Utilisation collaborative d'un mur d'écran en contexte critique

Arnaud Prouzeau

université PARIS-SACLAY

UNIVERSITÉ PARIS SUD
Comprendre le monde, construire l'avenir

NNT : 2017SACLS544

Collaboration around Wall Displays in Command and Control Contexts

Thèse de doctorat de l'Université Paris-Saclay
préparée à l'Université Paris Sud

École doctorale n°580 Sciences et Technologies de l'Information et de la Communication (STIC)
Spécialité de doctorat: Informatique

soutenue le 15 décembre 2017

Arnaud Prouzeau

Composition du Jury :

Stéphane Conversy Professeur, ENAC	Rapporteur
Raimund Dachselt Professeur, TU Dresden	Rapporteur
Jean-Daniel Fekete Directeur de Recherche, Inria Saclay	Président du jury
Edward Lank Professeur associé, U. of Waterloo	Examinateur
Olivier Chapuis Chargé de Recherche, CNRS	Directeur de thèse
Anastasia Bezerianos Maitre de Conférence, U. Paris-Sud	Encadrante de thèse

Thèse de doctorat

SYNTHÈSE

Les murs d'écrans interactifs à haute résolution (UHRIWD pour "Ultra-High Resolution Interactive Wall Displays") sont considérés comme bénéfique pour la collaboration. Grâce à leur taille, on peut interagir avec simultanément à plusieurs tout en communiquant en face à face. Grâce à leur résolution, cette collaboration est possible proche de l'écran, et en se reculant, un utilisateur peut prendre connaissance de ce que font les autres. L'interaction tactile permet d'amplifier ce phénomène. Cependant, peu d'études vérifie empiriquement ces affirmations. Dans cette thèse, je vais dans ce sens en étudiant les avantages de la collaboration devant un UHRIWD. Je me concentre sur un contexte de collaboration bien précis: la surveillance des systèmes critiques dans les salles de contrôle.

Des visites de salles de contrôle, des interviews avec des opérateurs et une revue de la littérature montrent que les salles de contrôle utilisent des grands écrans non-interactifs avec une faible résolution. Ils sont utilisés pour afficher une overview, alors qu'un affichage détaillé est disponible sur des postes de travail individuels, qui sont aussi utilisés pour manipuler les paramètres du système. Les opérateurs rencontrent deux types de situations: les situations normales, routinières et demandant peu de collaboration, et les situations exceptionnelles qui surviennent à la suite d'évènements inattendues. Dans ce dernier cas, une collaboration étroite est nécessaire impliquant plus de communication et une meilleure coordination des actions. C'est dans ce cas-là que je pense qu'un UHRIWD peut être bénéfique pour la collaboration.

Dans une première étude, je compare l'utilisation d'un UHRIWD avec deux ordinateurs pour une tâche collaborative de recherche de chemin. Sur l'UHRIWD, les participants collaborent étroitement pour résoudre la tâche, ils planifient leurs actions a-priori et communiquent plus. Sur les ordinateurs, les participants collaborent peu, ils sont plus rapides mais aussi plus susceptibles de se tromper. Lors d'une situation exceptionnelle dans une salle de contrôle, un UHRIWD pourrait donc favoriser une collaboration étroite.

J'étudie ensuite l'impact des techniques d'interaction sur la collaboration sur un mur. J'ai adapté deux techniques de sélection dans un graph pour les rendre collaboratives. La première est une technique de sélection basique, alors que la seconde est basée sur l'idée de propagation de la sélection à partir d'un noeud. Je les compare dans une tâche de plus court chemin. Les résultats montrent que les participants divisent le mur bien que la tâche ne soit elle pas divisible. Cette division combinée à l'empreinte visuelle locale de la technique basique conduit à une parallélisation de la tâche, ce qui impact négativement la performance. Au contraire, l'empreinte visuelle globale de la propagation conduit à une collaboration plus étroite bénéfique pour la vitesse et la précision.

Les visites dans les centres de contrôle du trafic routier montrent la difficulté qu'ont les opérateurs à évaluer l'impact de leurs actions sur le trafic. Utilisant les conclusions de l'étude précédente, je conçois deux techniques pour afficher des prévisions de trafic en parallèle du trafic en temps réel sur un mur d'écran. La première a une faible empreinte visuelle et permet la visualisation d'une prévision locale, alors que la deuxième concerne le réseau entier et en a donc une plus grande. Une expérience montre l'intérêt des deux techniques pour la prévision de trafic.

Pour finir, bien que l'UHRIWD soit utile pour la collaboration étroite, les opérateurs ont quand même besoin de travailler sur des tâches indépendantes, il faut donc aussi des écrans personnels. Dans une dernière partie, j'étudie l'intégration du UHRIWD dans un environnement complexe contenant plusieurs postes de travail, de la projection au sol et des appareils mobiles. Pour faciliter la transition entre les différents types de collaboration, j'ai conçu trois techniques d'interaction qui renseignent les utilisateurs sur les activitées de leurs collaborateurs, et une technique pour afficher des données du poste de travail sur le mur.

Pour conclure, je montre dans cette thèse que l'utilisation d'UHRIWD est bénéfique pour la collaboration, particulièrement lorsque celle ci doit être étroite. Cette collaboration peut être amélioré par des techniques d'interaction et de visualization adaptées. Combiné à d'autres dispositifs personnels, comme des ordinateurs, l'UHRIWD permet de gérer de manière complète des situations de collaboration complexe comme celle que l'on trouve dans des salles de contrôles.

ABSTRACT

Ultra-High Resolution Interactive Wall Displays (UHRIWD) are considered as an appropriate surface to support collaboration. Thanks to their size, several people can collaborate in front of them using face-to-face communication and deictic gestures. Thanks to their resolution, this collaboration can take place up-close to the display, while still supporting group awareness of who is working on what part of the display by taking a step back. This group awareness is amplified by the possibility of interacting directly using multitouch. However, while the above statements are assumed to be true, there are few studies that empirically support these assertions. In this thesis, I address the lack of studies by exploring the benefits of collaboration in front

of UHRIWD. This is done for a specific use case in which collaboration is crucial: the monitoring of critical systems in control rooms.

Based on visits to control rooms, interviews with operators and a literature review, I analyzed operators' activities and how operators collaborate. Data show first that control rooms are already equipped with low resolution non interactive large displays. They are used as contextual displays while individual workstations are used for detailed and interactive displays. Teams of operators undergo two types of situations: normal situations, during which the operators perform routine tasks and loosely collaborate, and exceptional situations, when unexpected events happen. During the later, a closer collaboration is needed with more communication and a better coordination of actions. I believe UHRIWD can be beneficial for collaboration in these exceptional situations.

In a first study, I compare the use of a UHRIWD with two desktops on a collaborative path-finding task. The comparison shows that, with the UHRIWD, participants collaborated closely to solve the task, planned the task with their partner, and communicated more. With the desktops, they collaborated loosely, which was generally faster but more error-prone than with the UHRIWD. The use of a UHRIWD could encourage a close collaboration between operators during exceptional situations in control rooms.

I then study the impact of interaction techniques on collaboration in front of a UHRIWD. I design two selection techniques for graphs, based on previous works and adapted for collaboration, and I compare them in a shortest path identification task. The first one is a basic localized selection, while the second uses the idea of propagation of the selection from an origin node. Results shows that participants divided space even if the task is not divisible. This division and the localized visual effect of the basic selection led to parallel work, which negatively impacts accuracy. The large visual footprint of the propagation selection led to close collaboration which improved speed and accuracy, especially for complex graphs.

Visits to road traffic control centres show that operators find it difficult to assess the impact of their actions on traffic. Using the previous study, I design two visualization techniques to visualize a forecast of traffic concurrently with the real time visualization. One technique affects a local area and has a small visual footprint; the other has large visual footprint as it affects the entire road network. The techniques are implemented in a prototype of a road traffic system running on a wall display. A laboratory experiment shows that both techniques are viable design options.

Finally, as there are different degrees of collaboration in a control room, different displays are needed. UHRIWD is beneficial when close collaboration is needed, but to work on more independent tasks, operators need individual displays. I studied the integration of the

UHRIWD in a more complex environment, with several workstations, ground projectors, and mobile devices. To help the transition between the different degrees of collaboration in such environments, I design three interaction techniques that show user's activities and two to transfer data between the workstations and the wall.

To conclude, I show in this thesis that the use of a UHRIWD is beneficial for collaboration, especially for close collaboration. This can be improved with the use of appropriate interaction and visualization techniques. Combined with personal devices, UHRIWD can be used to handle complex, mixed-focus collaboration tasks like those performed in command and control contexts.

PUBLICATIONS

PAPERS IN INTERNATIONAL JOURNAL

1. **Arnaud Prouzeau**, Anastasia Bezerianos, and Olivier Chapuis. Evaluating Multi-User Selection for Exploring Graph Topology on Wall-Displays. In *IEEE Transactions on Visualization and Computer Graphics* (TVCG), 14 pages, IEEE, August 2017.

PAPERS IN INTERNATIONAL CONFERENCE

2. **Arnaud Prouzeau**, Anastasia Bezerianos, and Olivier Chapuis. Towards Road Traffic Management with Forecasting on Wall Displays. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces* (ISS '16), 10 pages, ACM, November 2016.

3. **Arnaud Prouzeau**, Anastasia Bezerianos, Olivier Chapuis. Tradeoffs Between a Vertical Shared Display and Two Desktops in a Collaborative Path-Finding Task. In *Proceedings of Graphics Interface 2017* (GI '17), 6 pages, CHCCS, May 2017.

REFEREED WORKSHOP PAPERS

4. **Arnaud Prouzeau**, Anastasia Bezerianos, and Olivier Chapuis. Surveillance du trafic routier avec un mur d'écrans. In *Proceedings of the 27th Conference on l'Interaction Homme-Machine* (IHM '15), 6 pages, ACM, October 2015.

5. **Arnaud Prouzeau**, Anastasia Bezerianos, and Olivier Chapuis. Visual Immersion in the Context of Wall Displays. In *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces* (ISS Companion '16), 7 pages, ACM, November 2016.

ACKNOWLEDGMENTS

I would like to thank everybody who supported, influenced and accompanied me in the whole journey of my Ph.D.

First I would like to thank my 2 advisors, Anastasia Bezerianos and Olivier Chapuis, for giving me the opportunity to start this Ph.D. about a topic I am passionate about. You showed me how to do research: how to write a paper, to design and conduct an experiment, to analyze results. You were always optimistic and you taught me to deal with researcher's life issues (like paper rejection). You always took my ideas into consideration and showed me how to build on them. Thanks to you, I feel prepared to continue a career in research.

I also would like the members of the jury, Stéphane Conversy, Raimund Dachselt, Edward Lank and Jean-Daniel Fekete, for reviewing my thesis, giving me insightful comments and coming to my defense.

Then, I would like to thanks all the members of the ILDA team. Thanks to Emmanuel Pietriga and Caroline Appert for advice and help you gave me when I needed them. Thanks to Maria Lobo, who started her Ph.D. at the same time as me, for all the tea breaks and discussions (insightful about research or recreation ones). Thanks to Hugo Romat to always be motivated to have a few drinks on Thursday night. And thanks to the others for all the exchanges we had, for participating in my experiments and for all the other activities.

I also thanks the members of the other HCI team in Paris: AVIZ, Ex-Situ, and VIA. More specifically to all the Ph.D. students with whom I had great conversations (most of the time around a few beers): Marc Teyssier, Bruno Fruchard, Emmanouil Giannisakis, Thibaut Jacob, Marc-Emmanuel Perrin, Lonni Besançon, Abby Liu, Michael Wessely, German Leiva, Carla Griggio, Jessalyn Alvina and all the others (I am sorry for the ones I forgot to cite).

Thanks to all the researchers I met in conferences or summer schools who helped me shape my research project, who showed me different perspectives and who increased my motivation to continue a career in research. This includes (but is not limited to): Antoine Lhuillier, Emilien Dubois, Julie Ducasse, Racim Fahssi, Maxime Cordeil, Christophe Hurter, Alix Goguey. I would like also to specifically thanks Tim Dwyer who actually gave me the opportunity to continue my career in research in his team at Monash University.

I would not have started a Ph.D. without the inspiration and the help of several researchers from the ENAC: Stéphane Conversy, Yannick Jestin, Hélène Gaspard-Boulinc, Jean-Luc Vinot. You introduced me to the domain of HCI, but also to the field of aviation which became a passion.

Outside of research, I would like to thanks my parents, my brother, and sister, and also the rest of my family who supported me during this entire Ph.D. and before. All you did meant a lot to me.

Thanks also to all my friends. PM, who even from Singapore supported me and shared great and interesting discussions about almost everything. Romain, Pascal, Coline, Benoit, Caroline, Mika, Thomas (Carlier and Chartier), Jerome, Maryne, Eve, Nadia, Thierry, Elo, Yvanne, Tanguy and the others from the ENAC group, for all the nights at the James (and at other places), for all the others activities we did. You even sometimes listened to me talk about my research. Alban, my oldest friend with whom I always enjoy a great meal and a good drink. David, Can, Monireh, Mathieu and all the others great people I met in Paris during there years, and with whom I shared great moments.

Last, but not least, I would like to thanks Pauline, who supported me (in the English and French sense of the term) for the three years of this Ph.D. in good and bad times. You helped me stay optimistic, and, in general, helped me become a less stressed person. You make me a better person and I can't wait to start our new adventure in Australia.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AID Automatic Incident Detection

ALMA Atacama Large Millimeter Array

APA American Psychological Association

ATC Air Traffic Control

CCTV Closed-Circuit Television

CI Confidence Interval

CROGend Centre de Renseignement Operationel de la Gendarmerie Nationale – Police Operational Centre

CSV Comma-Separated Value

EOC Emergency Operation Centre

HCI Human-Computer Interaction

HML Hybrid Magic Lens

HSE Health and Safety Executive

IRD Information-Rich Design

ISOM Inverted Self-Organizing Map

JUNG Java Universal Network/Graph Framework

LCD Liquid-Crystal Display

LOCA Loss Of Coolant Accident

LWR Lighthill-Whitman-Richards

MAMMI Multi Actors Man Machine Interfaces

MDE Multi-Display Environment

MDG Multi-Display Groupware

NASA TLX NASA Task Load Index

PC Poste de Controle – Control Centre

RER Réseau Express Régional – Regional Express Train

SAGAT Situation Awareness Global Assessment Technique

SCOOT Split Cycle Offset Optimization Technique

SDG Single-Display Groupware

SESAR Single European Sky ATM Research

SURF Système Urbain de Régulation des Feu – Urban Traffic Light Regulation System

TV Television

UCD User-Centered Design

UHRIWD Ultra-High Resolution Interactive Wall Display

UK United-Kingdom

USA United-States of America

VIP Very Important People

VMS Variable Message Sign

ZUIST Multi-Scale Scene Manager for ZVTM

ZVTM Zoomable Visual Transformation Machine

1 INTRODUCTION

The last decade has witnessed the democratization of many new types of displays: touch enabled smartphones, interactive tabletops, wall displays, etc. This has led to research in Human Computer Interaction regarding their characteristics, interface design, and benefits compared to traditional desktops. One group of such promising new displays are Ultra-High Resolution Interactive Wall Displays (UHRIWD).

UHRIWD have several benefits. First they provide a large visualization space with a pixel density similar to a desktop display. The navigation in this space is physical rather than virtual and affords a natural pan-and-zoom in the information space to see overview from afar and details up-close. It allows direct (like multi-touch) or indirect (using hand-held devices or a workstation) interaction.

Thanks to their size, UHRIWD allow several people to be simultaneously in front of them [144] (See Figure 1). This large collaborative space enables direct communication: face-to-face communication including speech and the use of deictic gestures [119]. Deictic gestures allow users to add more information during a conversation by, for example, pointing to an object while talking about it. They can use different degrees of collaboration, from loose to close [204], and have an awareness of what their partners are doing [97].

Thanks to their pixel density, users can collaborate up-close and work with a high level of detail. A collaborator who takes a few steps back can have a global view of what is displayed. From a distance, she also has a global view of the others' activities in front of the wall [97].

This awareness of other activities and the support of different collaboration styles is amplified by the possibility to use multitouch interaction on the wall display [97]. Wall displays provide a good awareness of the objects with which a user is interacting and of what kind of actions she is doing [99].

However, while collaboration on regular shared displays like tabletops is well documented, there is less work on collaboration using wall displays, and how they impacts collaboration. In this thesis, I study this collaboration by studying a specific use case: the control of critical systems.

Critical systems are supervised from a control center in which collaboration is crucial [196]. Awareness of others is necessary so that operators can coordinate their action and take critical decision in a short time [78, 122]. I think that an interactive wall display can be

Figure 1: Two users collaborating in front of a UHRIWD. Dimension: $5.9 \times 1.96 meters$, resolution: $14400 \times 4800 pixels$.

profitable for collaboration in this context, and this is why most of the interaction techniques designed in this thesis are motivated by control rooms. However, evaluations, and laboratory experiments in general, were performed in a more abstract context in order to be as generalizable as possible.

1.1 CONTROL OF CRITICAL SYSTEMS

A critical infrastructure is defined as an important system or network (whether physical or virtual) whose failure or malfunction may result in potential fatalities, economical losses or environmental harm. Examples of such system are: the road network of a city, a power plant, a refinery, the air traffic in a country. Year by year, more and more automation is added to increase the system capacity, but also to allow a better allocation of resources. For example, in London, operators use the Split Cycle Offset Optimization Technique (SCOOT) system to manage road traffic. It automatically changes the traffic light timing of the city in function of the traffic. The timings are optimized using real-time traffic and other parameters (weather, public transportation traffic, etc.) to minimize the average journey time. This automation also leads to systems which are defined as ultra-safe (around 5×10^{-7} risks of disastrous accident) [3]. Nevertheless, human operators are still necessary, failures still happen and the consequences can be significant. Operators need to monitor the system and take over if necessary. This was the case in December 2014 in United-Kingdom (UK) [207]: the air traffic control system experienced a computer failure which required the controllers to manually handle air traffic.

Because of the complexity and the size of the system, control is done by multiple operators with different roles. For example, in a power plant, an operator is in charge of the primary circuit, and one is in charge of the secondary. In a control room, both operators monitor

Figure 2: One workstation in the main control room of the Texaco refinery. Image produced from [77]

the system, and act to optimize its functioning or avoid failures (see Chapter 3).

1.1.1 *Situation awareness in control rooms*

In all critical systems, it is important for operators to have a good representation of the state of the system and to assess the possible evolution of this state. For example, an air traffic controller should be able to mentally represent the position of all the aircrafts in her sector and if they are climbing or descending in order to predict potential risk of collision. Endsley defined this as situation awareness [61]. The role of the control room is to provide the necessary information for situation awareness in complex situations that a single operator cannot handle. A lack of information, or on the contrary, an overload of information can be fatal. The explosion of the Texaco refinery in 1994 is an example [77]. The Health and Safety Executive (HSE) in charge of the investigation concluded that the situation was caused by a combination of events, including the design of the control room (See Figure 2). They reported that no overview of the system was provided to the operators, which made it difficult for them to diagnose problems.

Research is done in HCI and in Information Visualization to improve these control rooms. This research helps handle the incoming information, process it to understand correctly the situation and predict the eventual outcomes, and, finally, facilitate the interaction with the different settings of the system. For example, Hurter et al. design a tangible interface for air traffic controllers: StripTIC [88]. The

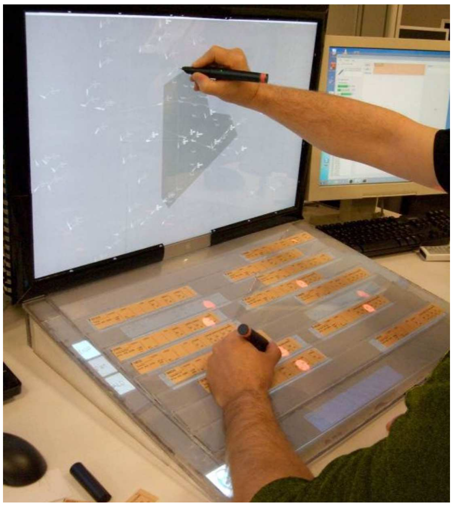


Figure 3: Two controllers using the Strip'TIC prototype. It features digital pens, augmented radar, stripboard, and paper strips. Image produced from [88]

system mixes augmented paper strip (currently used in French Air Traffic Control (ATC) centres) with digital pen, vision-based tracking, and augmented rear and front projection (See Figure 3). The goal is to keep the flexibility of the paper strip, but to provide additional information in real time by augmenting them.

1.1.2 *Group awareness in control rooms*

Not only do operators need to be aware of the situation, but also of what the other operators in the room are doing. Collaboration is then essential to be sure that each operator has all the necessary information to deal with an issue and to allow crosscheck between operators to increase safety. The system should, in that case, help the operator assess what her partners are doing and what information they have. This is called group awareness.

