6.00	1.13	6.58	0.67
My partner distracted me during the work	1.75	0.62	1.33	0.65

Table 6.1: Questionnaire results: the participants assessed the system using a 7-point Likert scale with 1 = bad / strongly disagree to 7 = good / strongly agree

Chapter 7

Conclusion and Outlook

This thesis has thoroughly investigated territorial behavior, the process of collaborative coupling, and the effects of workspace awareness during co-located collaborative work with fixed-positioned data on LHRDs. While many technical issues related to the domain of LHRDs were successfully solved, there is still a lack of understanding of groups' and intra-groups' behavioral patterns. However, this knowledge is a critical piece of information needed to produce practical groupware that will foster and not impede the process of co-located collaboration. This thesis aimed to address these issues. Narrowing the research focus applications with fixed-poison data was considered a constraint since such applications are most suitable for co-located collaboration on a shared display and are typical for domains.

This chapter recaps the research contributions made by this thesis and outlines possible future directions. The chapter is organized into three parts. First, the research goals presented in Chapter 1 are revisited and discussed in the light of investigation results. Finally, possible future research is discussed.

7.1 Research Goals and Summary

As stated in Chapter 1, the main research objective was *to provide a more profound understanding of co-located collaboration processes on vertical LHRDs during work with fixed-position data through investigation of socio-physiological phenomena reflecting in behavioral patterns of users/groups.* The research focus encompassed three social phenomena and one physiological phenomenon: collaborative coupling, territoriality, and workspace awareness, as well as physical navigation. A set of hypotheses was defined around these phenomena. The confirmations or refutations of the hypotheses must yield guidelines that allow more effective groupware to be designed.

Collaborative coupling. For collaborative coupling was expected that (H1) behavior during focus phases and overview phases would differ; (H2) creative tasks will result in tighter collaboration compared to analytical tasks; and (H3) transitions between loosely-coupled and tightly-coupled work could be detected employing cues like body movements, proximity, or auditory signals.

The research confirmed the hypothesis H1. The participants indeed spent more time working loosely-coupled during the overview phase, while during the focus phases, they spent the time equally between the loosely-coupled and tightly-coupled work. The research also partly confirmed the hypothesis H3. The transitions between the two types of work could be detected. However, the detection during the overview phases is much more difficult since users mainly provide auditory cues, while the emergence of all other cues decreases significantly. Finally, the expectations regarding the hypothesis H2 were not confirmed. The participants behave similarly in both analytical and creative tasks. However, the adoption of the user roles concept has shown that user behavior can be vectored towards more tightly-coupled work.

The findings regarding all three hypotheses suggest that co-located collaborative work exposes multiple workflows and interaction patterns. Thus, groupware designers must consider them all and design groupware interfaces that can evenly support all of them and allow smooth and probably automatical transactions between different work types. Designers must also bear in mind that they can effectively impact users' behavior by adjusting interfaces.

Territoriality. Previous research on territoriality showed that territoriality could play an important role during co-located collaborative work and must be considered during the design of groupware interfaces. Therefore it was also assumed that (H3) territoriality would play a significant role during work with fixed-position data in analytical and creative tasks. Additionally, since users are supposed to work with the entire display during the overview phases, it was also assumed that (H4) territoriality would not occur during the overview phases of work.

The investigation has partly disproved both hypotheses. Although territorial behavior could be clearly observed, it was not a source of interferences and, therefore, did not play any significant role (H3). The participants could successfully manage it, employing social protocols. As a result, a conclusion can be made that there is no need for any unique mechanisms and rules to handle territoriality. However, as mentioned in Chapter 3, territoriality can become critical if the number of users increases.

Similarly, (H4) could not be entirely validated since the territorial behavior could also be observed during the overview phases.

Both findings suggest that although territorial behavior takes place, the provided context – which includes fixed-position data, LHRD, and mobile devices with a secondary display for interaction – mitigates the effect of that behavior. Therefore, the efforts to exploit this behavior should also be minimized.

Workspace Awareness. The workspace awareness concept was developed to enhance collaborative work. While its advantages for tightly-coupled is barely impeachable, it seems that workspace awareness might also harm users' performance during loosely-coupled work, however. Indices in the literature let to conclude that, however, no investigations have been made in the context of LHRDs. Therefore, within the scope of this research, two hypotheses related to workspace awareness were examined, namely that (H5) visual events and clutter in peripheral vision might affect the performance of individual users; and (H6) that visual events and clutter in peripheral vision will not affect low mental load tasks.

The research has positively validated hypothesis H5 showing that task-irrelevant stimuli in peripheral vision can decrease users' efficiency during high mental load tasks if placed timely. Following the lead, similar stimuli were investigated in the context of a low mental load task. Interestingly, the hypothesis H6 was not confirmed. The effect of the stimuli in the low mental load task was even worse.

Considering that complex co-located collaboration processes frequently represent a mixed-focus collaboration (meaning users switch between loosely-coupled and tightly-coupled work), workspace awareness might have a positive and negative effect. Therefore, different workspace awareness handling approaches should be implemented and integrated into user interfaces. An approach for automatic detection of the current users' work state (loosely or tightly) discussed above can be a useful addition, in that case.