Large shared displays are often considered well suited for collaboration because they allow multiple users to interact at the same time, up-close or far from the display. However, while most control rooms possess a large vertical display, it is mostly used to provide a global, detail-less view of the system. A detailed view is provided to operators through individual workstations which also allow them to act on the system's settings. This layout makes communication difficult [76] and collaboration demanding [206] compared to face-to-face collaboration. This means that the use of face-to-face collaboration in critical situations might save time and cognitive load, two resources that operators lack in control room contexts.

1.2 thesis statement

Most command and control centers already have a large shared display. In general, this display has a low pixel resolution and is non interactive [181]. It displays an overview of the monitored system and so provides operators with a shared understanding of the situation. Operators get a detailed view and interact with it from their workstation. This layout allows operators to work on their own tasks on their workstation and to have a mental model of the state of the system thanks to the large visualization. Nevertheless, it makes the communication difficult [76], but also collaboration demanding [206] compared to collaboration on a shared display with face-to-face communication.

With a UHRIWD, thanks to its high pixel resolution and its interactivity, several operators can collaborate using it. They benefit from the face-to-face communication and group awareness, while, at the same time, they still have a view as detailed as their workstation. Several groups of operators can collaborate and interact close to the wall, and, with a few steps back, one operator can have a global awareness of who is working on what.

Characteristics of an interaction technique can impact the collaboration. Tang et al. showed that the visual footprint can encourage a close or a loose collaboration on tabletops [186]. However, no such study has been done on a wall display. It is important to encourage a close collaboration when users are working on the same task and a loose one otherwise, especially in a command and control context [26].

Finally, interacting standing in front of the wall can cause fatigue, due to the motion necessary to reach different parts of the workspace, and the different arm movements. Additionally, in complex collaborative situations, collaboration with other operators does not occur all the time [188]. For instance, in a crisis management control room, operators have to communicate with units at the location of the crisis and guide them on the site (see Chapter 3). The use of UHRIWD needs to be integrated in a more complex environment which includes individual workstations in front of which operators can sit. The use of such a Multi-Display Environment (MDE) requires the operators go from their workstation, on which they work on their own, to the wall, on which they collaborate closely. The impact of these transitions has to be assessed, and techniques need to be designed to help them.

In this dissertation, I study the benefits of collaboration using a UHRIWD. I show that these benefits come in situations in which close collaboration is needed, as the display encourages planning, coordination and communication. I also show that this effect can be magnified by interaction techniques with a large visualization footprint, which encourage close coordination and cross-checking. Finally, I propose solutions to integrate a wall display in an *actual control room and techniques to help operators in the transition from their workstation to the wall when needed.*

I decided to take as a motivation the command and control context. However, UHRIWD can be used in other contexts like large dataset analysis. It is an additional goal that our work can be applied to other application domains and be as generalizable as possible.

1.3 RESEARCH APPROACH

In this work, I use a User-Centered Design (UCD) approach [89], to iteratively understand the needs of the users, then design a solution and evaluate it.

1.3.1 *Gathering of needs*

To study the use of a wall display in a complex collaborative situation, it was important to first understand what happens in such control rooms.

I, therefore, visited 4 control centers: 3 road traffic control centers and 1 police operation center. Observations were done in all of them. This allowed me to identify the tasks performed by operators, and alongside interviews, the general layout of a control room and its issues.

I also interviewed operators in the visited control centers, a power plant operator and, an air traffic controller. During interviews, we used critical incident techniques to understand how operators handle exceptional situations. I oriented my questions on several issues noted during the visits. The purpose was to pinpoint the common characteristics between different control rooms and to have a more general view of common practices. The questions asked were about the layout of the control room, the different roles of the operators and the tasks they perform and the degree of collaboration needed in each of these tasks.

1.3.2 *Design of the solution*

During this work, 3 prototypes were implemented. The first one was a rapid prototype to visualize and interact with graphs on the wall and on several workstations; it is described in Chapter 4. This prototype was upgraded to a crisis management system which can display a tiled map and several layers of data (road traffic, public transportation, first responders vehicles); it is described in Chapter 7.

A second prototype was implemented to evaluate the impact of interaction techniques on collaboration. It visualizes and allows the use of different interaction techniques to do selection on graphs. It was used in Chapter 5. After the experiment, the prototype was upgraded following the comments of the participants.

Finally, a prototype of a road traffic management system was implemented. It displays a road network with simulated traffic. I implemented two techniques to visualize forecast traffic along with real-time traffic. After receiving feedback from expert users (Road traffic controllers and engineers), we upgraded our prototype.

1.3.3 *Evaluation*

To evaluate the interaction techniques, I performed two controlled experiments with non-expert users. I used abstract tasks that do not require domain knowledge. Additionally, these abstract tasks allow us to isolate only the factors we want to take into account and to reduce noise due to others.

When possible, I also showed the designed techniques to expert users in order to get their feedback.

1.4 CONTRIBUTIONS

The contributions of this dissertation are the following:

1. An analysis of the activities and the needs of operators in control rooms in different domains. It is based on observations, interviews and the current literature. It shows that close collaboration is necessary, more particularly in exceptional situations, situation in which the workload is already high. It also shows that current control rooms are not designed to facilitate close collaboration.

2. A laboratory experiment which quantitatively compares the collaboration in one large shared vertical display with a setup that doesn't possess these characteristics.

3. Adaptation of two graph selection techniques to use in a multi-user context on a wall display.

4. A laboratory experiment which studies how pairs use these techniques on a graph topology task (shortest path identification) on a wall display.

5. A set of design guidelines regarding the use of a wall display by pairs, and the importance of visual footprint for collaboration.

6. A prototype which demonstrates the use of a UHRIWD in a road traffic control room.

7. Visualization techniques to display multiple simulated and real situations in the context of traffic management on this prototype.

8. A laboratory experiment which evaluates the previous techniques in a situation-awareness task.

9. A prototype which demonstrates the use of a UHRIWD with several workstations in a crisis management control room.

10. Visualization techniques to provide operators with different types of group awareness in order to facilitate mixed-focus collaboration.

1.5 THESIS OVERVIEW

Chapter 2 starts with related work on the benefits of wall displays and their use in a control room contexts. Then it focuses more directly on how people collaborate in front of a wall display.

Chapter 3 describes observations in control rooms and interviews of operators. Additionally, I conducted an analysis of related work regarding the tasks performed in different control rooms to confirm the results found during the observations and interviews.

Chapter 4 presents the first laboratory experiment in which I compare quantitatively collaboration on a large vertical shared display and on two desktops. I found that the large vertical shared display encourages close collaboration and planning. The two desktops encourage a loose collaboration which is faster but more error-prone.

Chapter 5 presents the second laboratory experiment in which I study the impact of interaction techniques on the collaboration on a wall display. I took the specific case of graph exploration and adapted two selection techniques for multi-user use on a wall display. The results show that a technique with a large visual footprint encourages users to collaborate closely and to cross-check their partner's works.

Chapter 6 exposes the prototype of a road traffic management system and explains the design of two visualization techniques. These techniques allow operators to display a prediction of traffic concurrently with the real time traffic for a local area or the whole network. I evaluated both of these techniques in laboratory experiments and in a presentation with expert users.

Chapter 7 introduces the prototype of a crisis management system and details a set of techniques to increase group awareness. These techniques facilitate the transition between the different displays in the control rooms: the desktops and the wall display.

Chapter 8 summarizes the contributions of this thesis and discusses possible directions for future work.

2 BACKGROUND AND CONTEXT

Compared to regular desktop displays, recent wall displays, and more particularly UHRIWD, are larger, but their pixel density is about the same (around 100 pixel per inches), which means that they can display simultaneously more information [216]. Moreover, the navigation in this space can be done physically [16, 118], which means that users can move in front of the display to explore the data, instead of virtually using techniques such as pan-and-zoom. Potential benefits of these three characteristics have been studied in previous work.

Additionally, a UHRIWD provides a large collaborative space which allows direct communication [119]. Users can collaborate up-close on detailed data, or at a distance [99]. It provides good group awareness as the position of a user indicates on which part of the data she is working [97]. Thanks to its characteristics, wall displays could be useful in a command and control context, a context in which collaboration and group awareness are essential (See Chapter 3). However, only non interactive large displays are used in current control rooms to allow operators to build a shared understanding of the situation.

I will first focus on the benefits of large and wall displays compared to regular displays in individual work contexts. Then, I will present previous work on the use of wall displays as collaborative spaces: how being a shared surface can be good for collaboration, and what are the interaction and visualization techniques developed for collaboration. Finally, I will address the role of wall displays in a control room.

At the end of each sections, I summarize and I position my work with relation to previous work.

2.1 BENEFITS OF WALL DISPLAYS IN INDIVIDUAL WORK

In this part, I focus only on the individual context; benefits in the collaborative context are presented in the next part. I study incrementally the impacts of *large size*, *high pixel density*, and *physical navigation*.

2.1.1 *Impacts of large size*

First, I expand on work that demonstrated the impacts of large size over regular desktops.

Tan et al. [185] compared a regular 17.5" desktop display with a large 95" projected screen in a spatial orientation task and in a reading comprehension task with the same field of view (See Figure 4). They found participants performed better with the large display on

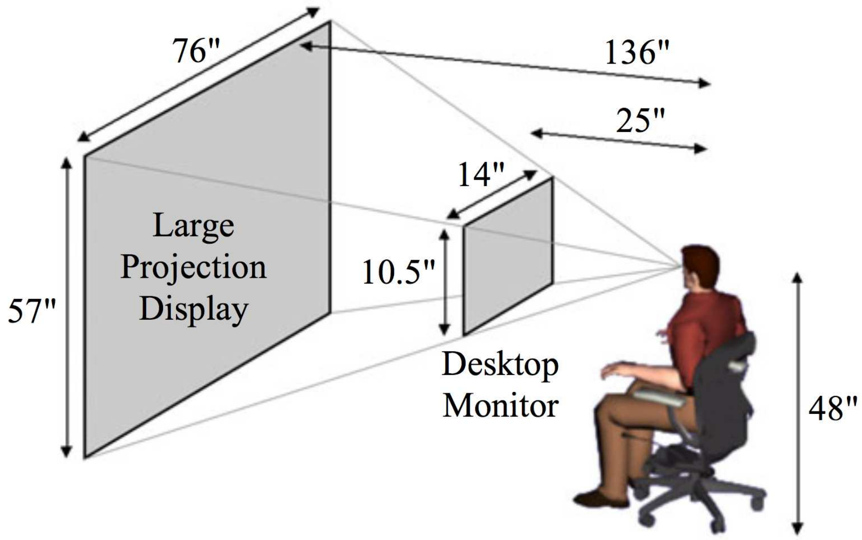


Figure 4: Study comparing a desktop display with a large display while keeping the same viewing angle. Image produced from [185]

the spatial orientation task, no differences were found for the reading comprehension.. In a second study, they showed that the large display provided a better sense of presence, and that it encourage users to use more egocentric strategies. An egocentric strategy in spatial orientation is a strategy in which the user will consider the position of other objects relative to herself.

Czerwinski et al. [47] compared a 15" desktop display with a 42" large display in a set of office tasks and found that users were faster on the large display. However, they also found specific issues related to the size of the display: first, more cursor travel was needed between windows, often the user lost the cursor; notifications sent to the user by the system went unnoticed because she was focused on another part of the display. They concluded that the user interface needs to be adapted to the size of the display.

Bi and Balakrishnan [22] observed users using a large display ($4.9m \times 1.8m$) and regular desktops to do their daily work (See Figure 5). Participants in general preferred the large display, except to browse the web, as the rendering of images was slow, and most of web pages didn't scale well. Thanks to the interaction logs, the authors observed that users divided the large display into a focal and a peripheral area. The main window was in the focal area and concentrated most of the mouse interaction, while windows giving addition information were placed in the peripheral area. This layout required more window moving and resizing than on the regular desktop, but fewer maximizing and minimizing actions.

Similar conclusions were reached by Andrews et al. [4] in their study of the use of a large display for a sense-making task. In a pilot study, they compared a large display ($2.6m \times 0.8m$) with a regular desktop. They found that, with the large display, participants used

Figure 5: Large display condition in a study comparing a desktop display with a large display for office tasks. Image produced from [22]

Figure 6: Study comparing a large with a small display for visual exploration. Image produced from [155]

the space to lay out the documents and tried to organize them. On the regular display, on the other hand, they displayed only one document at a time by maximizing it. Notes were used by participants to keep a general idea of the set of documents, and in both conditions, participants tried to have them visible all times. Thus, participants preferred to have them on paper with the small display, but with the large display they preferred write them electronically as it allowed them to have them displayed at all time. A deeper study with only a large display confirmed both these tendencies: the use of the space to organize the documents, and the use of the space to do note taking electronically.

Finally, Reda et al. [155] studied the influence of display size in a visual exploration task (See Figure 6). Users on the large display were more engaged in the visual exploration of the dataset and adopted a more exploratory behaviour. Thus, they spent more time exploring the dataset, and reached a larger number of observations that had broader insights than with the small display. The rate of observation per minute was the same, in general, for both displays, but the rate

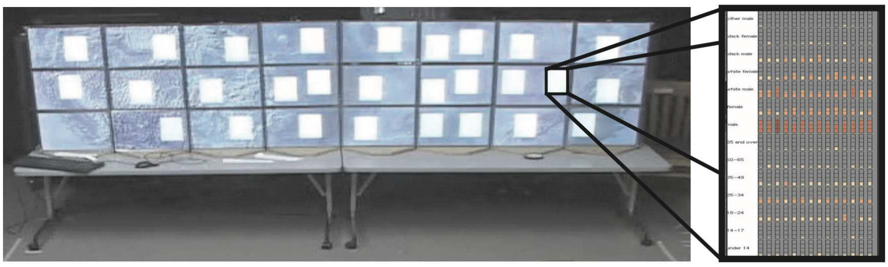


Figure 7: Study assessing the effect of resolution on different type of visualization. Image produced from [216]

of broad-insight observations per minute was higher on the large display. However, the first observations were done earlier with the small display than with the large one, suggesting a higher learning curve for the large display.

SUMMARY Thanks to its size, a large display gives a better feeling of presence to the user [185] and can lead to better performance for office tasks [22, 47], sense-making tasks [4], and for data exploration [155]. With a large display, users tend to divide the screen into a focal area, which condenses the interactions, and a peripheral area which brings additional information [4, 22]. However, for office tasks, the large size leads to more frequent loss of the cursor and to missed notifications by the users [47]. Finally, as their use is new for most users, it necessitates a higher learning curve [155].

2.1.2 *Impacts of high pixel density*

Additionally to their large size, wall displays have a high pixel density and can visualize data with the same level of detail as with a desktop display. Studies in the previous part did compare small and large display with similar pixel density. However the focus of the experiments was really the size. The studies below focused either on the effect of a high pixel density or on the effect of a high density plus a large size.

In their study, Ni et al. [140] compared the use of a small (18.8" long) and a large (48.0" long) display, each of them with a low (1280×720) and high (2560×1140) resolution, for a navigation task in a virtual environment. Participants were asked to find different information about paintings in a virtual museum. They found that participants were faster with the large high resolution display. With both displays, they also studied the impact of way-finding aids on the performance of participants. The authors found that they helped participants who use the small display, but it didn't have any effects for participants on the large display.

Yost and North [216] studied how different types of visualization scaled on a 32 millions pixels large tiled display for visualization tasks

(See Figure 7). They found that participants were as accurate on the large as on the small display. The dataset used on the wall display was twenty times bigger than the one on the small display, but it took participants only three times longer to finish the tasks. They also found that spatial encoding in visualization was really important on the large display, whereas on the small display, participants were more sensitive to graphical encoding.

Jakobsen and Hornbaek [96] examined the interplay between display size, information space size and scaling, and found that all these factors needed to be taken into account. They found that in some conditions, an increase of the display size did not lead to a better performance, (e.g. in a navigation task, when the targets were visible at all scales).

Finally, Rajabiyazdi et al. [153] studied a more concrete use-case. They proposed to researchers from different fields like humanities, biology or computer graphics, to use a high resolution large display to visualize their data. Their participants gained various new insights from the use of the wall display that have not been previously noticed on desktops. These included discoveries that were later published. They suggest that to bring new insights on a real dataset, what was important was not the size nor the resolution but the combination of both.

SUMMARY Thanks to its high pixel density, a wall display can have the same pixel density as in a desktop. Thus, given its large size, it can display more data than a regular display. Normalized by the amount of data displayed, the time to explore the data is shorter on a wall display than on a regular display [140, 216]. Finally, large high-density display allows users to find more insights when doing data exploration than on a desktop [153, 216]. However, for sparse data space, the wall display doesn't lead to better performance for navigation tasks compared to a desktop as everything can be seen at the maximum zoom level [96].

2.1.3 *Impacts of physical navigation*

A by-product of wall displays is that it is possible to navigate physically to explore the data. In a regular desktop display, because it is not always possible to render all data at the same time, it is necessary to provide users with interaction techniques such as Pan and Zoom to virtually navigate through the data. With a large high resolution wall display, it is possible to display a huge amount of data, but in that case, users need to physically move in front of the wall display to see the detailed data at different locations. The benefits of physical navigation over virtual navigation have been studied by several researchers in HCI.

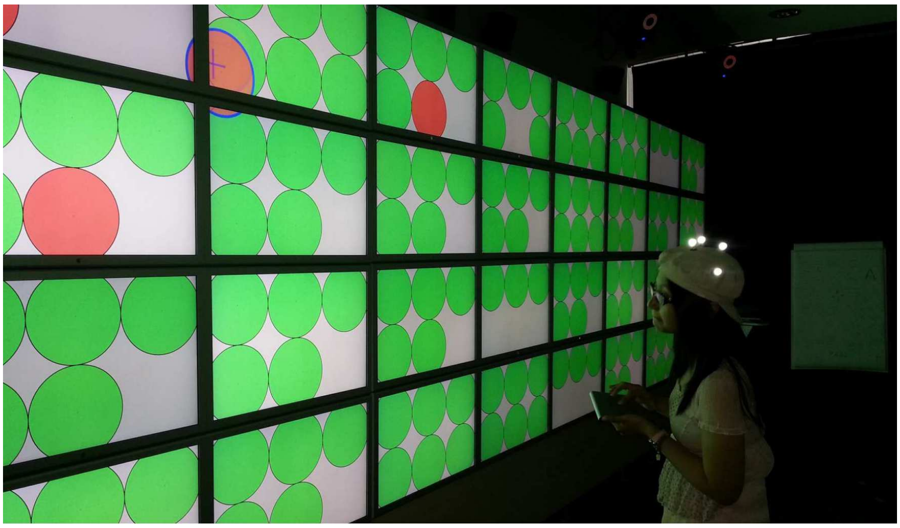


Figure 8: Wall condition in a study comparing virtual and physical navigation on a classification task. Image produced from [118]

Ball et al. [16] studied the influence of the size of the display on the type of navigation used (physical or virtual). They did their study with several data exploration tasks (navigation, search, pattern finding). Their results showed that the wall display encouraged participants to use physical navigation rather than virtual and that it led to better performance. They also showed that users preferred using physical navigation when possible.

Liu et al. [118] compared the use of physical navigation on a wall display, with the use of virtual navigation on a desktop using Pan and Zoom (See Figure 8). They used an abstract data classification task which involved data manipulation. A condition of the experiment was the need or not to use navigation to solve the task. Their results showed that when navigation was not required, performance was better on the desktop, but when it was necessary, physical navigation on the wall display was better. They attributed this improvement of performance to the ability of participants to visually reach more targets by moving their head on the wall than on the desktop, and possibly to other factors such as spatial memory.

Jakobsen and Hornbaek [98] assessed the impact of participants' ability to move or not while performing the same task as Liu et al. [118] on a wall display. They found that the ability to move did not improve performance and that participants in both conditions preferred using the virtual navigation technique that was provided (Pan and Zoom) rather than the physical navigation technique. The use of the virtual navigation technique was actually mandatory in both conditions because the information space was bigger than the size of the large display. In a second study, they directly compared the use of physical navigation with virtual navigation in the same setup and on the same task. They found that the use of physical navigation actually improved participants' performance compared to virtual. Both

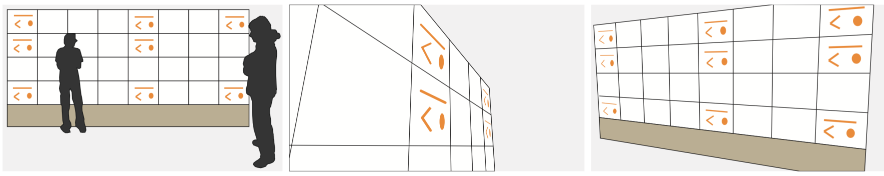
Figure 9: No peripheral view condition in a study assessing the effect of peripheral view and physical navigation. Image produced from [15]

studies showed that people did not mix the two types of navigation, even if it was detrimental to their performances, but that when the wall display fit all content, physical navigation improved their performance.