Physical Navigation. Physical navigation was already observed multiple times in various LHRD settings. The existence of this phenomenon and its potential to facilitate search processes are undeniable. Thus, this research aimed to investigate if (H7) physical navigation during focus phases of work will differ from physical navigation during overview phases. This question's answer could provide a cue if these different work types might eventually require different interaction modalities or even devices. Indeed the experiment described in Chapter 3 revealed a difference. During the focus task, participants navigated much alongside the display, while during the overview task, they remained in place, primarily reorienting their bodies. On the other hand, the experiment described in Chapter 4 showed that if there is no clear separation between the focus and overview conditions. Therefore it is somewhat unpredictable which mode participants will choose for physical navigation, although it seems that they prefer the overview mode.

All in all, these observations allow concluding that for the overview mode, a different interaction device can be utilized, even a stationary one that will allow taking a comfortable sitting pose. For long work sessions with the predominant overview condition, such an approach would be even recommended. However, if both conditions are expected or users are given the possibility freely to choose and switch between physical navigation modes, then a mid-air mobile device is preferable.

All hypotheses were successfully examined during the research, and multiple significant findings were gathered. In-depth insights into users' workflow while working co-located with fixed-position data on LHRDs were provided. As a result, a set of useful guidelines could be generated. These guidelines provide cues and suggestions on improving groupware interfaces and fostering a co-located collaboration process on vertical LHRDs.

7.2 Contributions

The research presented in this thesis leans onto previous research from the domains of large, high-resolution displays, CSCW, and HCI. It contributes new insights to these domains and extends the knowledge about humans' socio-physiological behavior. The research yielded the following main contributions: an in-depth analysis of territorial behavior, collaborative coupling, and workspace awareness effects during co-located work with fixed-position data on LHRDs. Based on the gained insights, the research proposes guidelines that should enhance co-located collaboration in LHRD environments. Moreover, the research has yielded two software artifacts that can help father investigations of co-located collaboration on LHRDs.

7.2.1 Providing in-depth analysis of territorial behavior and collaborative coupling during co-located work with fixed-position data on LHRDs

In this thesis, extensive studies took place. They targeted different task conditions of co-located collaboration on a large, tiled-display using smartphones for interaction. The studies revealed new user roles and a new coupling style that lies on edge between loosely-coupled and tightly-coupled styles. Both findings are data-independent and might be generalizable to applications with no fixed-position data. The findings are essential for the design of groupware systems and user interfaces. Ideally, the system should be intelligent enough to recognize users' work style and appropriately adjust the interface.

Based on in-situ observations and gathered qualitative and quantitative data, the thesis has yielded profound knowledge regarding transitions from loosely to tightly coupled work and vice versa. For the focus condition task, the results have revealed the most frequent action and reaction types and have shown that some user activities are more critical for actions while others were somewhat relevant for reactions. Hence, the importance of weights for individual activities could be derived.

For the overview condition task, the results were sobering. The transitions were barely detectable since participants predominantly used verbal communication only. Comparing the conditions allows concluding that user interfaces' visual design can be of great importance for successful classification of intra-group behavior. For instance, small workspaces – utilized in the focus condition task – frequently served as anchors for participants' visual attention. That, in turn, amplified the proximity and visual attention based activities making them more detectable.

Furthermore, one study compared users' behavior while working with and without specific roles distribution. The results revealed that whether users have to work with identical interfaces or with different interfaces that force them to undertake a specific role significantly affects the collaboration process. Providing interfaces that enforce the distribution of roles can help shape a more tightly-coupled and coordinated workflow and achieve more consistent results. Moreover, the majority did not perceive such limitations as awkward and welcomed the configuration.

The studies also revealed that putting users into a collaborative environment does not automatically cause close collaboration. More likely, users will search for task subdivision possibilities (e.g., spatial or logical) and process the sub-tasks in parallel. However, the tightness of collaboration depends on other factors. For instance, most groups with previous mutual collaborative experience worked more tightly than other groups, while lack of knowledge and uncertainty amplified the effect.

Regarding territoriality, the studies also revealed some mitigation of territorial sensitivity, probably caused by the employed indirect interaction technique. However, participants remained very sensitive to three territory types: *personal territory*, *personal-reserved*, and *in-between territory*.

The physical territory between the participant and the working area on display increased coordination workload. Since the tracking area limited the participants, and most of them stayed at the posterior border, there was no way to circuit the partner from the back. Thus, the participants had to coordinate their work by employing expressions of intentions and short agreements. Therefore, we suggest designing workspaces that do not inhibit participants from changing their locations, especially if using handheld interaction devices.

Additionally, a new territory type – never mentioned in the literature before – was detected, namely *temporarily abandoned territory*. Although the participants had never noticed this territory type during the studies since the territory only emerged if one participant left the personal territory for tightly-coupled work within another territory, this kind of territory might have an adverse effect if the number of co-located participants increases.

7.2.2 Identifying effects of workspace awareness during co-located work with fixed-position data on LHRDs

The thesis investigated the effects of extended workspace awareness. It showed that extended workspace awareness could positively impact users during creative tasks, providing users with new ideas and inspiring them. However, it also revealed that extended workspace awareness could negatively impact tasks with a high mental load.

The thesis reported two interrelated experiments that improve the understanding of the effects of dynamic visual task-irrelevant stimuli in far, central, and near peripheral vision areas on users' efficiency at very high-load memorization tasks. The experiments have shown that in some conditions, such stimuli might impair users' performance and, as such, can place requirements on the design of the graphical user interface. For example, the partitioning of private and public spaces on large wall displays could be affected, as in particular attention effects could be shown for the near peripheral visual field. The careful analysis also revealed that visual stimuli' insertion time might significantly impact users' performance. Since there is no way to control visual feedback emergence, designers can try to mitigate interference through visual attributes' manipulation of stimuli.

7.2.3 Providing Design Recommendations

Based on the gained results regarding territorial behavior, collaborative coupling, impacts of workspace awareness, and other observed behavioral patterns, the thesis provides a set of design recommendations. These recommendations are apt to improve future groupware for co-located collaboration on vertical LHRDs since they consider ergonomics and social aspects.

7.2.4 Implementing Development Tools for LHRDs and Groupware for Collaborative Creative Tasks

Finally, the thesis describes two software artifacts. The first one allows for the rapid implementation of experiments and studies. That is a significant contribution since the development of LHRD systems' applications is still an issue that significantly curbs the research. The developed tool is an extension for the Unity game engine, which is widespread in the research domain, provides good support, a large community, and many off-the-shelf solutions. Utilizing these tools for LHRDs will allow for better outcomes, resulting in a better experience and increased motivation. The extension allows for developing and adapting existing applications for LHRDs. The extension was used to develop the second software artifact, namely groupware for co-located collaborative 2D level design on LHRDs using tablet PCs for interaction. Level designers might benefit from using large, high-resolution displays for level prototyping, thanks to their features like large display real estate and a vast number of pixels. Within the scope of the thesis, an analysis of basic requirements for a level prototyping application on LHRDs was executed, and the implementation of the system was provided. The system is flexible regarding the utilized interaction device (e.g., the mobile client can run on smartphones, tablet-PCs, convertible laptops, or even stationary PCs). The system is also flexible regarding output devices. Developers can use any visual displays, such as CAVE, tiled displays, tabletops, and standard desktop displays).

Moreover, the system is scalable, which means that any reasonable number of clients is possible. The evaluation results also revealed a positive users' attitude and a high acceptance of the system. However, the system's main advantage is that it can be used not only for the investigation of the level prototyping task but also for the investigation of different creative and planning tasks on large displays.

7.3 Future Work

This thesis's findings suggest various research directions that require onward investigation or development. The most important directions are (a) father examination of socio-physiological phenomena in more complex settings and (b) investigation of possible ways to support both loosely-coupled and tightly-coupled work phases within a single collaboration process.

Increase the number of participants. The findings suggest that changing the number of participants will likely impact social phenomena differently. For instance, territoriality might become more critical than observed in the presented experiments.

Detection of abandoned territories indicates that territoriality can be a source of interference if the number of participants increases and might require mechanisms and rules that will mitigate a negative impact. Similarly, workspace awareness will probably expose more negative influence on individual users' effectiveness during loosely-coupled work phases since the number of task-irrelevant stimuli will grow with the number of users. Finally, collaborative coupling might reveal more behavioral patterns that need to be analyzed.

Analyse the effect of stimulus attributes. In the context of workspace awareness, father investigations must be done to reveal the ways of effective mitigation of distractions. One possibility is to analyze the effects of stimulus attributes, e.g., color, brightness, transparency, speed, or size, on users' perception. Knowing the impact intensity of different attributes, one can experiment with their values to detect if impairment factor can be reduced, e.g., to make a pointer of co-user semi-transparent if it nears the near area of user's peripheral vision.

Create a prediction model for groups' behavior. Previous research and the research presented in this thesis show that although behavioral patterns of collaborative coupling are multifold and complex, they can still be captured, decomposed, and represented as systems of simple attributes and actions. Therefore, using achievements in the domain of artificial intelligence and acquiring enough training data, a prediction model for groups' behavior can be generated. This model will enable groupware applications to understand groups' interaction dynamics and adjust their interface according to the current groups' state.

Vary display size. Having a large display real estate does not mean it should be entirely provided for users or applications. Fixed-position data forces users to navigate to all display regions where they are positioned since it cannot be placed into users' views otherwise. Thus, if the display size is extensive fixed-position data might cause users to drift far away. On the other hand, the observations made during this research suggest that users more likely switch to tightly-coupled work if they stay close to each other. Therefore, adjusting display size groupware designers might influence the collaborative process and enforce, if needed, tightly-coupled work.

Find ways for sensible utilization of critical display regions. As described in Chapter 3, the participants have not perceived all display regions as comfortable for work. The highest row of display units caused physical stress by half of the participants once they had to gaze at it for a while. In contrast, the lowest row did not cause any problems, thus increasing valuable display real estate. To utilize such critical regions to not cause discomfort to users, special interface elements can be placed there.