Researchers in previous studies showed that physical navigation can be more efficient than virtual navigation on a wall display. Endert et al. [59] compared the use of different visual encoding (color, length, slope and position) on a data exploration task. They found that the use of color allowed an accuracy of 96% and that it was twice as fast as other encodings. They concluded that, to support physical navigation, it was important to find an encoding which has a good balance between expressiveness of glyphs and good visual aggregation properties when seen at a distance.

Finally, Ball and North [15] compared the interplay of physical navigation with the peripheral view in a data exploration task (See Figure 9). Their results showed that physical navigation was more critical than the increased field of view, except for estimation tasks, in which a larger field of view combined with physical navigation improved performance. With physical navigation, participants tended to freely walk around at different distances from the display, which promoted higher order thinking. On the other hand, with virtual navigation, participants tended to sequentially pan around at one zoom level, and then increase the zoom level if nothing was found.

Its large size and resolution is a useful feature of the wall display to display a large amount of data, but this can lead to distortion of visual information depending of the position of users. Physical navigation



(a) The viewpoints of two observers. (b) Wall as seen by the left observer. (c) Wall as seen by the right observer.

Figure 10: Effect of visual distortion on a wall display in function of the position of the viewer. Image produced from [21]

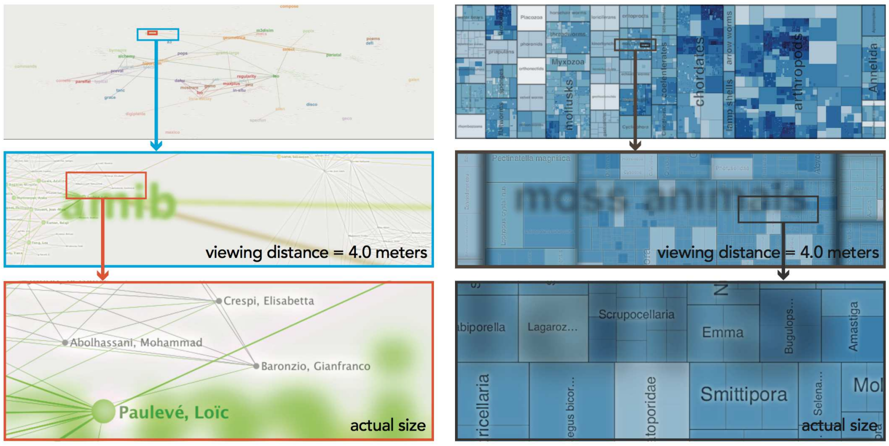


Figure 11: Demonstration of hybrid image, the visible visualization depends on the distance of the viewer. Image produced from [93]

can help to avoid distortion. Bezerianos and Isenberg [21] studied the impact of distance and viewing angle on the perception of basic visual encodings (See Figure 10). They found that these distortions affected perception accuracy for encodings using area and angle, especially close to the wall. In a second study, they showed that on a perception task, when participants were positioned farther from the wall, they were as accurate as if they are allowed to move freely, but they took half the time. They suggested recommendations to users to position themselves farther back when comparing data. If users needed to be close to the wall, they said it was important to place critical information in front of them, or to give them information about the level of distortion.

In the previous study, the same visualization was displayed whatever the position of users. However, it is also possible to change the visualization as a function of user position; for example, display detailed data points when the user is up-close, and a more global and clustered view when afar. Isenberg et al. [93], to this purpose, blended two visualizations so that each can be seen at different viewing distances without the necessity to track users (See Figure 11).

SUMMARY Wall displays encourage the use of physical navigation, which leads to better performance when navigation is actually needed with data exploration tasks [15, 16, 118], and especially with visualizations that use color encoding [98]. Physical navigation is preferred by users, except when it is necessary to mix it with virtual navigation [98] (if the wall doesn't fit the data space size). Physical navigation impacts performance more than peripheral view, but the performance can be further improved if both are mixed [15]. Physical navigation is also important to counter-balance the effect of visual distortion due to the size of the display [21]. Finally, researchers have used physical navigation to provide different information as a function of the position of the user [93].

2.1.4 *Overall summary*

Previous work shows that high resolution wall displays, and more particularly UHRIWD, are very useful displays to do various tasks, from data exploration to office tasks, thanks to their *large size* and *high pixel density*. Some of these tasks are also facilitated in some conditions by *physical navigation*, an upside of the two previous characteristics.Collaboration in front of wall displays is also impacted by these characteristics and this is what I study in the next two sections.

2.2 IMPACTS OF A SHARED DISPLAY FOR COLLABORATION

One characteristic of a wall display is that due to its size, it can be shared by several users and provides them with a common collaborative space. The collaborative space is physical, on a single shared display called SDG [178]. Other displays can be used as SDG: multi-touch tabletops and desktops with several mice. Before focusing on wall displays in the next subsection, I first expand on work that has demonstrated the impact of shared displays on collaboration. On the other hand, collaborative systems can be composed of several displays, co-located or remote, often called MDG [52]. In the case of MDG, the collaborative space is virtual. Because of this virtuality, it can be difficult for one user to be aware of the actions of another user in the shared workspace, i.e. to have good workspace awareness [72]. Several techniques have been developed to address this: multi-cursors, radar views [71], techniques to link common work [123], and arm embodiments for remote collaboration [51]. However, few studies compare SDG and MDG, to quantify the effects of the shared display on awareness, and more generally on the collaboration.

Wallace et al. [205] compared a tabletop with personal tablets for a sensemaking task. They found that the tabletop improved sensemaking performance and led to better prioritization, task comparisons, and critique of group hypotheses. Finally, their results showed that the use of the tabletop provided a better equality of interaction than the personal tablets.

Inkpen et al. [90] studied the impact of display factors on colocated collaboration, like the number of displays. In their laboratory experi-

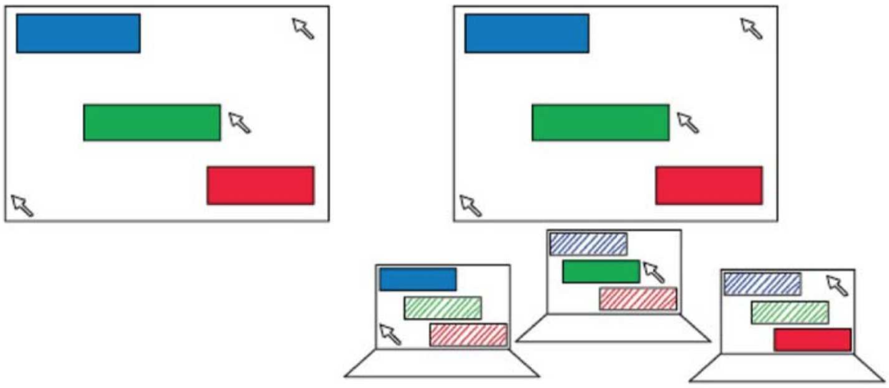


Figure 12: Comparison of a SDG with a MDG for the job shop scheduled task. Image produced from [206]

ment, they asked pairs of participants to do a subway path planning task either on a shared single tabletop or on two separate ones. Contrary to [205], they found that the work was more equally distributed with the MDG condition. But participants felt communication was easier and their work more efficient with the SDG.

With the same task, Hawkey et al. [76] studied the impact of the distance on colocated collaboration. To this purpose, they compared two users on a wall display and one user on a wall display and the other on a regular screen. Participants felt that collaboration was more enjoyable and efficient with the large display, and that the communication was more difficult with the MDG condition. Overall, the quality of participants' solutions was better with the SDG condition.

Finally, Wallace et al. [206] compared a large display (SDG), with a large display and three desktops (MDG) for a job shop scheduling task [184] (See Figure 12). Their results indicated that SDG provided more awareness of partners' activities, but could lead to distraction. In the MDG condition, there was less distraction, but collaboration was more demanding. Overall, no differences were found regarding performance.

SUMMARY The previous work show that SDG provides more group awareness [205, 206], and that collaboration with it is more enjoyable and feels more efficient [76, 90]. The downside is that it can distract others and impact performance [206]. On the other hand, collaboration is more demanding with MDG due to difficulties in communication [76, 90, 206].

2.2.1 *Position of my work*

These results are already useful in the design of collaborative applications; nevertheless, they focus mainly on subjective measures and on very high level tasks. In Chapter 4, I perform an empirical study that compares both setups with a low level task. It shows the impacts of the setup on collaboration with limited noise due to other effects, like for example physical navigation. As we saw in the last section, it can be beneficial in some conditions, but no study has been done to isolate its effects on a collaborative context.

2.3 COLLABORATION AROUND A WALL DISPLAY

There is a large body of work about collaboration on SDG, mostly about tabletops. Studies have been done to show how people collaborate [186], how social protocols affect collaboration [157], and also to compare the impact of the type of inputs (mice or multi-touch) [86] and of interaction techniques [138] on coordination. Tabletops are shared displays, but their size is smaller than that of a wall display, and their orientation is horizontal. This affects how people collaborate in front of them. Rogers et al. [160] showed that a horizontal display led to a less structured collaboration, but with more changes of roles, and that collaboration was more socially acceptable than on a vertical display. Inkpen et al. [90] added that there were more pointing gesture on the horizontal surface, but that the vertical one led to more movements, and information was easier to see. As a side note, vertical displays in each case were not large, in [160] it was a $96\mathrm{cm} \times 96\mathrm{cm}$ and 33" in [90]. In this work we focus only on large vertical displays.

2.3.1 *Collaboration with classic inputs*

One of the first studies on collaboration in large vertical displays was done by Vogt et al. in 2004 [201]. They compared the use of multiple mice with the use of multiple laser pointers in a collaborative maze task done on a large projected screen. They conducted the study with individuals and groups of 2 and 3 participants. They found that multiple mice were superior for the fine motor control aspect of the task, while the multiple laser pointers were better at encouraging collaboration. With the increase of the size of the groups, participants started having trouble to identify their pointer. Moreover, the constant movement of the other cursors were disrupting for some participants.

Later, Birnholtz et al. [24] focused on the use of the mouse as input. They studied the effect of the input configuration on collaboration on a negotiation task (See Figure 13). They asked groups of 3 participants to perform a newspaper layout task using two different input configurations: in one, the entire group had only one mouse to interact, in the other, each member of the group had their own mouse. They found that groups adapted their coordination behaviors to the input configuration. They tended to work in parallel with multiple mice, but adopted a term-based approach with a single mouse. In the latter case, the control of the mouse was not evenly distributed. Most of the time one participant was controlling it and the others is-

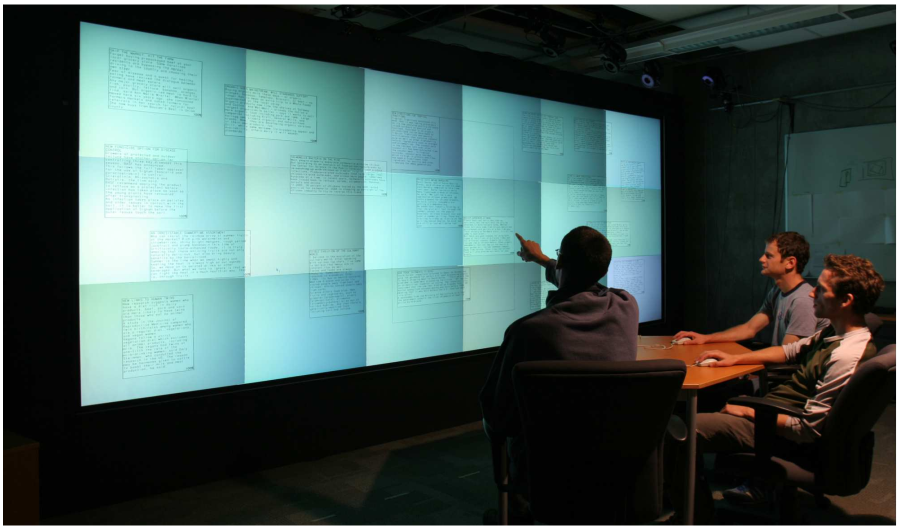


Figure 13: Multi mice condition in a study about input configuration with a wall display. Image produced from [24]

sued commands. Participants perceived that the quality of discussion was higher in the single mouse condition, but they also found that it could be frustrating as they didn't always control the mouse when they wanted. They concluded that the input configuration was important and should be chosen carefully in function of the task and also of the group dynamic.

The use of multiple mice was adopted by Isenberg et al. [94] in their multi-user social network analysis tool, NodeTrix, which ran on a large display. Each user had her own mouse with her own color, but there was only one keyboard for all the users. In their adaptation, they tried to avoid large footprints from a user's action in order not to bother her partner. A user study showed that participants often alternated between loose and close collaboration, and that they needed to interact with the whole visualization during the discussion. Object selection conflicts were managed by the participants themselves, and no specific mechanism was demanded. Finally, the visualization gave awareness of their partners' activities in real time, but also about past activities, as it acted as an archive of the participants' work.

Azad et al. [11] studied touch input, which is done up-close to the display. As it has been studied on tabletop [86], touch led to physical conflicts, and then to the division of space into territories by participants. They asked pairs of participants and pairs of groups of participants to do two jigsaws with magnets on a magnetic whiteboard. They found that participants divided the workspace in territories similarly as on a tabletop [169]: personal, storage and public. They also analysed the positions of participants in the space in front of the display and they found that participants spent most of their time looking at the large display, and they rarely looked at their partner. The distance between the two single participants was greater than the distance between the two groups. Finally, in the case of out-of-reach

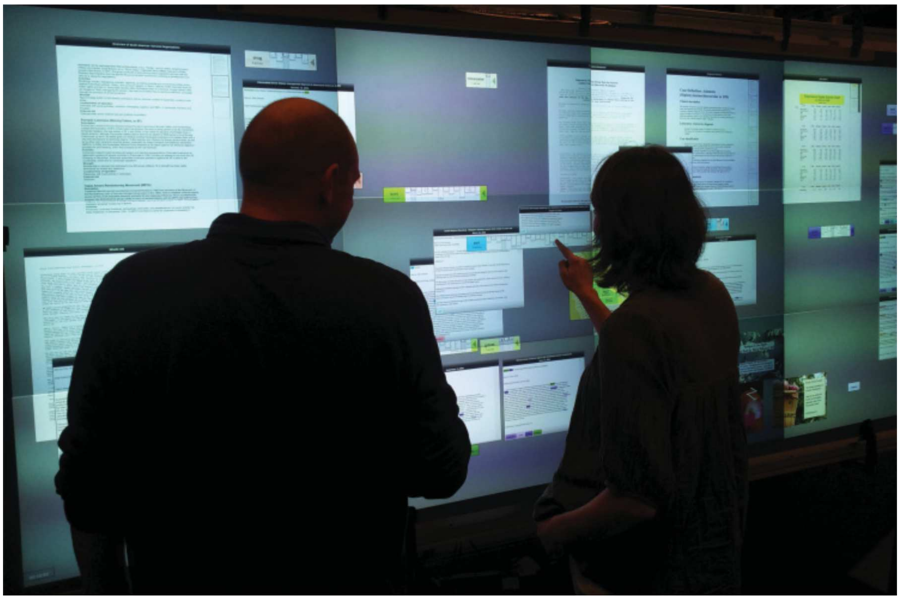


Figure 14: Users doing a sense making task on a wall display. Image produced from [97]

pieces, participants tended to walk over to grab them instead of asking for help. Nevertheless, when they identified a piece which did not belong to their jigsaw, they put it directly in the shared storage territory.

Bradel et al. [27] also studied territoriality, but for users using a mouse to interact with the display. They did an observation study of pairs of participants doing a text sensemaking task. Contrary to what was seen with tabletops and in [11], participants tended to have only one big shared space. As there is no issue with physical conflicts with multiple mice, participants probably didn't see the point of organizing their workspace using territories, and rather used it as a big shared space.

Jakobsen and Hornbæk focused on direct multitouch input [97]. They observed pairs of participants doing a sense making task on a corpus of documents (See Figure 14). Their results showed that participants switched fluidly between parallel and joint work and that in joint work, participants stayed closer to each other. Nevertheless, they didn't find any relation between the collaboration style and how they shared the workspace. They actually tended to share the wall display evenly between them. Finally, a loose collaboration style didn't imply silence, participants still talked in order to build a shared understanding of the situation. The study suggested that multitouch can support different collaboration styles on a wall display.

The findings about the relation between the distance between participants and the degree of collaboration were confirmed by Wallace et al. [204]. In a study, they asked pairs of participants to do either one jigsaw together (close collaboration) or two alone (loose collaboration). They found that participants who did one jigsaw together stood

Figure 15: Users playing to the game Miners on a wall display. Here, the right player doesn't see what the others are doing, this is an example of lack of awareness. Image produced from [218]

closer together. During the experiment, each participant tended to store her jigsaw pieces into a location that they considered as storage areas. This also confirmed the use of territories on the large display.

Jakobsen and Hornbæk also studied the effect of the input on collaboration by comparing in a study touch with regular mice [99]. They asked pairs of participants to do two tasks: a jigsaw puzzle and a newspaper task. Mice were faster and more accurate than touch, and also allowed participants to interact while having an overview of the situation and without too much physical movement. On the other hand, touch was considered as more fun, and gave a better awareness of each others' activities. Both have their limitations, the mouse led to more object selection conflicts between participants, but the touch led to physical interference.

Von Zadow et al. studied the influence of multitouch on collaboration in a game [218]. They found that close distance to the display could lead to a lack of awareness of each others' activities. Participants had a good local awareness, but didn't see what happened farther away from their area of action (See Figure 15). This impacted communication: as participants were mostly focused on the wall, and didn't look at each other often, they needed to use mechanisms to attract each other's attention (Calling player's name, Repeated call, light body contact, and even exertion of force). Once contact was established, communication was verbal, but deictic gestures were also used to add information.

SUMMARY These papers show us the different benefits and drawbacks of different input modalities on wall displays. Distant input techniques like mice can be more accurate [99, 201], faster [99], limit physical movement [99], and allow users to interact with an overview

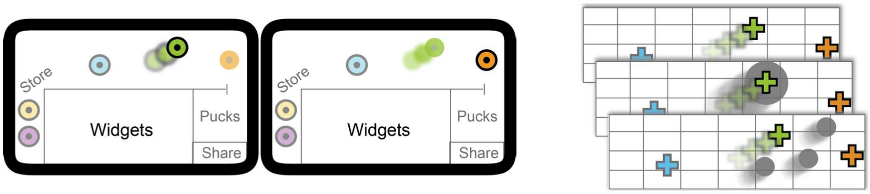


Figure 16: Schema of the Smarties system. The first image is the view from a mobile device, the green cursor is active, the user is moving it. The second image presents the view from another mobile device. Here the active cursor is the orange one and the green one looks faded-out as it is unavailable. The last image shows possible presentation and behavior of the cursors on a wall display, controlled by these pucks. For example a moving puck can be associated with a simple moving cursor (top), moving an object (middle), or a group of objects (bottom). Image produced from [39]

of the workspace [94], but they encourage loose collaboration [24] and lead to reduced awareness of others' activities [99]. On the other hand, direct input techniques like touch are more enjoyable [99] and allow an easy switch between loose and close collaboration [97]. With touch, when users collaborate closely, they get closer physically [97, 204]. Also, they give to users a good awareness inside their area of action, but to have an overview they need to step back [97]. Because of this setup, users lack global awareness when they are focused on their own task [218]. This is also reflected in territoriality; as on tabletops, with up-close interaction, users tend to respect private, shared and storage territories [11], but with distant interaction, they tend to adopt only one big shared territory [27]. Finally, touch interaction necessitates physical movement which can provoke fatigue. One way to address issues of each type is to adapt the interaction techniques to collaboration in order to compensate for the flaws of each type of input. It is possible to provide a better awareness of others with distant inputs as with tabletop [51]. It is also possible to improve global workspace awareness and reduce physical fatigue for up-close input.