These interface elements should provide added value and be ergonomic in terms of user interaction. How these interfaces should look like and what functionality should they provide depends heavily on the application and task type. Therefore this question must be investigated separately for each application.

Continue development of software artifacts. The presented in Chapter 6 software artifacts provide a reasonable basis for father development. The extension for rapid prototyping tools can be improved in terms of (a) world state synchronization, extending the support for more components that can be synchronized; and (b) configuration of a virtual LHRD, making it more developer-friendly. Additionally, a similar extension can be developed for the Unreal engine that is also becoming popular in the research labs.

For the level design groupware, the results have also identified the directions of future improvements, like more sophisticated tiles editor, more lightweight and more qualitative tablet-PCs, and eye-free techniques for asset placement.

7.4 Conclusion

This thesis has shown that co-located collaboration on LHRDs exposes many intricate social and physiological behavioral patterns. The research has provided a thorough investigation of these phenomena and revealed that collaborative coupling and workspace awareness phenomena might significantly impact the team's effectiveness and collaboration flow. The gathered and presented data, and the derived design guidelines can be used to create new groupware interfaces that will foster effective collaboration in LHRD environments, allow users to effectively concentrate on the primary task in cognitively demanding applications, and boost creativity in creative tasks.

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Appendix A

Surveys and Questionnaires

A.1 Mixed-focus Conditions: Personal data questionnaire

`Firstname:`

`Lastname:`

`E-Mail:`

`Age (18-99):`

`First language:`

`Gender:     Female [ ]      Male [ ]`

`Eyesight:   Normal [ ]      Corrected [ ]`

`Color blindness:    no [ ]      yes [ ]`

Large, high-resolution display experience:

[ ] I’ve never seen before

[ ] I’ve seen a couple of times

[ ] I’ve worked with them

Computer games experience:

Novice [ ] [ ] [ ] [ ] [ ] [ ] [ ] Professional

Mobile games experience:

Novice [ ] [ ] [ ] [ ] [ ] [ ] [ ] Professional

Privacy Policy

All data gained during this project will be handled confidentially within the limits of statutory regulations. Data will be kept for at least the duration of the project and will be stored securely. In cases of video and/or audio recordings the participants will be notified before hand and asked for permission. Your data will be anonymised and will be used only for calculation of statistics. We will not share your data with a third person.

Do you accept the privacy policy?

yes [ ]   no [ ]

Signature:

A.2 Mixed-focus Conditions: Stage survey

Interface

1. Did you change the size of the pointer?
   (a) Yes
   (b) No
2. If yes, why did you set the pointer to that size?
3. Did you change the color of the pointer?
   (a) Yes
   (b) No
4. If yes, why did you choose that color?
5. Did you make the pointer semi-transparent?
   (a) Yes
   (b) No
6. If yes, why did you?
7. Did you change the speed of the pointer?
   (a) Yes
   (b) No
8. If yes, why did you?
9. How important to you was the possibility to manipulate the parameters of the pointer? (Likert: 1 (totally unimportant) - 7 (very important))
10. Does the possibility to change pointer's parameters seem sensible to you? (Likert: 1 (total nonsense) - 7 (very sensible))
11. How easy was it to understand the interface? (Likert: 1 (very hard) - 7 (very easy))

NASA Task Load Index (General / Questions / Interface / Amount of data / Collaboration)

1. (Mental Demand) How mentally demanding was the stage? (Likert: 1 (very low) - 7 (very high))

2. (Physical Demand) How physically demanding was the stage? (Likert: 1 (very low) - 7 (very high))
3. (Temporal Demand) How hurried or rushed was the pace of the stage? (Likert: 1 (very low) - 7 (very high))
4. (Performance) How successful were you in accomplishing what you were asked to do during the stage? (Likert: 1 (perfect) - 7 (failure))
5. (Effort) How hard did you have to work to accomplish your level of performance during the stage? (Likert: 1 (very low) - 7 (very high))
6. (Frustration) How insecure, discouraged, irritated, stressed, and annoyed were you during the stage? (Likert: 1 (very low) - 7 (very high))

Input

1. How good did you find the interaction device (cell phone) in general? (Likert: 1 (very bad) - 7 (very good))
2. How easy was it to understand how the interaction device functions? (Likert: 1 (very hard) - 7 (very easy))
3. How easy was it to master the interaction device? (Likert: 1 (very hard) - 7 (very easy))
4. Was the interaction technique satisfying for this kind of task?
5. Would you suggest any improvements?
6. In your opinion, would it be better if the display was touch capable?
7. If you could choose another interaction device, would you choose one?
   (a) No, I would stick to this one
   (b) Yes, I would:

Display

1. Was it comfortable to work with this kind of display? What did you find comfortable, what not?
2. Did bezels distract you? If yes, in what way?
3. Was it comfortable to work with the highest row of display units?
4. Was it comfortable to work with the lowest row of display units?