2.3.2 *Collaboration with adapted interaction techniques*

There are yet very few interaction techniques which are adapted for collaboration on wall displays. Smarties, designed by Chapuis et al. [39] is an example. It is a mobile application which works like a touchpad, and users can use it to create and control one or several cursors. These cursors can be stored and shared by users. All the cursors are displayed in the touchpad area, which allows a user to have a quick awareness of others' cursors at a glance (See Figure 16). Additionally, it is possible to add several widgets to the mobile application (button, textfield, slider, etc...). Chapuis et al. evaluated their input system with different applications which run on a wall display. This

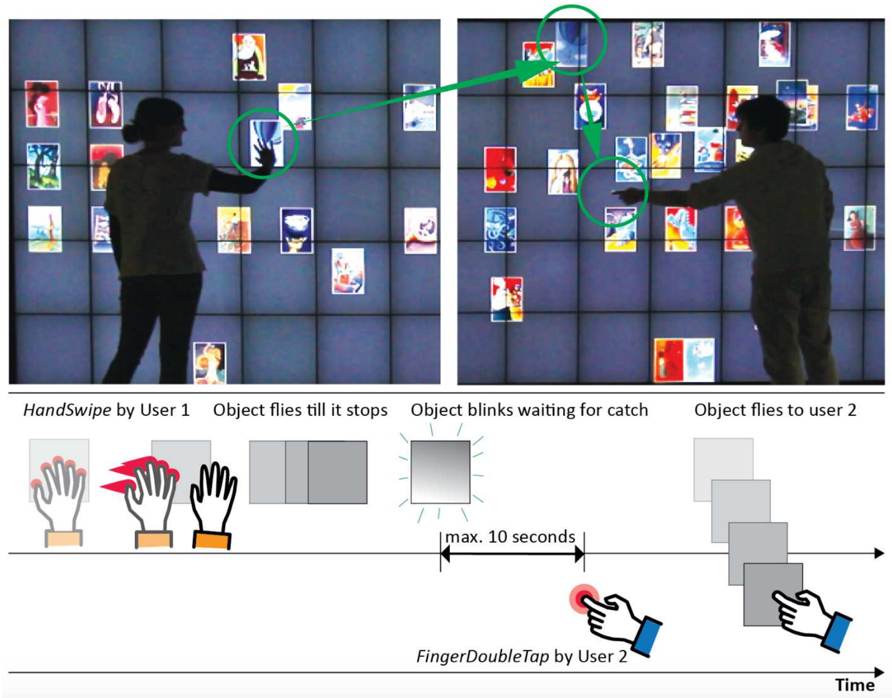


Figure 17: Users doing an image classification task on a wall display using shared interactions. Here users are doing the "Throw and Catch" gesture. Top: The object is thrown by the left user, and catch by the right one using the appropriate gesture.Bottom: the sequence of gestures on two timelines, one per user. Image produced from [120]

new distant input provides a better group awareness thanks to the cursor visualization, and allows a closer collaboration thanks to cursor sharing.

Liu et al. [119] focused on the concept of shared interaction, which is when multiple participants perform a single interaction together. They performed a laboratory experiment in which they asked pairs of participants to do a data manipulation task. Participants were forced to use a specific collaboration strategy, which allowed them to communicate or not, and to use a shared interaction technique or not. They found that, even if it induced a cost, participants preferred the strategy in which they could collaborate. Shared interaction actually increased collaboration and reduced the need for physical navigation. Thus, participants were more efficient with shared interaction, and considered it as more enjoyable.

In a second paper, Liu et al. [120] proposed a set of shared interaction techniques for multi-user data manipulation on a wall display: CoReach. They compared their set of gestures with non-cooperative gesture for an image classification task. They found that CoReach reduced physical fatigue, increased the rate of collaboration, and allowed close collaboration at distance. A second study showed that CoReach gestures could be used remotely using handheld devices.

Figure 18: Users doing a visual exploration task on a wall display using hybrid interaction techniques. Here users are doing a merge of two visualizations. It uses proxemics to stack the lenses when the users are close (left) and changes the merge mode to content overlay when they perform a collaborative gesture (right). Image produced from [14]

Their use enabled interesting collaboration strategies that combine the benefits of touch (direct and more natural) with the benefits of distant interaction (overview of the workspace and better awareness of what happens in remote areas).

Badam et al. [14] studied the influence of the type of interaction technique on visual exploration on large displays. They designed two sets of interaction techniques to manipulate small visualizations, one based on explicit mid-air gestures and another based on proxemics (use of inter-entity distance, so between people, digital and non-digital entities [69]). Their first study showed that participants preferred using explicit gestures for "direct" action but that proxemics can be more efficient for navigation and collaboration related commands (the consensus to merge two visualization). They designed a set of interaction techniques which mixed implicit and explicit gestures following the results of the first study. A second study showed that this hybrid set led to better performance.

In the previous papers, the authors provide interaction techniques to closely collaborate on a wall. Kister et al. do the opposite in their paper [105]; with BodyLens, they provided techniques to allow several users to work in parallel on the wall. Using proxemics, they displayed a magic lens [23] which moves with the user. This lens can provide an additional layer to the data displayed or a personal toolbox which allows user specific interactions (distant of up-close).

SUMMARY Previous work shows that it is possible to improve collaboration with different inputs by developing more sophisticated interaction techniques. For instance, the issue with distant inputs is the little amount of group awareness. Chapuis et al. with Smarties improved this awareness by using a handheld device with a display showing others' cursors positions and the possibility to share them

[39]. Badam et al., with the hybrid techniques [14], and Kister et al., with bodylens [105], improved it by using proxemics. With proxemics, users' position and orientation in front of the display give information related to their activities that is easily understandable for the others. With up-close input, such as touch, the issue is that because of the lack of a global view of the workspace, users tend to not collaborate when they are far from each other [204]. To fix that, Liu et al. designed shared interaction techniques [119, 120]. They demand coordination from two users to do a specific action and thus increase close collaboration when users are far.

2.3.3 *Overall summary and position of my work*

Each input technique has strengths and weaknesses regarding collaboration. However, the one that seems the best suited, and which is actually preferred by users, is touch. It provides a good group awareness, and allows a fluid switch between close and loose collaboration. With touch, it is easier to discern who is working together as people collaborating closely will be physically close. Nevertheless, because users need to be up-close to interact, they need to step back to get an overview of the workspace. This leads to attention blindness when they are focused on their task; i.e. they lose awareness of what is happening out of their field of view. The use of interaction techniques adapted for collaboration could solve this issue.

Few researchers have worked on adapting input techniques for collaboration. Most of them focused on distant techniques by using proxemic information or handheld devices to improve group awareness, which was shown as lacking with distant input. Liu et al. [120] focused on touch input and studied the effect of shared interaction techniques on touch. They showed that novel techniques allow close collaboration at distance in front of the wall and increases the rate of collaboration.

However, while the use of shared interaction techniques suits the context of data manipulation, it cannot be used for every other task. In this thesis, I study the effects of another factor on collaboration with touch input: visual footprint (e.g. the visual representation of the techniques). It has already been shown that when people need to collaborate closely, they prefer to use interaction with a large visual footprint [186]. Nevertheless, this result was found with tabletops and didn't show the other implication: that with a technique with a large visual footprint, users collaborate more closely. This is what I test (Chapter 5) for a specific context: graph exploration. I compare two interaction techniques with a small and large visual footprint in a laboratory experiment and see how this factor influences the participants' collaboration strategy.

Following on this work, I focused on collaboration around a wall display which is included in a MDE. Complex collaborative tasks can't be performed with just one degree of collaboration, they require mixed-focus collaboration, which consists in several transitions between loose and close collaboration [186]. I study the needs of users in order to simplify these transitions in a MDE composed of a UHRIWD with several workstations, focusing on a specific use case: crisis management. Then, I design interaction techniques to answer to these needs.

2.4 USE OF WALL DISPLAYS IN COMMAND AND CONTROL

Taking advantage of their characteristics, including collaborative space, researchers have investigated how to use wall displays, or more generally large displays, in different contexts. Some studied how to use them as public displays [136]. A public display is a display set in a public area like a mall or a street, and with which anyone can interact when passing by. It can be used for advertising [171], giving additional information to pedestrians [195] or allowing passers-by to play games [162]. Others studied their use in collaborative rooms, i.e. rooms composed of several public and private displays designed to enhance collaboration for a specific purpose [18]. It can be used for meetings, e.g. the space designed by Stefik et al. [177] composed of desktops and a large display, Dynamo [95] and Multispace [62], both composed of a wall display and an interactive tabletop, and MeetAlive [63], composed of several wall displays and laptops. This same configuration is also used in WeSpace [214] for scientific collaboration, I-Land [180] for collaborative creative work, and UD Co-Spaces [124] for urban design. In this thesis, I choose to focus on a different context: command and control.

Command and Control is originally a military term, defined as the exercise of authority, direction, and coordination by designated operators over resources in the accomplishment of a common goal [174]. It is now applied also to civil operations regarding the monitoring of critical infrastructures. There is less the notion of authority and more the notion of increasing the capacity and safety of the system. This monitoring is usually done from dedicated control rooms. The layout of control rooms is very similar: a large visualization display to show a global view of the monitored system, and several workstations to provide a detailed and interactive view to operators (See Chapter 3). Large displays typically just projected screens with low resolution; interaction, when it is possible, is done using mouse and keyboard [173, 175].

The control room context could benefit from the technology described in the previous sections, and research has been done on how to use and take advantage of the benefits of collaborative displays

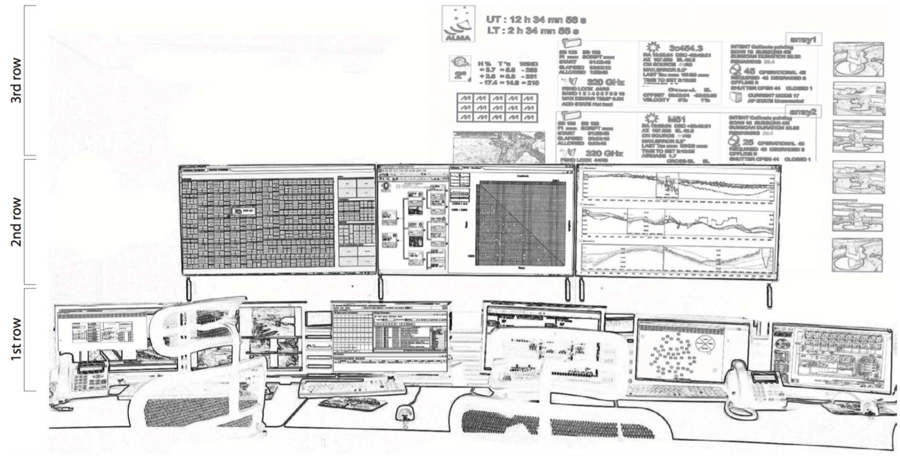


Figure 19: Sketch of the Alma control room. The first row contains UI components that users interact with frequently. The second row contains UI components that users interact with infrequently. The third row contains UI components that users never interact with. Image produced from [145]

In this section, I present research that studies the use of novel collaborative displays in control rooms. A more detailed analysis of the actual setup in control rooms and tasks done by operators is done in Chapter 3.

2.4.1 *A visualization display*

In the new design of the Atacama Large Millimeter Array (ALMA) telescope [145], Pietriga et al. decided to provide operators with 3 levels of displays (See Figure 19). The first level was directly in front of the operators and it provided visualizations with which operators interact frequently. The second level was composed of bigger displays farther back that covered a wider field of view. They displayed visualizations with which operators interact less, but that are important for real-time monitoring (e.g. time-series of parameters regarding antennas' operations). Finally, a large display composed the third level. It could be seen by anyone in the room, and displayed high level information about the global state of the telescope and currently running activities. It provided operators with a general awareness of the situation. Operators could not interact with it or modify what was displayed.

Similarly, large displays are used as overview displays in industrial process control room. However, Veland and Eikås argued in their paper [198] that their interfaces were not adapted for rapid scanning and anomaly detection, and they proposed a novel design. The design was based on the Information-Rich Design (IRD) concept [28]. First the information for the display were carefully selected to allow a good monitoring of the safety of the plant and of the production. The

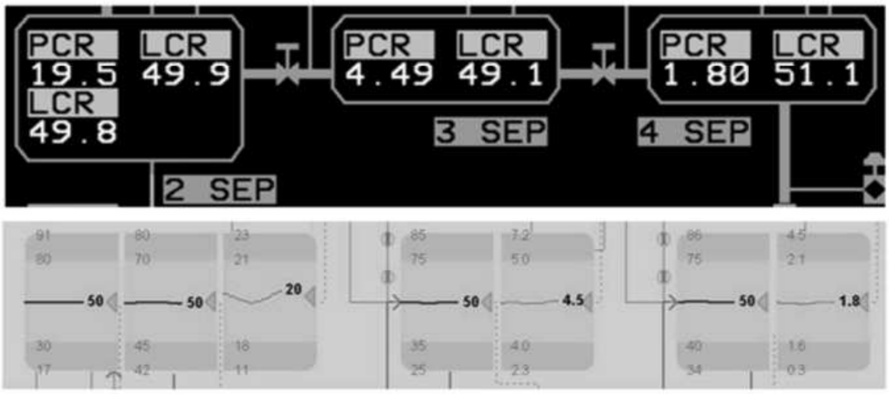


Figure 20: Demonstration of the IRD Design. At the top, there are traditional designs for three oil separators. At the bottom, there are IRD designs for the same oil separators. Image produced from [29]

selection depended on the criticality of parameters, and also on their frequency of usage. Regarding the visualizations, they needed to be perceived and interpreted with minimum effort. As the large display was used as an overview display, a brief glance should be enough for a quick detection of problems. For instance, they used mini-trends that were aligned and normalized to facilitate rapid visual scanning for anomalies (See Figure 20). Finally, they optimized the layout of the visual elements to facilitate a rapid visual scanning and to provide a sufficiently correct picture of the plant system topology.

Using the same concepts, Laarni et al. designed an overview display for a nuclear control room [108]. They compared this new design with the current large display used in the Loviisa nuclear plant in a usability study. They asked three pairs of operators to perform a set of six scenarios on both setups. The results showed that, in both conditions, the failure was mostly detected first on the large display. However, the failure was not detected quicker in the IRD condition. Interviews with the operators were done after the test and showed that the IRD solution was a promising solution. However, operators complained about the fact that the exact value for the parameters was not displayed in the IRD display, just the normalized trend, and that the layout of the visualization did not follow the actual process architecture, which was disturbing as it was supposed to be an overview display. The authors developed a final prototype of an IRD display which takes into account these comments. Braseth et al. [29] presented how a large display can be used in multi-layered HCI in the same context (See Figure 21). The large display was the overview layer, and a combination of workstations was used to be the two other layers: one to display an overview of each process in progress, and one to display details about each piece of physical equipment.

Chokshi et al. [41] decided on a more flexible use of their wall display to manage emergency response. Their system, ePlan, was composed of a wall display, a tabletop and several tablets (See Figure 22).

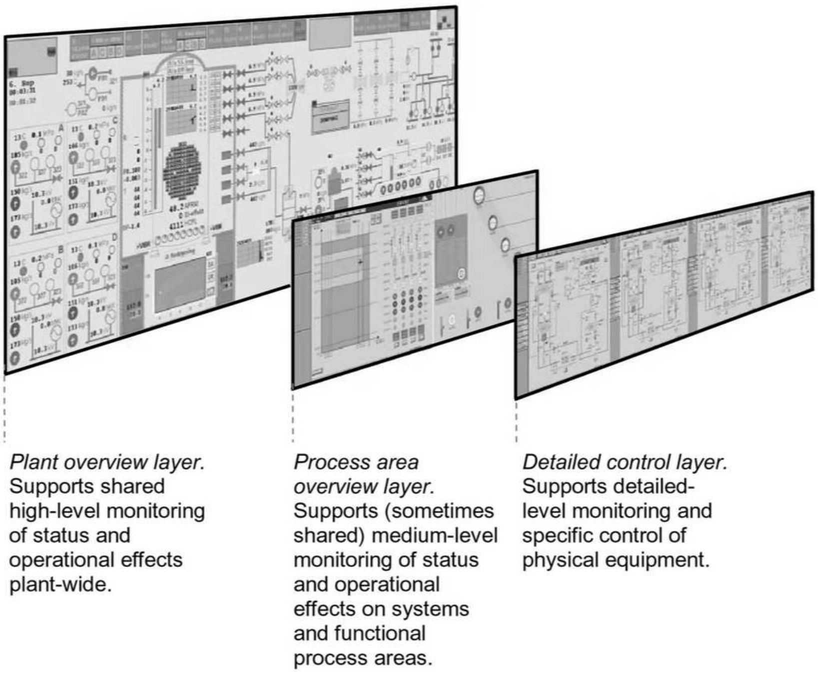


Figure 21: Sketch of the multi-layered HCI for a nuclear control room. Image produced from [29]

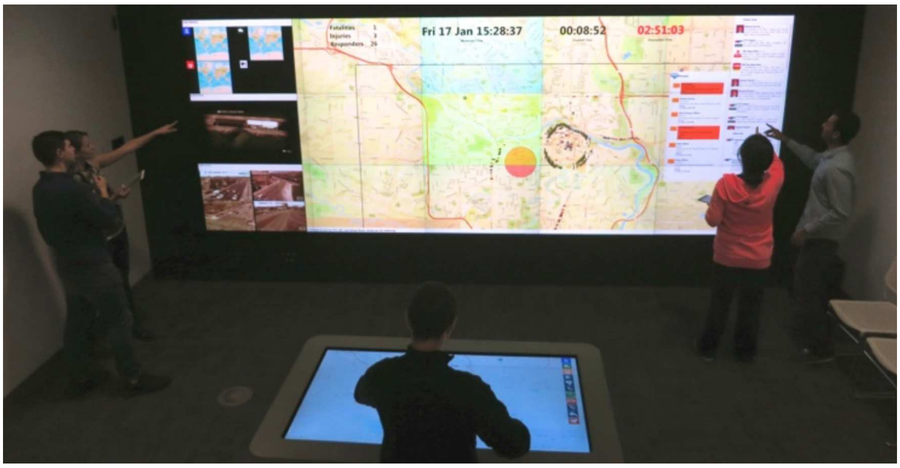


Figure 22: Users collaborating in the ePlan Multi-Surface environment. Image produced from [41]

Tablets were used as private displays, and the tabletop as a public display in which operators can integrate the information coming from the tablets and collaborate with each other to plan a response. Finally, the wall display was used to provide operators with factual information about the crisis. It was not interactive but operators could send information from the tabletop or tablets to the large display. A study with domain experts showed that the system answered to important requirements: first, the interactions with the system were natural, which was essential as experts non-familiar with the control room system were often called and asked to use the system. Second, it allowed an easy sharing of information, which is also very important in this context, as people then focused on what to share and not how to do it. The experts expressed the desire to be able to use more interaction modalities such as voice or haptic feedback.

Chan et al. [37] developed a similar setup. They added wearable devices like glass and smartwatch to easily dispatch notifications to operators, and a digital whiteboard, to allow operators to take notes that could be then distributed to other devices. The wall display provided contextual information about the ongoing incident, and was directly synchronized to the view of the tabletop. Finally, new functionalities were implemented, like the possibility to display a 3D map on the tabletop by using the tablets as augmented reality devices, and a social media filter to display only useful information from these streams.

Social media streams are considered as more and more reliable sources of information in crisis management. They provide operators with real-time information from people on-site. Nevertheless, they represent a huge amount of information to manage and to visualize. Onorati et al. [143] used a high resolution wall display to geographically display a large amount of tweets. Butscher et al. [33] explored this idea further by designing an emergency operation center prototype which was focused on the collaborative analysis of twitter data. Here, the central interactive display was a tabletop used to select a specific incident and also distribute valuable information to the other displays. A wall display was used to provide operators with an overview and to facilitate non-verbal coordination. Deeper data analysis was possible on personal curved displays. Finally, operators could use tablets to get details about a particular section of the data displayed on the wall.

An issue with data from social media is the necessity to be able to extract valuable information from it. To deal with this issue, Diaz et al. [49] designed an emergency operation center prototype which integrated citizen generated information among information from more traditional sources. Citizens are graded in 5 categories in function of their trustworthiness and their role in the emergency response. All of this information was displayed on an interactive tabletop. As in previ-

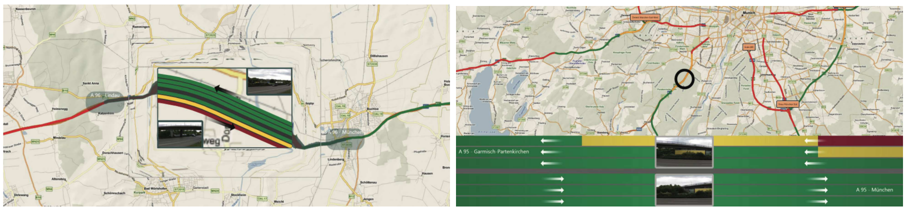


Figure 23: Visualization technique to display detailed information on a wall display in a road traffic control room. HML (left) displays the details directly within the context, while with the split screen technique (right) it is seperated. Image produced from [167]

ous systems, a large vertical display gave an overview of the situation, and operators could use tablets as personal devices. The authors evaluated their system by doing an exploratory focus group with experts, who were very positive about the system, but they identified issues like the risk of false information and misunderstanding due to the use of citizen generated data.

SUMMARY The strength of a wall display in control rooms is that it can be seen by anyone in the room. Most of the time, it provides a general awareness of the situation by displaying high level and factual information [145]. This kind of display can facilitate non-verbal collaboration [33]. Depending on the situation, the information on it can be static [33, 49, 108, 145, 198], synchronized with another device [37] (like a tabletop), or changed using another device [41] (like a tablet or a tabletop).

2.4.2 *An interactive display*

Interaction with a wall display is possible in multiple ways, using multiple types of input. Some studies explored how to use an interactive surface in the context of control rooms.

Schwarz et al. [167] proposed allowing operators to directly navigate on the wall display and to display the detailed information on it instead of on personal desktops. Contrary to what is currently done in an actual control room, this could reduce divided attention between detailed and contextual information. To facilitate navigation on the wall display, they used a 6 degrees of freedom input device: the SpaceNavigator. They also proposed two visualization techniques for sharing detailed information: split screen, in which the detailed is separated from the context, and HML, a fisheye lens displaying detailed information inside the context (See Figure 23). They evaluated their solutions in a user study. They found that the SpaceNavigator was good with both types of visualization, and was preferred over the mouse in the context of free navigation. They also found that participants preferred HML to split screen, due to the fact that with the latter, it was hard to associate the detailed information with its context.

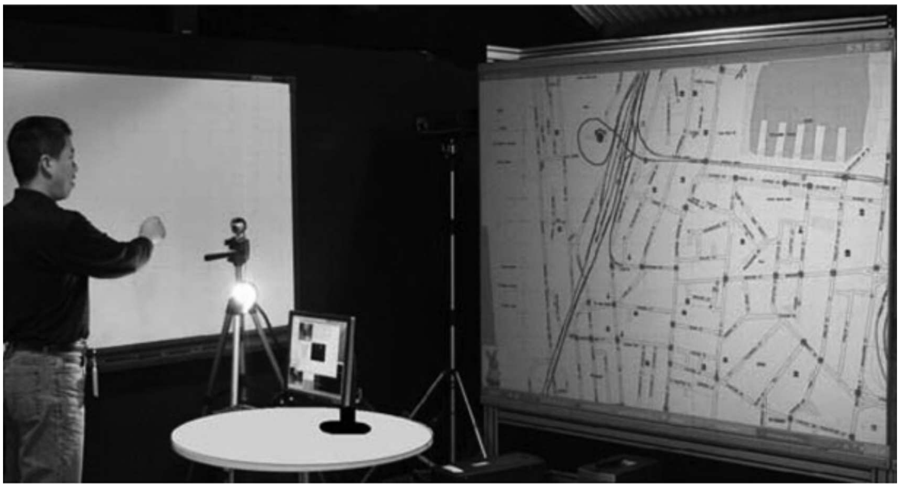


Figure 24: Physical setup of the speech/hand-gesture interface prototype for road traffic control. Image produced from [40]

In this last study, Schwarz et al. studied distant inputs to interact with the wall display. Other up-close inputs can be used with a wall display, like touch or the use of tangible artifacts. Müller et al. [135] presented a study in which they evaluated the benefits of two interaction modalities: touch and tangibility, and two traditional ones: mouse and keyboard. The use of both modalities allowed a direct manipulation of the different parameters in the control room and thus could improve the mental model of the operators of the state of the system. In addition, tangibility affords haptic feedback, has physical constraints, and requires control skills. They found that traditional modalities were faster, but that tangibility allowed a better recall of the selected value of a parameter, and brought a better sense of control. The authors advised to use both types of input: tangible input in normal process conditions, and more traditional and faster input in abnormal situations.

Heimonen et al. [81] studied the use of multimodal interactions in process control rooms[1]. Despite an evolving technology for interactive displays, operators in these control rooms are still using regular desktops. The authors developed techniques using speech and mid air gesture recognition for controlling parameters and manipulating windows on a large display. They did an observation study to assess if the techniques supported users' freedom and flexibility, while still providing a sense of safety and control. Speech was considered as a good modality by operators, but they feared it could interfere with casual conversation. Mid-air gestures were less appreciated, possibly due to the limitation of current tracking technology and to the UI which was originally built for mouse and keyboard interactions.

Choi et al. [40] similarly studied the use of multimodal interactions in road traffic control rooms. They proposed techniques that used

1 i.e. A process control room is the location from where the production of a highly automated plant is monitored

speech recognition and mid-air gestures to perform complex task like guiding an ambulance to an accident site (See Figure 24). They evaluated different types of feedback for a selection task: audio, audio + visual, visual, no feedback. Their results showed that audio feedback was the most efficient (fastest way to notify user that her command had been validated).

SUMMARY The use of a wall display as an interactive display leads to new opportunities for control rooms. It is now possible to directly manipulate parameters of the system on the wall display using innovative techniques like tangible controllers [135], speech recognition, and mid-air gestures [40, 81]. This leads to a better recall of the actions done by the operators and a better sense of control over the parameters [81, 135]. However, these new techniques can be slower to use than traditional inputs like mouse and keyboard [81, 135], and interfaces have to be designed with these techniques in mind to be adopted [81]. The different modalities should be used concurrently. The direct control of the visualization on the wall display also allows the display of detailed views within their context and thus provides a better association between the views and their context [167].

2.4.3 *Collaborative use of a tabletop in control room*

In most studies regarding the use of a wall display in control rooms, the scenario of use involved the presence of several operators. However, none of them considered the impact of the use of a wall display on collaboration. To find results regarding the use of a shared display in control rooms and its impact on collaboration, we explored the work on tabletops.

Conversy et al. designed an air traffic control system which ran on a digital tabletop [45] (See Figure 25). The purpose of air traffic control is to increase the air traffic flows, and still provide the highest level of safety possible. To do that, controllers rely more and more on automation for routine tasks to reduce their workload so that they can better focus on unusual situations. Their observations showed that collaboration between controllers was central in the management of these situations. Moreover, controllers talk a lot with pilots and so cannot use a lot of verbal communication with each other. They proposed using a tabletop, a shared display as opposed to the separate displays currently used in control rooms. Communication could be done using Post-its with actions related to a specific aircraft. A timeline was displayed to help controllers remember future actions for which they could add Post-its. Pilot studies showed that the system supported communication and coordination, and it allowed controllers to communicate verbally and non-verbally with gestures.

Figure 25: Prototype of a collaborative air traffic control system on tabletops. Image produced from [45]

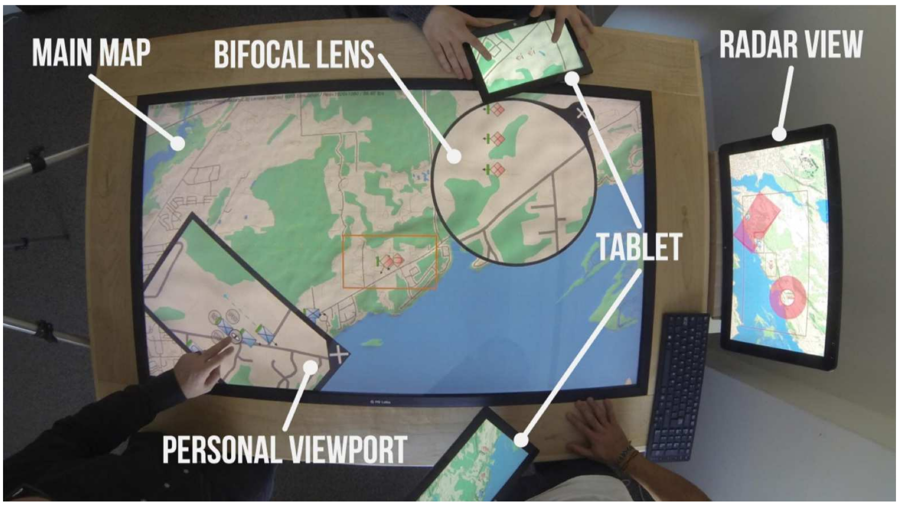


Figure 26: OrMIS: a prototype of a military command and control system. Image produced from [34]

Bortolaso et al. [34] proposed a tabletop system that simulated a military command and control system in order to help in the training of militaries for battlefield management. The current system is composed of a large vertical display and several workstations, the large display gives an overview of the situation, while all the interactions are done from the workstation. The manipulation of this system is complex and it is not designed for collaboration. OrMiS proposed several techniques to allow different degrees of collaboration (See Figure 26). Operators can collaborate closely by interacting directly on the tabletop, a little less closely by using bifocal lenses, and loosely by using personal viewports. Finally, they can work on their own personal display thanks to tablets. The use of these techniques was partially validated in a controlled experiment [26]. The authors compared the use of direct interaction on the tabletop and the bifocal lenses for a path planing task that required users to either work on the same areas together or on a different area in parallel. The results showed that users were faster using direct interaction when they needed to work at the same area and faster with the lenses when they needed to work at different areas.

SUMMARY Studies showed that the use of a tabletop is beneficial for close collaboration in control rooms. Its shared surface allows users to communicate verbally, non-verbally and with gestures [45]. Additionally, participants can work on their own data or collaborate loosely when they work on different areas by using personal displays [34] (like tablets). The shared display is used to share information with colleagues and to work on the same area of the situation; it is thus more adapted for close collaboration [34]. Given this, it is clear that interaction techniques to transfer data between displays will be useful. It would be interesting to verify these findings for wall displays. Wall displays are actually very different from tabletops. Wall displays are bigger, vertical and a privileged orientation. Information on wall displays can be seen from afar, which make them suitable to be used as contextual displays.

2.4.4 *Overall summary and position of my work*

The use of wall displays in control rooms has been envisioned in prevous work, sometimes just as a contextual display which allowed operators to have a shared understanding of the situation, sometimes as an interactive display that allowed direct interaction and displayed detailed information within its context. However, the collaboration with a wall display in a control room has not been studied. Collaboration has been studied in this context using tabletops used when close collaboration was needed. During loose collaboration, more personal displays were used.

In this thesis, I want to study whether an interactive wall can positively impact collaboration in control rooms. The two abstract studies presented in Chapter 4 and Chapter 5 have a broader range of application but are also valid in this specific case. The first confirms what was presented in the OrMiS project for tabletops, that the use of a wall display should be reserved for situation in which close collaboration is needed. The second shows how to encourage closer collaboration using interaction techniques.

Finally, I study more concrete use of a wall display in control rooms. In Chapter 6 I study how to use a UHRIWD for road traffic control, and in Chapter 7 I study how to use a UHRIWD for crisis management, and more specifically, how to enhance team awareness in order to facilitate transition between collaboration degrees.

2.5 CONCLUSION

This chapter presented a review of previous studies showing benefits of wall displays in individual and collaborative contexts. Wall displays have been considered as an interactive surface in a control room, but their impact on collaboration is not yet studied. In the next chapter, I talk about the current tasks and activities performed in control rooms, and about the importance of collaboration in this context.

3 ANALYSIS OF CONTROL ROOM ACTIVITIES

To study the benefits of an UHRIWD on collaboration, I take as a motivation a challenging collaborative environment: command and control. It is an environment which can become stressful, demanding for operators and where collaboration is necessary but should not come at a cost of time or workload.

Previous work has already proposed the use of large interactive displays for control rooms. Nevertheless, none studied the impact these displays had on how operators collaborate. Before we discuss the impact of large interactive displays on collaboration inside control rooms, it is important to understand how collaboration takes place in actual control rooms.

To this purpose, I first visited three road control centers in Paris: the PC Berlier, the PC Bedier and the PC Lutece. I also visited the French center of police operations. In addition to these visits, I interviewed two operators: one nuclear power plant operator and one air traffic operator. Finally, I compared our observations with observations made by other researchers in command and control centers.

3.1 ROAD TRAFFIC CONTROL ROOMS

The cost of traffic jams represents 19 billion euros in France and 124 billion dollars in the United-States of America (USA). It is predicted that these costs will increase by up to 50% by 2030 [57]. One solution to limit this cost is to improve traffic flows. This traffic management is done by operators in dedicated control rooms, that monitor traffic and act on it in case of perturbations.

The road traffic in Paris is monitored by two control centers: the PC Lutece is in charge of monitoring the traffic for the center of Paris. The PC Bedier (previously the PC Berlier) is in charge of the traffic in the peripherique motorway and of the tunnels inside the city.

3.1.1 *PC Lutece*

We visited the PC Lutece twice (See Figure 27). In these two days, I did a semi-structured interview with one traffic engineer and two road traffic controllers. They explained to us the context of road traffic management, their role, and their activities. I was also allowed to stay each time in the control room for an hour in order to observe how road traffic controllers really work.

Figure 27: Control room of the PC Lutece. Source: Polis

The PC Lutece is in charge of traffic monitoring in the centre of Paris. This represents more than 800000 cars a day, and operators also have to deal with more than 2.5 million pedestrian movements. Their system, Système Urbain de Régulation des Feu – Urban Traffic Light Regulation System (SURF) 3, allows them to change the timing of traffic-lights of more than 1500 intersections. It chooses automatically a global traffic-light plan as a function of the context (day, time of the day, etc...). Under normal conditions, the automated system gives priority to public transportation and pedestrian flows.

3.1.1.1 *Layout of the room*

The room is composed of one row of workstations and a large projected screen in front of this row. A workstation is composed of one or several displays which are organized in a semi-circle around the operator. The large display is a large projected display with a low pixel resolution, and at each side of it there are 2 columns of displays that stream live videos from Closed-Circuit Television (CCTV) cameras.

The large projected screen displays a map of the entire street network. The streets are colored in function of their traffic flow measured by induction loops (green for fluid traffic, yellow, orange and red for severe congestion). For each operator, one screen of the workstation displays the same map, which she can zoom in and out of to get more details. She can also interact with the map, for example, to change the traffic-light timing-plan or to report an accident. The other displays of the workstation can display CCTV camera streams or other useful information such as the road traffic conditions in the greater Paris region and suburbs (Île-de-France).

3.1.1.2 *Operators' activities*

Under normal circumstances, there are 3 operators in the control room, each with a specific role:

MONITORING OPERATOR She is in charge of monitoring the traffic and controlling the CCTV cameras. She also has to manage traffic-light

Figure 28: Control room of the PC Berlier

malfunctions, and finally change, if necessary, the traffic-light timing-plan.

MATERIAL OPERATOR She is in charge of monitoring the status of all the equipment, like the induction loops used to count the number of cars. She can, if necessary, also act on the traffic-light timing-plan.

POLICE OPERATOR She is the contact between the operators and the prefecture. She has also access to the police video cameras, which can be useful when incidents happen in areas not covered by traffic cameras.

In case of major accidents, or important events which may greatly impact the traffic (e.g., state visits, marathons, demonstrations), more operators can be present in the control room.

Most of the interventions on traffic during normal activities are done by the system SURF3 that is in charge of choosing the appropriate global traffic-light timing-plan and that suggests timing-plans at a local level for intersections when needed. All local changes suggested by the system are indicated in the map using green arrows. The operators can, if they think it is necessary, manually change the timing-plan. In that case, the intervention is indicated in the map using different colored arrows. Yellow if the system agrees with the intervention, and red if it disagrees.

When an accident is identified, either by an operator or by someone who informs them (e.g, the public or emergency services), the monitoring operator has to check its severity using cameras. She records it on the system and then takes necessary measures as a function of its severity: inform other drivers using Variable Message Sign (VMS) that appear on message boards on the roads, ask the police to close streets, choose to reroute the traffic, or reach first responders. Depending on

Figure 29: Control room of the PC Bedier

the situation, the police operator can be involved, giving access to the police video cameras that cover areas that may not be covered by CCTV traffic cameras. As the police operator doesn't have access to the SURF3 system, close collaboration is needed between her and the monitoring operator. In case of important accidents, the police can decide to take control of the situation, and move operations to their own control room.

The large projected display gives operators an overview of the traffic situation, while their workstation allows them to have a detailed view but also to act on the traffic. Operators currently never stand up to work directly on the projected screen with other operators, but they do stand up in front of the display to present an ongoing situation to important decision makers. They have the possibility to display what they do on the workstation on the projected screen, but they reported doing so rarely.

3.1.2 *PC Berlier & PC Bedier*

We visited PC Berlier once. We did informal interviews using the critical incident technique, trying to identify past memorable incidents in their work, with the control room manager and two operators (See Figure 28). They explained us the specific task of managing the traffic on the Peripheric ring and in the tunnels. We were allowed to stay in the control room for an hour in order to observe how road traffic controllers really work. In 2016, the PC Berlier was closed and replaced by the PC Bedier (See Figure 29). Its role is the same as that of PC Berlier, and we had the opportunity to visit it as well. Both visits are explained in this subsection. Most of what is said here is valid for both PC, and the differences between the two are clarified when necessary.

These PC are in charge of the management of the traffic on the Peripheric ring. This motorway surrounds Paris and handles 1.2 million car movements each day. In 2002, it represented 60% of the traffic in the region. Because of its traffic, the ring is subject to several perturbations: around 16 car breakdowns, and 6 severe accidents per day. The PC is also in charge of the tunnels on the Peripheric ring and inside Paris. Since the Mont-Blanc tunnel fire [54], all tunnels have to be monitored using live-video streams and Automatic Incident Detection (AID).

3.1.2.1 *Layout of the room*

The room is composed of a large projected display, and at its sides, there are several smaller displays that show video streams from video cameras and data streams from sensors in the Peripheric ring and tunnels (See Figure 29). There are two rows of workstations, one for the police and one for the road traffic controllers.

The information displayed on both the projected screen and the workstations are the same as in the PC Lutèce: a road traffic map, video streams from video cameras, and other useful information such as the road traffic conditions inside Paris and a map with the position of all the road traffic cameras.

3.1.2.2 *Operators' activities*

The PC Bedier (and the PC Berlier before) operates 24 hours a day, 7 days a week. Ordinarily, there are two or three road traffic controllers with two specific roles and between 2 and 4 police operators:

THE TRAFFIC OPERATOR She is in charge of monitoring the traffic on the Peripheric ring. She has to identify accidents, warn drivers using the VMS if necessary, and report the accidents in the software. The positions of the VMS are shown on the displayed road map, in white when an operator has displayed a message on the VMS, or in green otherwise. In the PC Berlier, the operator could activate/deactivate the bus lane to and from Charles De Gaulle airport, but it is no longer the case in the PC Bedier. She is also in charge of road equipment maintenance (Road sensors, cameras, ...): she manages the coordination of the maintenance teams with the police, both during the day for small interventions which do not necessitate stopping the traffic, and during the night when part of the ring needs to be closed for large maintenance operations (at least once a week).

THE TUNNEL OPERATOR She is in charge of monitoring the traffic in the tunnels on the Peripheric ring and inside Paris (the latter are not shown on the road map). Each tunnel is under video surveillance and an AID algorithm runs though all of the images. When the algorithm detects a problem, it raises an alarm and shows the relevant video stream to the operator. The operator needs then to acknowledge and verify the alarm, which is either a false alarm (around 90% of the cases), or is a real situation in progress. In the latter case, the operator needs to follow a strict procedure, closing lanes or even the entire tunnel (in case of fire, otherwise complete tunnel closure is usually decided by the police). Even though there is a strict procedure to follow, it is not possible to be prepared for every problem that can happen. One case we were told about was the flood of the tunnel under the Parc des Prince on the Peripheric caused by a burst pipe. In one section of the tunnel there was more than 2 meters of water. This section was closed for 11 hours, and because no procedure was available to deal with such an eventuality, close collaboration with police and firefighters was needed to manage the flood and reroute traffic.

POLICE OPERATOR Along with the road traffic operators, there are between two and four police operators. Their role is to dispatch police patrols in case of accidents in tunnels or on the ring, and stay in contact with the patrol teams on site to coordinate the interventions. These patrols are also called to escort the maintenance teams during planned or unplanned maintenances on the ring, and to block the traffic when sections of it are closed.

When a driver calls the emergency line (either from a fixed telephone post or with their phone), the police is in charge of answering the call, and getting as much information as possible regarding the problem, and its location. During our visit, one driver called from his phone to report an accident he saw, but he wasn't able to give a precise location. The operator answering the phone started repeating the information out loud, implicitly asking the other operators (both road traffic operators and police) to start looking for the accident. This type of collaboration is frequent in this room. As the operators are seated close to each other, they can easily hear what the others are saying and help one another when they can without being asked. In fact, I noticed almost no explicit communication between operators during my visit (except for a few questions from one police operator to the other about a past intervention).

Operators also use the map of the large display to spot accidents before they are reported. One police operator was managing an accident when we visited. He told us that he spotted the accident by noticing a unusual traffic pattern on the traffic map (abnormal traffic congestion in an unexpected location for that time of day). He confirmed the accident using a CCTV camera, and sent a police team on site.

Finally, in case of big accidents (like a fire in a tunnel), a fire fighter operator comes to help the control room coordinate the firefighters and police units on site, along with the traffic.

3.1.3 *Literature*

Collaboration in road traffic control rooms has also been studied in the literature. Zeilstra et al. [219] studied the mental workload in a road traffic control room in the city of Amsterdam. At the time of the study, there were 3 operators, 2 in charge of the traffic in the tunnels and 1 in charge of the traffic in the rest of the city. The control room was composed of 3 workstations, placed in front of a video wall. Then they developed 2 scenarios of control, one which took place during a regular rush hour and one during a rush hour with disturbances, and they calculated the global mental workload for each scenario. They found that the mental workload was 40% greater in the scenario with disturbance, due to the additional tasks that the operators had to do to manage the disturbance. In order to manage that extra workload, the operators needed to prioritize their actions and collaborate.