Collaboration

1. How tightly did you collaborate with your partner? (Likert: 1 (I did not collaborate) - 7 (very tightly))
2. How do you think, what would be the result if you had to do the task alone?
   (a) It would take less time to do the task
   (b) It would take more time to do the task
   (c) The result would be the same
3. How do you think, what would be the result if you had to do the task alone?
   (a) It would take less effort to do the task
   (b) It would take more effort to do the task
   (c) The result would be the same
4. Were there periods during this stage where you worked alone?
   (a) No, I worked all the time with my partner
   (b) I worked all the time alone
   (c) I worked periodically alone
5. In case you worked alone, whose decision, was it?
   (a) It was my decision, which I communicated to my partner
   (b) It was my decision and I didn't communicate it to my partner
   (c) It was my partner's decision, which he/she communicated to me
   (d) It was my partner's decision, and he/she didn't communicate it to me
   (e) It was mutual decision (we discussed it and agreed upon)
6. Did the presence of your partner (physical world) distract you at some point during the experiment?
7. Did the visual feedback produced on the display for your partner (virtual world) distract you at some point during the experiment?
8. What was your strategy, if you didn't know the correct answer?
9. Did you agree upon a strategy how to approach the task with your partner?
10. If you had the strategy, please describe it in few words.

11. If you had a strategy, would you go for another strategy in case you should repeat the task?

A.3 Mixed-focus Conditions Study: Questions and answers used during the Focus task

1. If 2468 is subtracted from 8642, what is left?
   (a) 6174
   (b) 6176
   (c) 6214
   (d) 6274
2. What is the next number in the sequence 7, 18, 62, 238?
   (a) 812
   (b) 872
   (c) 942
   (d) 972
3. What results when the cube of 4 is added to half of 8?
   (a) 6
   (b) 20
   (c) 68
   (d) 260
4. If a winning candidate secured 55% of the 12000 votes cast, how many voted for him?
   (a) 6000
   (b) 6400
   (c) 6600
   (d) 7200
5. What is 884 divided by 26?
   (a) 28

(b) 32

(c) 34

(d) 38

6. What is the only prime number between 98 and 102?

(a) 99

(b) 100

(c) 101

(d) 102

7. How long will it take a car travelling at 45mph to cover 150 miles?

(a) 2 hours 50 minutes

(b) 3 hours 10 minutes

(c) 3 hours 20 minutes

(d) 3 hours 30 minutes

8. 220 books were sold at a price of £11 each. How much money was taken?