3.1.4 *Summary*

In the three visited control rooms, the layout is similar: there are several workstations for the operators, a large display with a map of the monitored network (and information like the traffic density), and several screens with CCTV streams. The interaction with the system is only possible through the workstations.

Each operator has a specific task, which is fairly independent so close collaboration with other operators is generally not needed during normal situations. This holds even when the situation deteriorates a little (e.g. if there is a small equipment breakdown to handle). And most communications, in that case, are implicit, consisting mostly in operators speaking out-loud. This allows operators to quickly get necessary information for their task, and it also helps them identify opportunities to help each other without having to be asked. Operators can then deal quickly with the situation and prevent the situation from deteriorating further (for instance, an accident that leads to a pile-up).

However, in the case of a large accident (several severe car accidents, or a fire in a tunnel), other operators can come to the control rooms to help, such as a firefighter operator to help the coordination with the units on-site. During such situations, closer collaboration is needed between operators to coordinate their actions. The lack of precise procedures in such cases also necessitates that they collaborate closely to formulate new and effective strategies. Literature shows that in exceptional situations, the workload of operators increases by

Figure 30: Crisis control room of the French national police. Source: GEND'Info 383

40%, and that collaboration, along with prioritization, helps operators handle this additional workload.

Using a High-Resolution Interactive Wall Display could help them in this last type of situation. First, it can help them coordinate their actions by providing them good group awareness. And secondly, it provides a face-to-face communication space which can help them in planning and formulating strategies to face unusual events.

3.2 POLICE OPERATION CENTRE

3.2.1 *Visit*

In France, all police operations inside or outside the territory are managed from a single operation centre. This operation centre is the link between different agencies, but also between units on site and the government (See Figure 30). It is called Centre de Renseignement Operationel de la Gendarmerie Nationale – Police Operational Centre (CROGend).

We visited the CROGend once with one of the operators, who explained the different activities and the different types of situations they have to face. He illustrated each case with an example. Our visit took place during a period in which the centre wasn't dealing with a specific emergency, and thus we did not see it during a crisis.

3.2.1.1 *Types of supervision*

The CROGend ensures two types of supervision:

REGULAR SUPERVISION This is the most frequent kind of supervision performed by the operation centre when no specific event is in progress. During that time only a few operators are working.

CRISIS SUPERVISION This is activated in case of major events that necessitate the intervention and the coordination of a large amount of units from different agencies. The activation of the crisis unit takes 30 minutes. Examples of such events are:

- Charlie Hebdo terror attack: On the 7th of January 2015 in Paris, the editorial office of the French satyric newspaper Charlie Hebdo is attacked by two terrorists. They managed to escape and were tracked for two days. They were found in a town in the north of Paris. The same day, another terrorist took hostages in a Jewish mini-market. The police launched two coordinated assaults and all terrorists were killed.

- Germanwings A320 crash: On the 24th of March 2015, the Germanwings flight 9525 crashed in the Alps. The crash was caused by the deliberate action of the first-officer. The police led the search and rescue operation and then the investigation to find out the cause of the crash. The crisis unit stayed active for 3 weeks.

- Saint-Quentin-Fallavier terror attack: On the 26th of June 2015 in Saint-Quentin-Fallavier a city near Lyon, a terrorist killed his employer and then drove his van into a gas factory causing an explosion which injured 2 other people.

3.2.1.2 *Layout of the room*

There are two rooms in the operation centre: the main crisis room (See Figure 30), and a secondary one, which is dedicated to regular supervision. They are separated by a large glass wall.

A large wall display composed of 16 screens is in the main room, but it is also seen from the secondary room. In regular supervision, the 4 top screens of the wall are tuned to Television (TV) news channels to monitor national events. In crisis supervision, the news channels are toggled to other TV screens. Instead, the wall is used to share various information from several sources: documents (like a map explaining the current situation or reports), video stream from helicopters or drones, and real-time police operations using dedicated software (map with real-time position of units, remarks from officers, etc...). It is also used to prepare the situation briefing. In that case, everybody collaborates closely to share useful information, but only one person edits the documents.

Each operator has a workstation which is a computer with two displays. By convention, if an operator wants to share information, she shares the right one by projecting it on the wall and keeps the left one for personal work.

Finally, the main room also contains a smartboard. It is used to annotate the real-time map of the situation in order to help produce a new map that will be used in the situation briefings.

3.2.1.3 *Operators' activities*

In regular supervision, only a few operators are present. Their role is to filter information from police reports about operations in progress and from TV news channels (operational media monitoring). They are looking for information about important accidents, Very Important People (VIP) and any fact that can have safety implications. Then, they have to report to their hierarchy about new events or updates about current ones and to provide extra equipment or reinforcements to any units in the territory (like anti-terrorist units).

In the case of crisis supervision, up to 14 people can work in the room depending on the needs. Most of the operators come from the police, but some crises can necessitate the presence of experts from other agencies, like the Air Transport Gendarmerie in the case of the Germanwings crash.

During a crisis, the role of the operators is to act as the link between the command (head of the police, government, president) and the different entities on site. They need to get information about the situation, produce various documents (explanatory text, situation map, timeline) and then do situation briefings to command. These briefings can be very frequent during the peak of a crisis (every 30 minutes).

In general, the units during the operation are managed by several smaller regional centres. Nevertheless, in some situations, the operators of the national centre have to directly manage the units on site. This is the case if the crisis happens in Paris or if it concerns multiple regions at the same time.

Operators have different tasks: produce the documents which will be used in briefings, manage the communication, manage the information requests that come from different units on site. As we said before, some operators are experts coming from specific fields (anti-terrorist, coast guard, air police, criminal experts); in that case, they have their own specific tasks.

Most of the time, the operators stay seated at their workstation. They stand up in front of the wall display only to do tactical meetings or presentations of the work done to important visitors. They also stand up to annotate the smartboard, but this is done generally just by one person.

3.2.2 *Summary*

There are two types of specific situations: regular and crisis supervision. First, during regular supervision, operators monitor information from different sources; they use workstations and monitor TV news channels, and their workload is relatively low.

During crisis supervision, operators use a wall display, a smartboard, and several workstations. Their role is to gather information for the command center or other units on-site, to manage units on-site, and to produce briefing documents (notes + annotated maps).

The wall is used to display information from different sources: video from TV, CCTV, drones, documents, and maps with real time positions of units. The smartboard is used to annotate in real-time a map of the events.

Collaboration during a crisis is essential as there are operators from different agencies with different expertise in the room. Experts manage and coordinate the different agency units, indicate which information from each agency can be useful, and select useful information for the briefing documents.

The use of an interactive wall display that shows all the useful information at the same place could provide a face-to-face communication space to choose which information to put in the briefing notes. Operators could also use it to annotate the map with the real-time position of units, and so be sure to take into account all the useful information while managing units.

3.3 NUCLEAR POWER PLANT

3.3.1 *Interview*

We conducted a critical incident interview with an operator from the power plant of Flamenville in France. During this interview, we asked him questions about his workplace, his activities and how he collaborated in different situations with his colleagues.

In France, more than 70% of the electricity is produced by nuclear power plants. The principle is to use controlled nuclear fission of uranium to heat water to a very high temperature. Due to its high pressure, this water is still in a liquid state. This is called the primary circuit. This primary circuit warms water from a secondary circuit and turns it into steam, that moves a turbine which generates alternative current. This steam is then changed back to liquid state. Due to their particular conditions of temperature and pressure and to their closeness with radioactive material, both circuits are considered as critical and are monitored closely a in dedicated control room.

Figure 31: Control room of the power plant of Flamenville. Source: Reuters

3.3.1.1 *Layout of the room*

Three out of four walls in the room are covered with control and visualization boards that are considered a large physical shared display. The visualization board is a vertical panel on the top part of the walls, and the control board is a horizontal one on the bottom part. Both boards are composed of leds, displays and buttons (See Figure 31).

There are 2 workstations for operators with one screen each. Between the stations, there is a mic system which allows them to do announcements in the power plant. Finally, behind the workstations, there are tables and chairs that are used to do briefing, and to debrief teams during shift changes.

All actions on the system are done through the control board on the physical wall. The workstations provide operators with simulation tools, visualization of the parameters and documentation. In the control rooms of the new power plants, the visualization boards are replaced by a large wall display, and all the controls are done from the workstations.

3.3.1.2 *Operators' activities*

In normal situations, there are two operators in the control room. One is in charge of the primary circuit and a second is in charge of the secondary circuit. Due to the links between the two circuits, each action on one circuit impacts the other.

Operators have different tasks:

- Surveillance: They have to check the different parameters of both circuits: pressure and temperature.
- Control the power: Change the production of power as a function of the energy needs of the population.

- Maintenance: maintenance is planned for various equipment in the power plant, and is not done at the same time for safety reasons. It can require the shutting down of the whole power plant. For example, for a check of the primary system, pressure has to go from 150 bar to 1 bar, and the temperature from 300 °C to 20 °C, a process that lasts up to 10 days and has to be monitored carefully by operators.

The daily activities of the operators do not demand a lot of actions from them. In order to stay alert, they are required to stand up and check the parameters of the visualization board every two hours. In between, if they have a doubt about a parameter, they stand up to check the visualization board. This action serves as a signal for their partner who starts checking her own system.

Their activities increase greatly in case of abnormal events (sensor malfunctions, parameters that vary too much). During these events operators have to switch to manual control and follow specific procedures. If they don't switch to manual control, the system's automated safety procedures may take drastic action, like to shut down the reactor. Because of the time constraint and the high cognitive resources needed, explicit communication between operators is not always possible. As they have to stand up in front of the control board to act on the system, their position in front of the board is an indication for their partner about their current action. Apart from this implicit communication, each procedure contains explicit communication points between operators to encourage them to share information that can be useful for both. Finally, in this situation, another operator and the room supervisor may come to help and double check what actions have been taken.

The procedures followed in the powerplant tend to be very specific; nevertheless. They cannot account for all possible issues that arise in a crisis. One month before the interview, the operator underwent a transformer breakdown during a maintenance stop. The transformer is in charge of providing power to the power plant when it is in maintenance stop. The operators were in charge of turning on the emergency power generator, and had to check all the equipment, especially the cooling system of the reactor which was opened for maintenance. Because the emergency power generator has a limited capacity, only vital equipment was powered. In the control room, most lights, the workstations and several other displays were off. But in the plant, this caused the elevators to stop with workers getting trapped. Operators had to manage their evacuation, which was very time consuming, and not planned in the procedure.

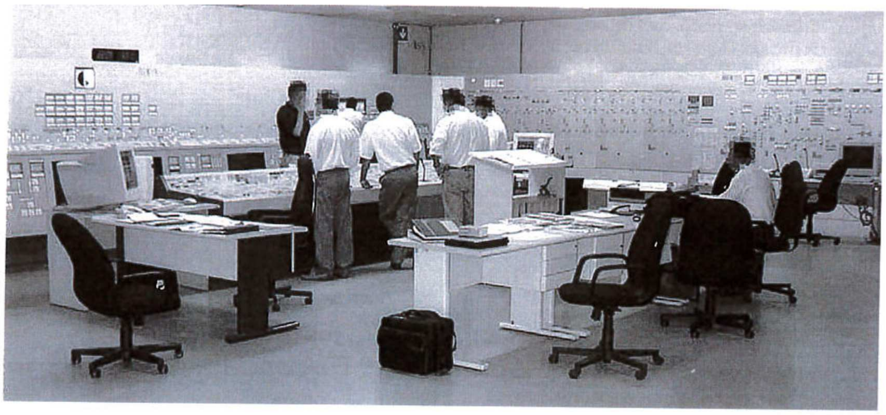


Figure 32: Control room of a power plant in Brazil. Image produces from [36]

3.3.2 *Literature*

Some studies have focused their research on collaboration in nuclear power plants control rooms.

De Carvalho [36] studied how operators handle micro incidents during normal operation in a field study in a Brazilian power plant during simulator training. The layout was similar to the one described in our interview. The procedure was that for any incidents, operators had to stand up to act on the shared physical display. But actually, from that point onward, operators stopped following the procedure and started collaborating to find an appropriate solution. The tasks were redistributed among operators in function of the needs.

A similar situation has been observed by Merand et al. [129], again in a simulator training. They observed three teams dealing with a failure of the cooling system of the reactor and studied the role of communication between team members in the resolution of the issue. Because of the different roles and information owned by each operator, communication allowed them to share the same mental model, but also to confront their opinions and to make good decisions. They found that the team that communicated more increased their understanding of the situation. Because they understood the situation, operators took more liberty with the procedures and solved the issue quickly. The team which communicated less tended to keep following the procedure for normal operation and failed to solve the issue.

Stubler and O'Hara studied computer-based control rooms [181], in which operators can have access to the parameters they monitor and act on parameters on their personal workstations. As it is also mentioned in our interview, these types of control rooms are considered as the next generation of control rooms after the panel-based ones (See Figure 31). The authors argued in their paper that it was important to provide operators with group-view displays in this type of control room. Group-view displays are displays which present information to multiple people at the same time. It could be just a large display visible from the entire control room, or several individual displays. They suggested that group displays were important to provide an overview of the state of the power plant, but more importantly, that it could enhance crew performance. First, to support teamwork in such complex environments, it was important to provide operators with the activities of others. With individual workstations, operators are more isolated than in panel-based control rooms. They advocated that group-view displays could allow operators to monitor others' tasks, and ongoing collaborations, and provide them with enough information to detect a situation in which they could make a contribution. Finally they claimed that such displays could help operators do one task collaboratively by providing them with a common view and facilitating discussions.

Recently, Lee et al. [114] studied the impact of the setup of control rooms on the team situation awareness. They compared how teams handled a Loss Of Coolant Accident (LOCA) in a panel-based control room and in a computer-based control room with a large display. They measured the amount of different types of conversations: inquiry, announcement, judgment, and suggestion. The results showed that there were more conversations of type "announcement" with the computer-based control room. This was due to the room leader who read out-loud the important steps of procedures and called out important information. Operators in this control room could access more information compared to the panel-based one, and the leader was concerned that the operators were being distracted by non-relevant information. More effort was necessary to synchronize the operators' actions. There were also more conversations of type "inquiry"; this was due to the fact that the room leader had to follow and check all the steps of the procedures on a specific interface (which was not the case on the panel-based control room). Because of the necessity to officially check a step, the leader felt the need to ask the operators for confirmation. Authors suggested that because the computer-based control room provided operators with more information regarding the plant's status and allowed a more formal follow-up of the procedure, it led to a better individual situation awareness of the situation. However, because they were isolated at their workstation, they could not really see what the others were doing, and more communication was needed to synchronize their actions or to check information.

Finally, Myers and Jamieson [137] reviewed the different group-view display alternatives to provide an overview of the state of the plant, and also enhanced two types of collaboration: on different tasks, and on the same one. The authors argued that the use of several mobile devices could be detrimental for collaboration, as it was not a shared display. On the other hand, they claimed that while a tabletop may be able to enhance coordination and verbal and gesturing communication, it was not possible to see it from afar, and so it could not be used as a monitoring display. The last alternative was to use a large touchscreen display. Because it is a large display, authors argued operators could used it as a monitoring screen, but thanks to its interactivity it may be able to enhance coordination and communication.

3.3.3 *Summary*

There are 2 types of layouts for power plant control rooms. The first one is present in the older power plants. It consists in 3 out 4 four walls used as physical large displays with controls and small visualizations of parameters. Two workstations allow the operators to do simulations and look for documentation, but all the actions on the systems have to be done on the walls. The second type exists in more recent power plants. It consists of a large wall display with visualizations of the parameters of the system and of individual workstations. All the parameters can be monitored from these workstations, and the actions on the system are done from them. The individual situation awareness of operators is improved because information regarding the different parameters is easy to get.

There are typically two operators, each of them with a specific interdependent task. Routine standing in front of the wall is frequent to force the operators to look at every parameter. Besides that, an operator stands-up to check a parameter each times he thinks there is an issue, implicitly warning the other operator to start looking at her own parameters. The position of the operator in front of the wall gives information to the other about what she is doing, avoiding costly explicit communication. However, this is no longer the case with the new layout, as operators don't move away from their workstation. This leads to a higher need for explicit communication to coordinate actions.

During low workload situations, all the actions on the system are done by the system itself; the operators just have to monitor it. When there is an issue, or during a maintenance action, operators have to manually act on the power plant, and their workload increases significantly. Most of the time they have to follow a procedure. However, some cases are not covered. In that case, they have to collaborate and communicate about the situation to first build a shared mental model of the situation, and also to expose their opinion on how to deal with the situation. Keep following the procedure when the situation doesn't fit with it can be dangerous and aggravate the situation.

By using a High-Resolution Interactive Wall Display, it would be possible to take the best of the two layouts presented at the beginning. Thanks to its high resolution, it would be possible to display every visualization necessary on it and use various algorithms on it to augment them. The interactivity would allow operators to stand up

Figure 33: Control tower of Charles de Gaulle airport. At the foreground there is the tower supervisor, and in the background we can see LOC and SOL controllers. Source: Direction Générale de l'Aviation Civile

and to interact directly on the wall as is the case in old power plants and to thus benefit from group awareness and face-to-face communication available there.

3.4 AIR TRAFFIC CONTROL

3.4.1 *Interview*

We conducted a critical incident interview with an air traffic controller at the control tower of Charles De Gaulle airport in Paris. During this interview, we asked him questions about his workplace, his activities and how he collaborated in different situations with his colleagues.

Charles De Gaulle is the biggest airport in France, it has 2 control towers, and each of them is in charge of 2 runways. 4 controllers work in each tower: 1 SOL controller, 2 LOC controllers and 1 tower coordinator. In case of light traffic, only 1 SOL and 1 LOC controller are needed. The role of each controller is explained later in this section.

3.4.1.1 *Layout of the room*

The control towers in Charles De Gaulle do not have a large visualization wall, but they are designed to provide a view of the actual runways and the main taxiways[1], which can be considered as a global visualization (see Figure 33). There are workstations for each

1 a route that allows an aircraft to move between a runway and the parking space

controller. Their configuration is different depending on the role of the controller.

The SOL position is composed of 2 radar screens, one is used as an overview and one is zoomed into the used holding points[2]. Both of these configurations can be changed, but they rarely are. There are 2 other screens, one with general documentation, and one with information regarding ground operations.

The LOC position is composed of 2 radar screens. One is for the ground radar to have information about aircraft that are going to take off, and one is for the approach radar, to have information about aircraft that are going to land. There are 2 other screens, one for the arrival manager[3] and one with the weather forecast.

Finally, at all the positions, there are 2 phones for keeping in contact with other control centres or ground operations.

3.4.1.2 *Operators' activities*

SOL CONTROLLER She is in charge of the aircraft between the parking space and the runway. If there are 2, one is in charge of the holding points (by default there are 2) and the other is in charge of giving runway clearances.

LOC CONTROLLER She is in charge of the landing and take-off of the aircraft. In case of incidents, she is in charge of managing the go-around[4] of an aircrafts. Finally, she is in charge of planning the runway inspection, during which airport vehicles go on the runway to check for objects.

TOWER COORDINATOR She is in charge of the management of the control of the traffic. She gives all the necessary information to her team: runway configuration, runway pressure (number of aircraft to take care of) and possible rerouting. Finally, she is in contact with the approach control centre and parking space manager.

Most collaborations happen between the LOC and the SOL controllers. As the room for maneuver is tight for the LOC (it is difficult to interrupt a landing), the role of the SOL is to simplify her job. As soon as the SOL has useful information, like the switch of a holding point, she has to transmit it. In case of light traffic, the SOL informs the LOC about the incoming aircraft, and sends them early on the LOC frequency. In case of heavy traffic, the SOL tries to avoid disturbing the LOC with explicit communication.

2 A holding point is a location on the taxyway at which the aircraft has to stop and wait for the clearance of the controller to resume. Holding points are generally at the entrance of the runways, they can also be at important intersections.
3 A tool that helps the controller sequencing the aircraft arriving at the airport.
4 Aborted landing of an aircraft that is on final approach.

Various ways of implicitly communicating are used in the control tower:

- The SOL can highlight the used holding points in the radar through the system.
- Warnings can be put on an aircraft on the radar in the system. It is also possible to just make one stand out, which doesn't mean that there is an emergency, but just that it needs a check.
- The SOL can write information about flights on their paper strip[5], and she gives them to the LOC in a specific order.

In case of an emergency (like an aircraft which lands in the wrong runway, or an aircraft which has a priority to land), controllers will try to avoid explicit communication: the LOC gives all the necessary information out-loud and the SOL has to understand what she should do. If necessary, another controller can join any time to help.

For example, a few weeks before the interview, the controller had an aircraft with landing gears that wouldn't retract. The LOC had to deal with the aircraft and integrated it in the approach circuit to make it land. Meanwhile, the SOL was managing the arrival of the firefighters, who in that case shouldn't be slowed down on their path[6]. Both controllers had to coordinate to find where the firefighters should meet the aircraft.

Another example was a sick passenger in an aircraft. The LOC had to land the aircraft as soon as possible, and the SOL to manage the aircraft between the runway and the parking space. Such an aircraft shouldn't have to slow down at any time.

3.4.2 *Literature*

Most studies of air traffic control rooms have been done in En-Route control centres. Controllers in it are in charge of aircrafts that have already reached their cruise level. They can see them only on their radar screen and contact them by radio. This control is very different from the one done in a control tower.

The layout of the control room is very similar in all the centres, it contains several control positions which consist in two workstations (See Figure 34). Each workstation has a large radar display and other smaller displays. Finally, there is a stripboard to position the strips, which can be physical or digital (Few organizations choose to get rid of the strips, but it is not the subject of this thesis).

There are two controllers at one control position: the tactic controller is in charge of contacting the aircraft, managing the guidance

5 piece of paper that represents an aircraft and contains all the useful information

6 When in an intervention, firefighters have a high priority on the taxiway, controllers have to make sure they are not slowed down by any other aircraft/vehicles.

Figure 34: One control position (type ODS). Image produces from [196]

and separation and resolving conflicts (equivalent to the LOC in a control tower). The planner controller is in charge of the coordination with other positions, integrating new flights and helping the tactic controller by early spotting the possible conflicts (equivalent to the SOL in a control tower).

Bressole et al. [31] observed how air traffic controllers solved conflicts between aircrafts in a simulated environment. A conflicts in ATC is a time-constrained situation, controllers have to act quickly, and each communication during this situation is costly and should be optimized (they have to make sure they won't have to repeat themselves). They measured the amount of verbal and non-verbal communication, and they found that in these situations, controllers mostly used verbal and non-verbal communication simultaneously. Non-verbal allowed them to add additional information for the recipient (like using deictic gestures), and it also gave context about the conversation to other controllers listening in. In specific situations, they used only non-verbal communication, if the verbal channel was already in use (a controller talking to a pilot), or if a controller wanted to communicate with another that seemed focused on an important task and did not want to be disturbed. The authors concluded that in such critical situations, it is important to have several communication channels.

Mackay [122] studied this non-verbal communication in 2 ethnographic studies in 5 air traffic control centres in France and the Netherlands. She focused on the use of paper strips which allowed complex communication without disturbing the recipient. It was particularly used in high workload situations, during peak of traffic or unusual events. Several controllers developed ways to provide the degree of importance of their message to the recipient without disturbing her. For example, they put the strip on the peripheral visual field of their partner if the message was not urgent but should be taken care of,

Figure 35: New organization of the control room proposed by the MAMMI project. Image produces from [197]

and in the focus of their partner's visual field if the message was urgent.

A more recent observation of collaboration in ATC centre in France has been performed by Vales et al. [196]. They noticed that even if there was not much collaboration in low traffic periods, controllers still mutually monitored each other's work. This allowed a better detection of errors and a higher shared understanding of the situation. In cases of high workload, the collaboration increased, with the planner controller starting to take on part of the tactic controller's job. In extreme situations, a third controller can come to help, immersing herself in the situation by doing easy tasks at first. In that case, there was an increase of vocal communication as the controllers needed to synchronized their actions and bring the newcomer up to speed.

Europe is expected to see an increase of air traffic in the coming years. To face it, European countries decided to unify their skies in a project called Single European Sky ATM Research (SESAR). SESAR identified several issues regarding collaboration between controllers, one being that the actual layout of the room (several workstations) doesn't support collaboration which is necessary, especially in high workload situations. Vales et al., with the MAMMI project [197] proposed a solution to that based on their observations of current control rooms [196] (presented below). First, they proposed a new organization of the control room, with a dispatcher who monitored the traffic flows, and several experts who solved the different issues. This led to a suggestion for a new control room, where the dispatcher used an interactive tabletop, and the experts used workstations disposed around it (see Figure 35). They also had mobile devices to be able to move in the room. Finally, a wall display was there to display contextual information, but, if interactive, it could be used by experts to collaborate. The authors demonstrated its use on a scenario: a storm in a sector.

The dispatcher chose a few experts to work on the rerouting of the aircrafts involved. They could use one of the shared surfaces (tabletop or wall display) to collaboratively design a solution. The application of the solution could be monitored by one expert on his workstation.

3.4.3 *Summary*

In all the studies and our interview, the control room was similar. There are several individual workstations and no shared displays. However, the displays are close to each other, and one controller can point at something on her neighbor's screen (see Figure 34). Some projects focus on re-organizing the control room and integrating more interactive surfaces like a tabletop and a large display (see Figure 35).

In most cases, controllers work in pairs, but can be three in a case of high workload. During low workload, there is little verbal communication, mostly explicit in that case. Controllers still monitor the actions of others, in order to detect potential errors and to build a shared understanding of the situation. In a case of high workload, like high traffic or emergency situations, the need for collaboration increases. Controllers use more implicit verbal communication, e.g. outline their actions out loud. They also use more non-verbal communication (deictic gestures or the use of other artifacts). When used with verbal communication, non-verbal adds information and gives context to controllers not involved in the conversation but still interested in it. It is also used if the recipient is already busy talking on the radio or focused on a highly cognitive task.

Close collaboration is very important in high workload situations; however, the interview and the literature show that controllers can't afford the cost of explicit verbal communication. The displays in the control room should help the controllers build a shared understanding of the situation easily, and provide group awareness. This group awareness should allow operators to gather information about what the others are doing without communication.

As envisioned by Vales et al. [197], the use of a shared UHRIWD could provide this group awareness. I think that a wall display could encourage close collaboration during a high workload situation and allow controllers to deal faster with the situation. In low workload situations, the wall could help improve shared understanding of the situation.

3.5 PUBLIC TRANSPORTATION MANAGEMENT

3.5.1 *Literature*

Most large cities have a subway system and sometimes a network of suburban trains. To be efficient, their traffic has to be optimized, and

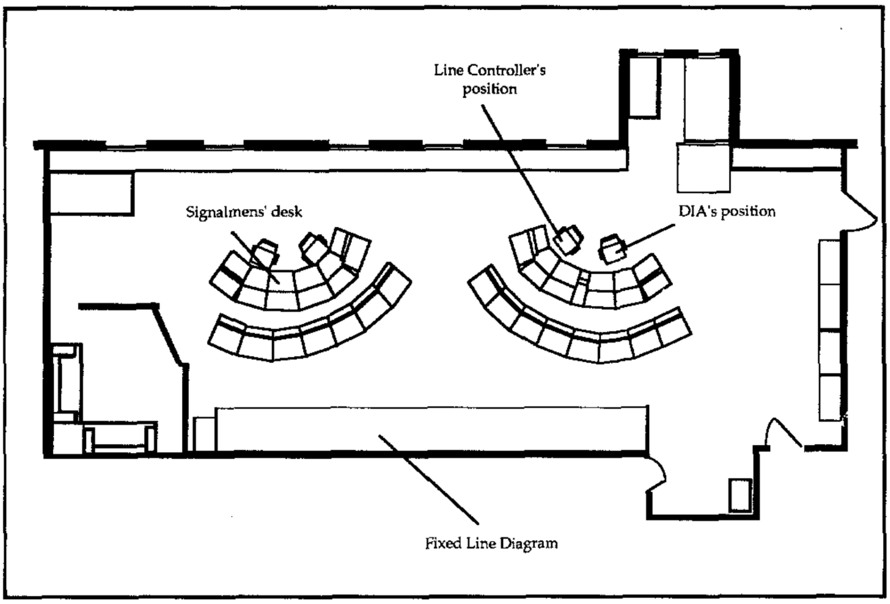


Figure 36: The Bakerloo line control room. Image produces from [78]

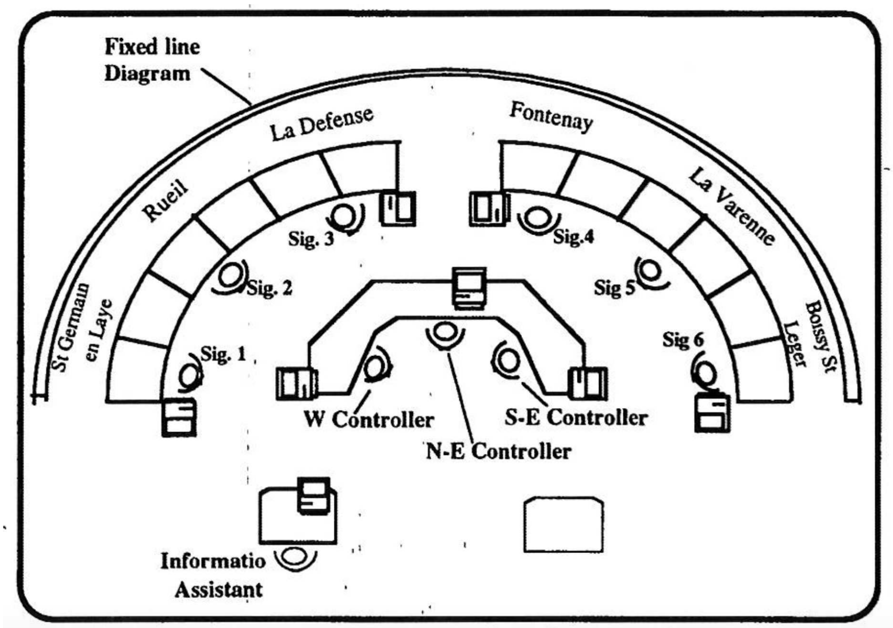


Figure 37: The RER A line control room. Image produces from [65]

an incident can provoke important delays along the lines. To avoid that, each line is monitored in a control room by operators.

Heath and Luff did an ethnographic study in the control room of the Bakerloo line of the London subway [78]. The control room was composed of two separate blocks of two workstations with several displays and a large fixed line diagram visualization (See Figure 36). The large visualization allowed the operators to have a vision of the traffic on the line, and it gave them context about the interventions of the other operators. Each operator had a specific task in the control room: communication with the passengers, with the driver or rescheduling trains in case of a disturbance. Nevertheless, their tasks were closely coupled, and their interventions had to be coordinated. For example, if a controller asked a driver to reverse at a certain station, another controller had to do a public announcement. To coordinate themselves, they monitored each other's actions by overhearing radio conversations, or other controllers talking to themselves, and by looking at where controllers were looking on the shared visualization. This group awareness was very important, especially during emergency situations, when they didn't have the time to communicate explicitly and they had to act quickly.

Filippi et al. [65] observed how operators collaborated in the control room of the RER A, a high speed suburban train in Paris. The control room was composed of several workstations and a large visualization which showed the real-time state of the traffic on the line (See Figure 37). The line was divided in 3 sectors, each of them controlled by a controller. Each controller was assisted by 3 other operators. In normal operation, the controllers didn't collaborate a lot, each of them stayed on her sector. In cases of an incident in one sector (e.g., a breakdown of one train), the controller in charge of the sector started by first understanding the situation before trying to find a solution. In the mean time, the other controllers handled the traffic around the incident location, managed secondary issues related with the incident and finally provided the first operator with advice and information. In this situation, controllers needed to have a high group awareness, to know what happened globally and what the others were doing. There wasn't a complete procedure in case of incidents (as each incident is different), so controllers needed to collaborate to find the best solution in each situation.

Wahlström et al. chose to focus on a high workload situation and observed the rehearsal of a major subway accident in Helsinki [203] in a control room. There were 4 operators in the control room, and ordinarily they all had different tasks to do. When they learned about the accident, they started following a general procedure: an operator tried to get precise information about the traffic around the incident, another contacted the emergency centre, and finally, the others managed the traffic around it. They had to closely collaborate, as some information were accessible only by one operator. For example, the fact that the electricity was on or off, or other technical details were known only by the Tec Controller, but it was an interesting information for the controller handling directly the accident to know. They couldn't afford explicit communication, so they tried to give information to the others by talking out-loud and repeating information they heard from the radio.

3.5.2 *Summary*

Public transportation control rooms are typically composed of a large visualization (usually a physical display) which gives a global vision of the line to all the operators. It also allows operators to acquire context when others are talking.

Each operator has their own task to do (in charge of the traffic, or in charge of the equipment), and specific information related to their task. During low workload situations, they must monitor, and only occasionally act on the system. Actions usually need coordination from different operators, as the operators act on a different part of the system and have different information. They also monitor each other's actions to build a shared understanding of the situation. This monitoring can be done by overhearing conversations of controllers talking out loud, or just by seeing where other controllers are looking.

When incidents happen, controllers are required to do more actions, which increases their workload. In that case, collaboration is needed for different reasons. First, it is needed for coordinating their actions, then to get information from others, and finally to find the best solution in case no procedure exists to solve the situation. Due to the high workload and time constraints, operators have less time to communicate explicitly.

Using a UHRIWD, controllers could engage in face-to-face collaboration in this high workload situations, thanks to non-verbal communication. Additionally, thanks to the awareness of others' activities, operators could easily gather information about what they are doing, to build a shared understanding of the situation. It could also be used by operators to be proactive, one operator could predict that another operator will need a specific information (by knowing what action she is doing), and directly share it on the wall without explicit communication.

3.6 Crisis management

3.6.1 *Literature*

The management of an important disaster requires the intervention of several agencies for a period that can last a few days. In order to

Figure 38: Overview of the situation room with the conference table in the middle of the room and workstations along the whiteboard covered walls. Image produces from [111]

coordinate all the agencies and give the necessary information to anyone who needs it, specific control rooms are set up. They are called situation room, or Emergency Operation Centre (EOC).

Landgren and Bergstrand [111] did an ethnographic study of one situation room. The room was composed of several tables on which laptops or desktop computers could be put on, and of a large digital whiteboard, which displayed a map of the situation on which operators can add relevant information (See Figure 38). The digital whiteboard allowed operators to have a big picture of the situation. The task of the operators was first to monitor the situation, and then to explore different possible solutions to manage it, and to predict the various consequences of the situation. This exploration required collaboration between operators with different roles. Finally, there were frequent big meetings, in which each operator presented the latest development of the situation. During these meetings, they upgraded the situation on the digital whiteboard. The procedures to deal with disasters were very general and of limited use for each specific case.

Fischer et al. [66] did an ethnographic study of a disaster response organization: Rescue Global. One difference with the previous paper is that they directly install their control room on site. They had several laptops and a large map of the concerned area on paper was put on a table. Physical overlays were used to add information on it. They had 2 overlays, one to put information about the situation and one to put information about the decisions taken. During a crisis, there were several phases in which operators had to gather information and worked on their own. Then there were also phases in which several of them collaborated around the table. Either one of them briefed the other about a specific task or situation, or they talked about a specific issue trying to make a decision. Because of the uncertainty of the situation, the authors suggested that collaboration helped operators make decisions as each of them added to the discussion their information and own opinion.

3.6.2 *Summary*

Due to their ephemeral nature, the crisis management control rooms have a more basic setup. Most of them are composed of several laptop/workstations, and some have a digital whiteboard to display and interact with a map of the location of the crisis. However, even when there is no such digital display, there is a physical map, which can be in some way annotated.

The operators can come from several agencies (fire fighter, police, road traffic, etc...), they have different tasks and access to different information. Their overall goal is to monitor the situation and handle it in real-time. When possible, they try to predict future events and find a way to handle them.

Some actions necessitate a collaboration between several operators, either because different roles are needed, or because discussions are needed due to the uncertainty of the situation. Awareness of what other are doing can help operators in being proactive: they can decide to act, or share information by seeing what another operator is working on.

Finally, several big meetings are held during the crisis. Their purpose is to upgrade the situation, and also to plan for important decisions about the next action.

A wall display could help to start the collaboration because it provides easily awareness of others, and provides a face-to-face collaboration space. It could help also during big meetings in the planning phase: if everyone is standing in front of it, it could encourage everyone to be more involved and have more debate and more quality discussion before a decision.

3.7 OIL AND GAS PIPELINES SYSTEM

3.7.1 *Literature*

The last domain I will talk about is the monitoring of oil and gas pipelines in dedicated control rooms. Meshkati [130] studied the factors that can affect operators' performance in a western USA pipeline control room. In normal operation, operators had to monitor between 7 and 9 pipelines. There was little communication between them, and all operations followed pre-planned routines. But when there was an incident, like for example a leak, in addition to their regular tasks they had to first diagnose the leak and then handle the response (cut the flow in the involved pipeline, send a maintenance team, etc...).

Incidents brought uncertainty with them and pre-planned routines couldn't cope with this sort of situation. This led to a higher mental workload, and to more communication between the operators. This high workload led to more errors, incorrect evaluations of the situation and a slowness to take decisions.

3.7.2 *Summary*

Similarly to the previous studies, the oil and gas pipeline monitoring is divided into low and high workload situation. During the low workload situations, operators mostly need to monitor the system, and can follow pre-planned routines. When incidents happen, the workload increases significantly, the situation become more uncertain, and routines are not enough to deal with it.

Collaboration in this situation leads to better situation assessment and so to better decision making. A wall display could, in this high workload situation, improve the collaboration and make it less costly by providing a face-to-face communication space.

3.8 CHAPTER SUMMARY

Based on observations, interviews and a literature review, we now have a clear idea about the activities in a control room. More especially, we know why and how operators collaborate.

I first summarize the type of layout found in a control room, and then the activities done by the operators. Finally, I explain why the use of a UHRIWD can be useful in such contexts.

3.8.1 *Layout of the room*

With a few exceptions (e.g., air traffic control room), the layout of control rooms is very similar in the different domains. Operators work in front of their individual workstation, and there is a large visualization, seen by everybody in the room, that is not interactive. One exception to that is the physical panels in old nuclear power plants. However they are switching for large non-interactive wall displays to benefit from the advantages of having digital screens (See Section 3.3.1). This large visualization gives a contextual view of the situation, and it allows operators to maintain a big picture of it. On the other hand, the workstation gives the operators a detailed view of the situation at a specific location, and it also allows them to act on it. For example, in the road control, the traffic of the entire road-network is shown in the projected large screen. While on the workstation, operators can pan and zoom, and do actions on it (e.g., like change the traffic-light plan). The workstations are also used to display additional information about the situation, and as a non-shared display. For example in the police operation centre, the operators use one of their display for non-shared work and share the other one with their colleagues by projecting it on the large screen.

3.8.2 *Operators activities*

I identified two types of situations in control rooms. For each situation, the activities, but also the types of collaboration are different.

I call the first situation *Normal situation*. This is the situation when the system operates normally, without any major incidents. Small incidents can happen during this type of situation, but operators handle them quickly and go back to normal operations. In this type of situation, each operator has a precise task to do, which mainly consists in monitoring a part of the system. Specific procedures are followed, that allow operators to act on the system without precise knowledge of all the parts of the system.

However, even during this time, operators monitor each other's actions to have an approximate shared mental model of the system. There is little explicit communication between them, most of it is implicit, like listening to other operators talking out loud, or identifying where others are looking.

In general, the collaboration is loose, and procedures are designed to limit the need for intense collaboration during normal operations.

The second type of situation is what I call *Exceptional situation*. It is a situation in which, because of an unusual event or an overload, the monitored system is in a downgraded mode. Examples include flood of the tunnel under the Parc des Princes in Paris, or a loss of electrical power in the power plant.

In this type of situation, operators need to take action to help the system recover, or in some extreme cases completely shut it down. Extreme situations increase the workload of operators, as they still need to do their usual tasks and have to perform additional ones to handle the situation. Then, the additional tasks require a more global understanding of the system's state, and so information and actions from other operators. For instance, when closing a tunnel because of a fire, the tunnel operator needs to assess the impact on the traffic and how to reroute it (global understanding of the system state), and also start coordinating with the police operators to organize the rerouting and the intervention of the firefighters (coordination with other operators). Thus, exceptional situations require more coordination from operators, and so, more awareness of what others are currently doing.

Additionally, the original event responsible for an exceptional situation (e.g., the cause of the flood for the Parc des Princes) is often not known from the beginning. This makes the situation uncertain, and so operators can not always find an adequate procedure to follow. Close collaboration is needed in that case, to first consolidate all available information about the situation, and to then hypothesize about the causes and formulate a strategy to solve it.

To sum up, compared to normal situations, exceptional situations require more coordination and more communication, all while dealing with time constraints (it is important that operators prevent the situation from worsening) with a higher than normal workload.

3.8.3 *Use of a Ultra High-Resolution Interactive Wall Display*

While the use of tabletops for control rooms has already been suggested, I believe that UHRIWD could be useful in control room context as they could prove useful in both *Normal* and *Exceptional* situations. First, they could be used as contextual displays in the *Normal situation*, similarly to large displays in current control rooms.