(a) 2140

(b) 2220

(c) 2222

(d) 2420

9. In a class of 32 children, 12 are boys. What percentage does this represent?

(a) 30

(b) 33

(c) 37.5

(d) 40

10. In a bag of 28 sweets, 7 of them were lemon flavour. What percentage were not lemon?

(a) 60

(b) 66

(c) 70

(d) 75

11. Which is the smallest out of two thirds, 60%, 0.65 or seven elevenths?

    (a) 2/3

    (b) 60%

    (c) 0.65

    (d) 7/11

12. What is the next number in the series 4, 17, 160, 1733 ...?

    (a) 18,760

    (b) 19,036

    (c) 21,364

    (d) 22,030

13. What is 232 multiplied by 11?

    (a) 2,332

    (b) 2,442

    (c) 2,552

    (d) 2,662

14. If 27 items are bought at a price of €2.45 each, what is the total bill?

    (a) 66

    (b) 69

    (c) 70

    (d) 72

15. What is the cube root of 1,331?

    (a) 9

    (b) 11

    (c) 13

    (d) 17

16. What is the area of a triangle whose height is 35cm and whose base is 32cm?

    (a) 280 sq cm

(b) 360 sq cm

(c) 560 sq cm

(d) 1120 sq cm

17. How many seconds are there in 28 minutes?

    (a) 1,680

    (b) 1,684

    (c) 1,690

    (d) 1,696

18. What is 3,844 divided by 16?

    (a) 211

    (b) 240

    (c) 280

    (d) 291

19. If a plane covers 375km in 45 minutes, how far will it travel in 6 hours?

    (a) 2,450km

    (b) 2,750km

    (c) 3,000km

    (d) 3,200km

20. If £350 interest was received at a rate of 2.8%, how much was invested?

    (a) £7,500

    (b) £11,000

    (c) £12,500

    (d) £14,500

21. What is 27,764 subtracted from 73,351?

    (a) 44,587

    (b) 45,587

    (c) 45,877

    (d) 45,887

22. What is the square root of 784?

    (a) 22
    (b) 24
    (c) 26
    (d) 28

23. What results when the cube of 6 is added to the square root of 361?

    (a) 53
    (b) 55
    (c) 233
    (d) 235

24. What is the cost of 18kg of plums at a price of 23.5 pence per kg?

    (a) 4.13
    (b) 4.17
    (c) 4.23
    (d) 4.27

25. What is the next number in the series 2, 3, 8, 63 ...?

    (a) 125
    (b) 248
    (c) 2848
    (d) 3968

26. What is the sum of the numbers between 31 and 36 (inclusive)?

    (a) 201
    (b) 202
    (c) 203
    (d) 204

27. If two sides of a right-angled triangle are 5cm and 12cm long, how long is the third side?

    (a) 6cm

(b) 9cm

(c) 13cm

(d) 17cm

28. What is the quarts in a gallon multiplied by the acres in a square mile?

(a) 256

(b) 384

(c) 2560

(d) 3840

29. What is $5^2 + 13^2 + 15^2$?

(a) 369

(b) 399

(c) 419

(d) 439

30. If a bakers dozen of items costs £3.51, what does each item cost individually?

(a) 19 pence

(b) 27 pence

(c) 29 pence

(d) 31 pence

31. What is the next number in the series 3, 12, 102 ...?

(a) 304

(b) 408

(c) 622

(d) 1002

32. A 3 hour conference uses 6 speakers. How much time will each one get on average?

(a) 15 minutes

(b) 20 minutes

(c) 30 minutes

(d) 45 minutes

33. A car costs a dealer \$6,775 to buy and he sells it for \$10,350. What profit is made?

    (a) \$3,355

    (b) \$3,575

    (c) \$3,735

    (d) \$3,755

34. How much is a 15% service charge on top of a bill of £84.40?

    (a) 12.06

    (b) 12.6

    (c) 12.61

    (d) 12.66

35. When will someone born in 1978 celebrate their 53rd birthday?

    (a) 2011

    (b) 2021

    (c) 2031

    (d) 2041

36. How many 250cc glasses are needed to hold 17.5 litres of water?

    (a) 70

    (b) 72

    (c) 76

    (d) 80

37. How many minutes are there between mid-day on Tuesday and mid-day on Thursday?

    (a) 2008

    (b) 2080

    (c) 2800

    (d) 2880

38. Starting with 48, three sixteenths of items are sold within an hour. How many are left?

  (a) 31

  (b) 33

  (c) 36

  (d) 39

39. Three people bank amounts of £35.75, £42.75 and £63.55 respectively. What is the total?

  (a) 132.05

  (b) 138.35

  (c) 141.55

  (d) 142.05

40. What is the cost of 120 chocolate bars at 31 pence each?

  (a) 31.4

  (b) 37.2

  (c) 39.6

  (d) 42

41. An invoice must be paid exactly 30 days after 25th March - when will that be?

  (a) 20th April

  (b) 24th April

  (c) 28th April

  (d) 1st May

42. A CD holds 78 minutes worth of music. How many 3 minute tracks can be included?

  (a) 19

  (b) 26

  (c) 29

  (d) 31

43. A rugby team won 60% of its 30 games, and drew one. How many did it lose?

(a) 9

(b) 10

(c) 11

(d) 12

44. If steel wool costs £9 per yard, how many feet would £243 buy?

(a) 67

(b) 71

(c) 76

(d) 81

45. How many months of the year have less than 31 days?

(a) 3

(b) 4

(c) 5

(d) 6

46. What is nine squared, added to the square root of nine?

(a) 30

(b) 57

(c) 84

(d) 90

47. How many euros would £15 buy at an exchange rate of £1 = €1.48?

(a) 21.4

(b) 22.2

(c) 23.6

(d) 27.7

48. What percentage is two fifths?

(a) 25

(b) 35

(c) 40

(d) 45

49. What is 24,624 divided by 6?

(a) 404

(b) 4004

(c) 4014

(d) 4104

50. What is 9,342 subtracted from 17831?

(a) 7699

(b) 8039

(c) 8399

(d) 8489

51. What is one third of 102?

(a) 34

(b) 35

(c) 36

(d) 37

52. In Physics what is resistance to change in a state of motion called?

(a) Inertia

(b) Inflexibility

(c) Mass

(d) Solidarity

53. Which body causes incident light to separate by colour upon exiting?

(a) Lens

(b) Mirror

(c) Prism

(d) Water

54. What is created in space upon the collapse of a neutron star?

(a) Asteroids

(b) Black Hole

(c) Galaxy

(d) Solar System

55. What does ”supersonic” speed exceed?

(a) The Speed of a Space Shuttle

(b) The Speed of Concorde

(c) The Speed of Light

(d) The Speed of Sound

56. What name is given to the path taken by a projectile?

(a) Ballistic

(b) Circumference

(c) Parabola

(d) Trajectory

57. What name is given to a device which measures atmospheric pressure?

(a) Ammeter

(b) Barometer

(c) Thermometer

(d) Weather Vane

58. What in Physics is the opposite of condensation?

(a) Compression

(b) Freezing

(c) Meltdown

(d) Vaporisation

59. As a general law of mechanics, what is stress directly proportional to?

(a) Density

(b) Force

(c) Pressure

(d) Strain

60. In Physics, what does STP stand for?

    (a) Standard temperature and pressure

    (b) Standard thermal policy

    (c) Standard time and place

    (d) Standard tonnage and placement

61. At what Fahrenheit temperature does water boil?

    (a) 100 degrees

    (b) 152 degrees

    (c) 212 degrees

    (d) 792 degrees

62. With which branch of Physics does the Kirchhoff Junction Rule apply?

    (a) Electricity

    (b) Light

    (c) Sound

    (d) Wave Motion

63. Which electronic components have impedance?

    (a) Batteries

    (b) Capacitors

    (c) Resisitors

    (d) Switches

64. In Physics, what is the angle called between a ray and the surface normal?

    (a) Angle of Deflection

    (b) Angle of Incidence

    (c) Angle of Reflection

    (d) Angle of Refraction

65. What is electric potential more commonly known as?

    (a) Current

(b) Power

(c) Voltage

(d) Wattage

66. With what is Archimedes' Principle concerned?

(a) Air Pressure

(b) Buoyancy

(c) Heat Transfer

(d) Light Refraction

67. In Physics, what are the two distinctive types of friction?

(a) Inert and Dynamic

(b) Motive and Immotive

(c) Permanent and Temporary

(d) Static and Kinetic

68. What does an anemometer measure?

(a) Relative Density

(b) Relative Humidity

(c) Viscosity

(d) Wind Speed

69. What temperature on the Kelvin Scale is equivalent to minus 273 Celcius?

(a) Minus 173

(b) Minus 273

(c) Plus 100

(d) Zero

70. What frequencies of sound energy exceed the human upper hearing limit?

(a) Extrasonic

(b) Supersonic

(c) Ultrasonic

(d) Uppersonic

A.4 2D Level Design: Personal data questionnaire

```
Level Design Experiment

Date:                         ID:


Age:


Gender:     M[ ]        F[ ]


Eyesight:   Normal[ ]   Corrected[ ]


Large, high-resolution displays experience:

    [ ] Have never seen before
    [ ] Have seen a couple of times
    [ ] Have worked with them


2D Level Design experience:

Novice [ ] [ ] [ ] [ ] [ ] [ ] [ ] Professional
```

A.5 2D Level Design: Survey

For the overall assessment of the system, we utilized the questions from the following surveys: USE, Nielsen's Attributes of Usability, UTAUT (Attitude Toward Using Technology).

```
Overall Assessment of the System

1. It is easy to use

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

2. It is simple to use

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

3. It is user friendly

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

4. It is flexible

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

5.Using it is effortless

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

6. I learned to use it quickly

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

7. I easily remember how to use it

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

8. It is easy to learn to use it
```

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

9. I quickly became skillful with it

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

10. I am satisfied with it

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

11. It is fun to use

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

12. It works the way I want it to work

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

13. Learnability

bad [ ] [ ] [ ] [ ] [ ] [ ] [ ] good

14. Efficiency

bad [ ] [ ] [ ] [ ] [ ] [ ] [ ] good

15. Errors (Accuracy)

bad [ ] [ ] [ ] [ ] [ ] [ ] [ ] good

16. Subjective Satisfaction

bad [ ] [ ] [ ] [ ] [ ] [ ] [ ] good

17. Using the system is a good idea

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

18. The system makes work more interesting

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

19. Working with the system is fun

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

20. I like working with the system

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

21. The provided setup makes sense for the prototyping of 2d game levels

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

22. The collaborative prototyping of game levels makes sense

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

Assessment of the Large, High-Resolution Display as Output device

23. The provided display is suitable for the prototyping of 2d game levels

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

24. A common desktop display will be more suitable for the collaborative prototyping of 2d game levels

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

25. The provided display is suitable for co-located collaboration

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

26. I felt comfortable working with the display

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

27. I felt physical discomfort while working with the display

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

28. I appreciated the possibility to move in front of the display

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

29. I would prefer to sit or have a sitting accommodation while working with the display

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

30. I think the display is too large for the collaborative prototyping of 2d game levels

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

31. I think it would be better if the display will be flat and not curved

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

32. Working with the display was mentally demanding

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

33. Bezels between the display units did not disturb me

    strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

Assessment of the Mobile Device as Interaction Device

34. I felt comfortable working with the mobile device

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

35. I felt physical discomfort while working with the display

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

36. The provided mobile device is suitable for the task

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

37. I would prefer to use another interaction device

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

38. Working with the mobile device was mentally demanding

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

39. It was easy to master the interaction device

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

Assessment of the Collaboration Aspects of the Level Prototyping Task

40. I and my partner worked...

entirely independent [ ] [ ] [ ] [ ] [ ] [ ] [ ] entirely cooperative

41. I would prefer working alone

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

42. I would perform better working alone

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

43. My partner distracted me during the work

did not distract [ ] [ ] [ ] [ ] [ ] [ ] [ ] distracted frequently

44. It was fun to work collaboratively

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

Assessment of the Groupware

45. The software is functionally suitable for the provided task

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

46. I used coarse pointer to navigate between display units

did not use [ ] [ ] [ ] [ ] [ ] [ ] [ ] used very often

47. The size of the tiles was OK

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

48. The size of the tiles must be larger

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

49. The size of the tiles must be smaller

strongly disagree [ ] [ ] [ ] [ ] [ ] [ ] [ ] strongly agree

Free text questions

50. List of missing Groupware Functionality:

51. Would you prefer to use a different interaction device?
    If yes, which one?

52. Free comments:

A.6 Workspace Awareness Experiment: Personal data questionnaire

```
STM Experiment

Date:                           ID:

Sequence-File:                  Stimuli-File:

Case:                  STM[ ]   Attention[ ]

Age:


Gender:                M[ ]     F[ ]


Eyesight:              Normal[ ] Corrected[ ]

Color blindness:       Yes[ ]   No[ ]

Large, high-resolution displays experience:

    [ ] Have never seen before
    [ ] Have seen a couple of times
    [ ] Have worked with them


Computer games experience:

Novice [ ] [ ] [ ] [ ] [ ] [ ] [ ] Professional
```

A.7 Workspace Awareness Experiment: Questions asked between stages

1. How mentally demanding was the last series of the tasks?

   very low [ ] [ ] [ ] [ ] [ ] [ ] [ ] very high

2. How well could you concentrate during the last series of the tasks?

   very bad [ ] [ ] [ ] [ ] [ ] [ ] [ ] very well

A.8 Workspace Awareness Experiment: Final survey

1. What was your level of awareness of the individual stimuli?

   Single window (low) [ ] [ ] [ ] [ ] [ ] [ ] [ ] (high)

   Multiple windows (low) [ ] [ ] [ ] [ ] [ ] [ ] [ ] (high)

   Moving window (low) [ ] [ ] [ ] [ ] [ ] [ ] [ ] (high)

2. Did the background distract you from the task?
   If yes, could you explain in detail how/why it distracted you?

A.9 NASA Task Load Index

Name: Task: Date:

Mental Demand — How mentally demanding was the task?

[ ]
Very Low — Very High

Physical Demand — How physically demanding was the task?

[ ]
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

[ ]
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

[ ]
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

[ ]
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed were you?

[ ]
Very Low — Very High

Theses

Author: M. Sc. Anton Sigitov

Title: Behavioral Patterns of Individuals and Groups during Co-located Collaboration on Large, High-Resolution Displays

Objective: To provide more profound understanding of co-located collaboration processes on vertical LHRDs during work with fixed-position data through investigation of socio-physiological phenomena reflecting in behavioral patterns of users/groups.

The following theses are based on the results of the research conducted in this dissertation:

1. Large display environments such as high-resolution, tiled display walls are highly suitable for co-located analytical and creative collaborative work.
2. Putting multiple users in an LHRD environment results in intricate behavioral patterns and group dynamics expressed through such phenomena as collaborative coupling, territoriality, and workspace awareness.
3. Fixed-position data affect group behavior.
4. Proper display design is essential to support different task conditions such as focus condition and overview condition.
5. Although mobile devices solve the problem of object reaching in distant display regions, they do not solve the problem of critical display regions entirely.
6. Loosely-coupled and tightly-coupled work are of different natures.
7. During tightly-coupled work, users expose different intricate, collaborative coupling patterns.
8. Compared to tightly-coupled work, in loosely-coupled work, the patterns are less intricate.
9. Users' coupling behavior during the focus and the overview conditions in the context of an analytical task are different.
10. Task nature does not affect collaboration tightness.
11. During creative tasks, users do not expose more tightly-coupled work in comparison to analytical tasks.
12. During creative and analytical tasks, phases of loosely-coupled work are as frequent as phases of tightly-coupled work. In some cases, the total duration of loosely-coupled work even prevails compared to the tightly-coupled work.

13. Coupling styles might be ambiguous and do not always provide enough information regarding the current collaboration state.

14. Information about transitions could provide the system with valuable data about user activities. Extending the system with a transitions detection mechanism can help to disambiguate coupling styles.

15. During focus task conditions, transitions between loosely-coupled and tightly-coupled work contain distinct cues that allow their detection.

16. The overview condition lacks the most transition indicators. The indicators are predominantly verbal and required speech analysis.

17. User interfaces should provide enough intelligence to recognize current group behavior or change in it to support multiple coordination strategies and ensure proper switch between them.

18. Groups with previous mutual experience of cooperative work behave differently compared to other groups.

19. User roles are an integral part of the collaboration process.

20. Users tend to subdivide the task to process it more efficiently.

21. Fixed user roles could be a valuable tool for enforcing tightly-coupled collaboration.

22. Users expose a positive attitude towards fixed user roles.

23. With fixed user roles, the results are more consistent, and users are more productive.

24. Territoriality is an essential element of the collaborative process.

25. Territorial behavior is present during the focus condition and overview condition.

26. Fixed-position data promotes the emergence of territories.

27. Fixed-position data can cause the emergence of abandoned territory.

28. Although territories have a significant role during the collaboration process, users do not need any explicit tools for managing territories. They could handle them through social protocols.

29. Workspace awareness might increase the risk of interferences and subsequently negatively affect users' performance.

30. Visual events in peripheral vision affect the performance of individual users.

31. Extended workspace awareness can break an interaction flow.
32. Extended workspace awareness might inspire and help to generate new ideas during creative tasks.
33. The mental load of the task impacts the size of the peripheral vision where users can perceive visual stimuli. Low-mental demand tasks do not affect users' awareness, while mentally demanding tasks shrink the area distinctly.
34. No matter how mentally demanding the task is, the near peripheral area is always affected by visual task-irrelevant stimuli.
35. Physical navigation during focus phases of work differs from physical navigation during overview phases of work.
36. While processing fixed-position data, users navigate more often column-wise compared to row-wise or erratic navigation.
37. During the focus condition, users use predominantly translational movements to reposition themselves in front of the display. During the overview condition, users use more rotational movements remaining in the overview position.