In the *Exceptional situation*, their high pixel resolution and their interactivity could allow operators to stand up and directly interact with them up-close. This would provide a face-to-face collaboration space which should allow for less costly communication and coordination than across different workstations as is currently done. Finally, due to their central position in the room, operators, standing, but also seated, could easily see what their colleagues, working on the wall, are currently focusing on, providing increased awareness of the actions of others, as it is currently done in power plants' control rooms (See Section 3.3.1).

To conclude, I think that the use of UHRIWD could encourage operators to collaborate more closely, which could facilitate coordination and planning of actions, helping to deal with extreme situations more efficiently.

To this end, in the next chapter, I present our first study which qualitatively assesses the impact of display types (shared vs. workstations) on coordination for a low-level task.

4 IMPACT OF A SHARED INTERACTIVE DISPLAY ON COLLABORATION

In the previous chapter, I showed that close collaboration is essential in control rooms, especially in exceptional situations. I believe that the actual layout of control rooms does not encourage close collaboration and that using a shared interactive surface instead of several individual desktops as a collaborative space is better suited to these situations.

In Chapter 2 I reviewed previous work regarding the comparison of collaboration on a shared display and on individual ones, and I discussed how there are no empirical studies that assessed quantitatively the impact of a shared display on collaboration compared to several non-shared ones. In this chapter, I described a laboratory experiment in which I compared the use of a shared display with the use of several individual desktops on a collaborative path-finding task.

Main portions of this chapter were previously published in [151][1].

4.1 INTRODUCTION

As it was stated in the introduction, large shared displays are often considered well-suited for collaboration. Their large size allows multiple users to interact simultaneously [144], collaborators can easily define personal and shared territories [97], and can choose to work close or far from each other [204]. They facilitate face-to-face communication and deictic references [119], and provide awareness of actions of others [187].

Empirical studies support the idea that large displays foster collaboration. Nevertheless, to our knowledge, no study quantitatively compares collaboration using a large vertical display, with a setup that doesn't possess its characteristics, i.e., the large and shared surface. In this chapter, we measure performance and coordination differences when pairs use a large display, compared to two desktops that share a common view. The large shared surface is an area of 2×1.5 meters (of a larger display, Figure 39), a size that users can comfortably reach with limited physical movements. The two desktops are motivated by setups where collaborators use individual workstations (e.g., command and control centers, see Chapter 3), that are often dis-

1 Thus any use of "we" in this chapter refers to me, Anastasia Bezerianos and Olivier Chapuis

tant and cannot support deictic communication, but allow for verbal communication (Figure 39).

To quantitatively study collaboration, we chose an abstract and simple task, to better control task difficulty across setups, and to allow for multiple repetitions. Inspired by previous work on collaboration [90, 186] we used a simplified path-finding task with constraints. We expected our pairs to develop collaboration strategies over multiple trials, that likely differ across setups, eventually reducing the need for coordination and decision making that are essential in collaboration [126]. We did not provide any training to our participants, but rather compared the learning phase across settings, as this is where pairs need to communicate and coordinate to improve their strategy. Learning rate has been used in the past as a measure of coordination [70]. To study possible trade-offs between the setups, we also measured other metrics that could shed light to differences in collaboration, such as the amount of communication between pairs and their coordination strategies.

Results did not indicate a significant difference in learning between setups, but pairs were generally faster using desktops. Nevertheless, the quality of the solution, defined as the number of corrections needed to reach an optimal solution that meets the imposed constraints, was more consistent with the large display, and pairs communicated and planned more ahead of time in this setup. With desktops, pairs divided the task as much as possible, requiring less communication, and affecting their quality of work.

4.2 EXPERIMENT

There is a lack of quantitative studies that attempt to objectively measure differences in how pairs use a large vertical surface, compared to a setup of two desktops showing the same view, that does not have the main characteristics of large displays (large and shared surface) that are considered beneficial for collaboration. These two conditions represent the extrema of a continuum of possible co-located collaboration setups. We take a step in that direction.

We chose to use touch as input for the shared display, as it provides direct interaction and better group awareness, which are accepted benefits of this technology [99]. As these cues are not supported in desktops, we provided awareness of others through multiple cursors, where both cursors were visible on both desktops.

Workstation layouts in control rooms can vary greatly, from one long line or semicircle of workstations, to several rows, and often operators cannot see each others' screen [65, 78, 109, 173, 175] (See Chapter 3). In our desktop condition, participants were positioned such that they could not see each other's screen, in order to represent a worst-case layout in terms of collaboration.

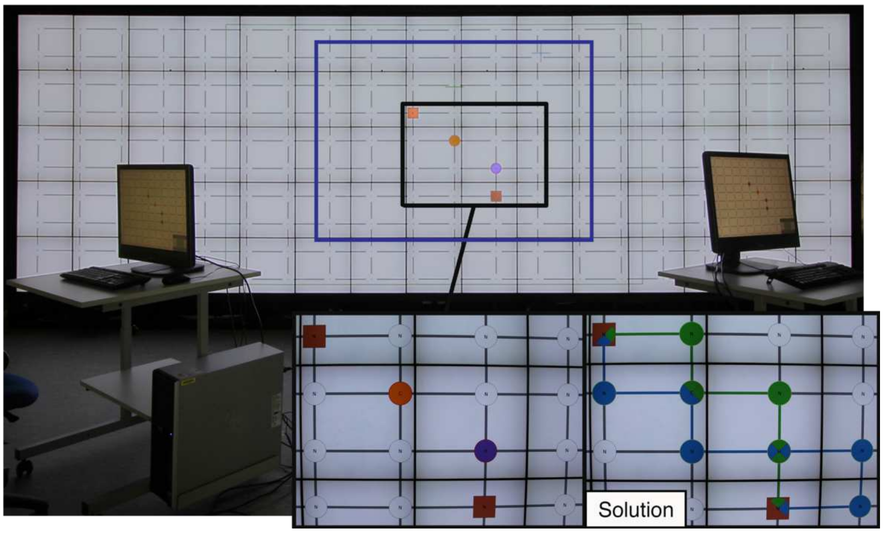


Figure 39: Setup of the experiment, with both conditions: large display, and two desktops with a common view (the large display was off in the two desktops condition and vice versa). The blue rectangle represents the effective area of interaction for all trials during the experiment. Left cut-out shows a close-up of a task, and right a possible solution.

4.2.1 *Task*

For our quantitative study, we needed a task that is abstract and simple enough to allow us to control task difficulty across setups and multiple repetitions per setup. Additionally, we wanted to avoiding purely mechanical tasks, such as target selection, to ensure that it incorporated complex aspects of collaboration, like the need to coordinate and make decisions [126]. Inspired by previous work on studying collaboration [90, 186], we chose a task where participants had to perform a path-planning task under some constraints. In Inkpen et al. [90] participants planned a route in a subway map. In Tang et al. [186] pairs created bus routes that had to pass through specific locations and at the same time not overlap. This type of constrained path-planning is an abstraction of resource-routing and planning tasks common in real situations, such as traffic control centers [176]. For example, during accidents, traffic operators need to guide first responder teams to the location of the accident, and at the same time reroute regular traffic at the accident location. An abstracted path-planning tasks differs from the real one in that aspects of it are simplified (e.g., simple layout and no road context) to reduce effects due to complex layout (discussed next) and due to context knowledge. It also has specific constraints to encourage coordination (next). These characteristics ensure that the task can be performed by participants without domain knowledge, and the findings will be more generalizable as we limit possible effects caused by factors not related to collaboration.

We chose to focus on path-planning on an abstract graph instead of an existing road network graph. In a pilot we experimented with different graph layouts, but found that task difficulty varied depending on the layout, edge length and overlap of different edges in the graph. To ensure a common difficulty across tasks so as to measure learning, we settled on a grid, where all edges are similar in size and and do not overlap. The final graph was a grid of 10 rows by 20 columns (Figure 39).

The task was then presented in a rectangle of 4 rows and 5 columns in the center of the graph. Possible solutions took up to 7×7, which corresponds to $2 \times 1.5\text{m}$ (Figure 39 blue rectangle).

Within this grid, each participant had to form a separate path between two "end-nodes", represented as brown squares (Figure 39). To encourage pairs to coordinate and make decisions, we enforced constraints in their planning: (1) the two paths were required to cross at two specific nodes, one colored purple and the other orange; and (2) their paths could not cross anywhere else, and could not overlap (i.e, share an edge). Each participant was responsible for constructing one of the paths, differentiated by color (green/blue). In the large display, participants used either one or two fingers for input to differentiate between them. In the desktop condition they used mice, and shared a common view of the graph, with both mouse cursors (theirs, and their partner's) always visible on the screen.

To ensure consistent difficulty across trials, the constraint nodes were always at a distance of 2 edges, and were next or across one of the two end-nodes. Their positioning was such that, in each trial, it was impossible for both participants to form the shortest path between the two end-nodes without crossing or overlap, thus necessitating negotiation and planning to find a good compromise (Figure 39). We generated 6 tasks with these properties, and used them, and their mirrors (on the x and y axis) during the experiment. Three independent users went through all the generated trials beforehand and rated their difficulty, to verify we had consistent difficulty across trials.

In Chapter 2 I showed that the interplay of display size and physical navigation is complex. In this work, we study the effect of a shared display on *collaboration*, and thus decided to use only part of a larger display, reducing the navigation component, to ensure that any performance differences are not due to navigation.

4.2.2 *Pilot Study*

To assess the validity of our task and the relevance of our measures, we conducted a preliminary study with 3 pairs of participants. We experimented with different levels of difficulty (e.g., one and three constraint nodes to cross) and a third setup: two desktops and a shared display available at the same time.

In order to avoid any effects due to the order of presentation of the setups, we trained the pairs for the task with each setup in a first block (5 trials per setup). Then, they redid the task on each setup in a second block (again 5 trials per setup), and this time we measured the time they took to finish the task and the time they spent communicating.

Results showed no difference in the time to finish between each setup in the second block, and that participants didn't communicate in that same block.

However, they did communicate during the training block. We observed that during the training, participants developed progressively an optimal strategy to solve the task, and thus didn't need to communicate and coordinate in the second block. This led us to focus more on this training phase, in which participants learn to do the task and elaborate a strategy. As we decided to focus on training, in order to avoid noise due to different complexity tasks, we considered only a single difficulty that required planning but was not too hard.

Finally, participants reported (and we observed) that they did not looked at the shared display in the third condition (2 desktops and a shared display). Thus, we decided to remove this condition from the study.

4.2.3 *Measures*

Using the results of our pilot study we expected pairs to spend a fair amount of time coordinating and planning in the first trials (learning phase). But after a number of trials, as they became more familiar with the task, we expected them to eventually converge to a strategy that would require little coordination and planning, as the task would become almost mechanical (convergence phase). We thus decided to not train our pairs, but rather to assess how they learn to perform the task on both setups.

Previous work has also studied coordination in collaborative environments by assessing the *learning curve* of collaborating groups [70]. We expected the two phases would differ across setup: with the large display pairs would learn to coordinate and plan faster than with desktops, due to the implicit cues available in this setup. This is supported by previous findings showing that SDG provides more awareness of partner's activities [206], and that collaborators have the feeling they are more efficient [76, 90]. Beyond learning time, we also report absolute *time* performance for each setup.

Task *quality* is measured as the number of unnecessary edge selections, which is the difference between the total number of all selections made by participants during the trial, and the minimum number of selections necessary to do the task. While we were interested to see if the setup influences quality, this remains a secondary measure compared to learning.

Finally, we measured additional information that could help us assess the differences in collaboration between the two setups. As shared displays provide awareness and allow for deictic references, we expected differences in the *amount of communication* between the two setups, with shared displays requiring less explicit communication. Wallace et al. observed that collaboration was more demanding with MDG [206], and thus we expected that participants would talk more to counter this effect in the desktops condition. We also expected that the divided nature of the desktops would lead to looser collaboration *strategies* than the large display.

4.2.4 *Participants*

We recruited 32 participants in pairs (7 females, 25 males), aged 21 to 41 (Median: 26), with corrected-to-normal vision. They were computer science graduate students and researchers who didn't participate in the pilot study. Most were familiar with touch interaction (30/32) had used a large display in the past (31/32). Almost all pairs (15/16) knew each other beforehand and we did not observe performance or communication differences in the pair that didn't know each other.

4.2.5 *Apparatus*

Our large display was an interactive wall (5.9m×1.96 m) made of 75 Liquid-Crystal Display (LCD) screens (21.6 inches, 3mm bezels each), with a resolution of 14400×4800 pixels, and driven by a rendering cluster of 10 computers. Multi-touch support was provided by a PQ labs[2] frame. The task took up 2×1.5 meters, which represents 4800×3600 pixels. See Figure 39.

The 2 desktops had a 24.1 inch display, with a resolution of 1920×1200 pixels. They were positioned at 3.8m from each other. On each screen the task took up 30×23 cm.

The experiment program was implemented using Java and the Zoomable Visual Transformation Machine (ZVTM) Cluster toolkit [146], and ran on a master machine connected to the cluster and the desktops through 1 Gbit Ethernet. The operator controlled the sequence of the experiment using a smartphone which ran an android application implemented with the Smarties toolkit [39].

4.2.6 *Procedure*

The experiment was a between-subjects design with SETUP (*Shared-Display* or *Desktops*) as the between-subjects factor. Participants per-

2 http://www.pqlabs.com

formed 12 trials with a given SETUP. Overall, the experiment consisted of: 16 pairs × 12 trials = 192 trials and lasted 30 min on average.

Participants were first trained on how to select edges in the grid, without any task training. They were then given the task instructions and path constraint details and the experiment started. Their instructions were to be as quick as possible and to not try to find the optimal (shortest) paths, however they were reminded that long paths take more time to select and thus increase experiment duration. At each trial, when pairs completed both paths in a way that respected the constraints, paths would change color. Complete paths that did not respect the constraints would turn red. During the trial, an experimenter measured the conversation time using a toggle button on the smartphone, that was then verified with video coding. To ensure we captured all collaboration aspects during the trials, participants were asked to not communicate in any way between trials but were informed that they could talk as much as they wanted during the trials. No further instruction was given on how to communicate and plan their strategy. At the end of the experiment, participants filled a demographic and a post-study questionnaire, that prompted them to assess the ease of coordination of the setup using a 8-point Likert scale, and to describe the strategy they used in an open ended field.

4.3 RESULTS

To minimize noise in our data, we averaged together trials in blocks of two. This means that the experiment is composed of 6 blocks (b1 - b6). However, when visually inspecting our data we observed a consistent time spike for both setups and all pairs in block b5 (w.r.t. the first block 1 where pairs see the task for the first time). Detailed video viewing identified that one trial in this block required users to make a compromise at the top left part of the graph, the usual position participants started from. Their strategies developed until then relied on making compromises later on in the trials, and thus failed them. As this particular task required new path strategies and affected both conditions, we decided to remove it from our analysis to satisfy our assumption of equal task difficulty.

We analyzed our data using ANOVAS with between factor SETUP, within factor BLOCK, and participants as a random factor. (The analysis including b5 led to very similar results.)

4.3.0.1 *Time*

Overall, participants were faster on the *Desktops* than on the *Shared-Display* ($F_{1,14} = 4.79$, $p = 0.05$, see Figure 40-(a)). In contrast, Wallace et al. [206] found no difference in performance between SDG and MDG, a fact that can be explained by the nature of the task used in their study, that was longer and less controlled than ours. Our analysis

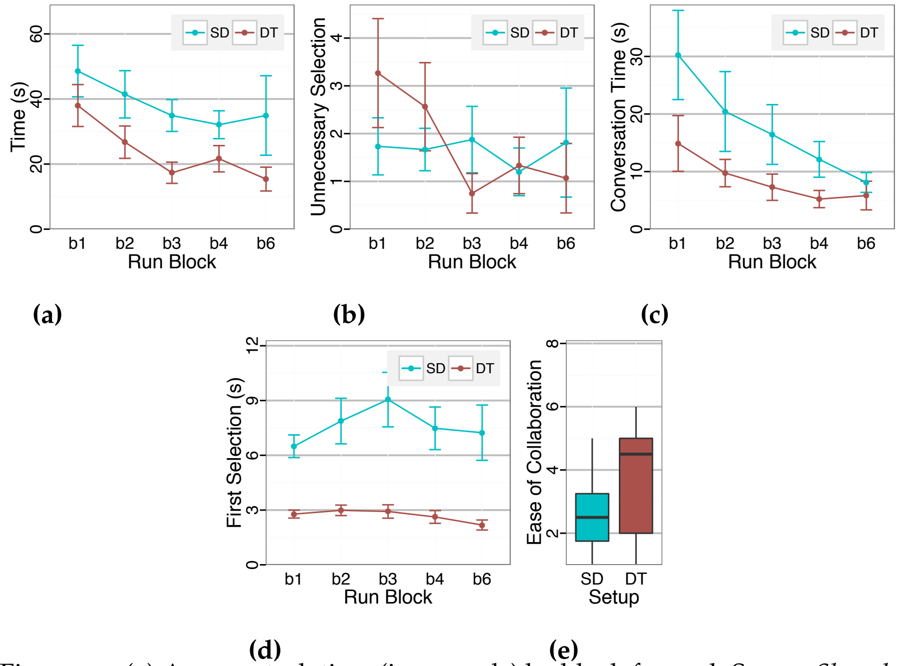


Figure 40: (a) Average task time (in seconds) by block for each Setup, *Shared-Display* (*SD*) and *Desktops* (*DT*). (b) Average unnecessary selection by block for each Setup. (c) Average conversation time by block for each Setup. (d) Average time before the first selection by block for each Setup. (e) Boxplot for the ease of coordination by Setup (1-8 likert scale, small is "better"). Error bars show the standard error.

also revealed a main effect of Block ($F_{5,70} = 2.86$, $p = 0.02$), confirming that learning took place and that our participants' performance improved over time. We see that the learning phase continues until block 3 in both setups, and after that pairs performance converges. However, contrary to our expectations, we found no interaction between Setup and Block ($F_{5,70} = 0.40$, $p = 0.85$), thus we were unable to measure a difference in learning phases between the two Setups.

4.3.0.2 *Solution Quality*

Quality is measured as the number of unnecessary edge selections made by participants. A strictly positive number can mean that either the final path is not the optimal solution or that participants made corrections, first selecting edges, and then unselecting them when they ran into a conflict with their partner. We found that in 97% of the trials, participants found the optimal path, so we consider that unnecessary edge selections are due to path correction. The number is stable with the *SharedDisplay* and of good quality (on average 1.66 touches per trial). The situation is different for *Desktops*, where unnecessary selections start at 3.27 for block 1 and consistently decrease, reaching 1.07 for block 6 (a result confirmed by an effect of Block on *Desktops* $F_{4,28} = 3.12$, $p = 0.03$). See Figure 40-(b). This indicates that quality in the *SharedDisplay* is stable and consistently good, even in situations where participants are unfamiliar with a task. This can be explained by the extensive coordination and planning performed by participants in this setup, discussed next.

4.3.0.3 *Coordination and Planning*

To further study collaboration differences, we first looked at the amount of verbal communication between setups. Contrary to our expectations that using the *SharedDisplay* would require less verbal communication, participants in fact talked more in this condition ($F_{1,14} = 6.90$, $p = 0.02$, see Figure 40-(c)). There is also an effect of BLOCK ($F_{5,70} = 3.72$, $p < 0.01$), indicating that in both setups participant talked less as trials progressed (the interaction SETUP × BLOCK is not significant, $p = 0.62$).

Observing our pairs, we noticed that they took more time in the *SharedDisplay* to coordinate and plan their actions, compared to *Desktops*. We verified this by additionally analyzing the time for first interaction in the two setups. Indeed, participants took more time before interacting for the first time with the *SharedDisplay* than with the *Desktops* ($F_{1,14} = 10.89$, $p = 0.01$, see Figure 40-(d)). This additional planning time could explain the difference in quality observed before.

Differences in coordination and planning are also visible in both self-reported and observed strategies. On the *SharedDisplay* half of the groups reported using a strategy involving a-priori planning and close collaboration. Conversely, all groups on *Desktops* reported starting the task with little communication and planning. To verify these differences, an experimenter conducted video coding for all trials looking for planning phases. Results showed that planning was performed for 65% of trials with the large display, and for only 9% of trials with desktops. More specifically, during the first two blocks where pairs are still developing their strategy, in the *SharedDisplay* most pairs (4 in block 1 and 6 in block 2) performed extensive planning, and kept this strategy in the remaining blocks. Of the two pairs that didn't have a planning phase, observations showed that 1 pair actually talked during the trial, gradually planning the path. The other applied a loose collaboration strategy, working mostly individually. With the *Desktops*, only one pair adopted a planning phase starting at block 2, likely due to coordination difficulties in this setup. This higher effort needed to collaborate in MDG was also observed by Wallace et al. [206] and can explain why our participants choose strategies that don't need too much communication.

Regarding ease of collaboration, as it is reported by participants, there is a trend that it felt easier on the *SharedDisplay* ($p = 0.08$, see Figure 40-(e)). This confirmed results by Inkpen et al. [90] and Hawkey et al. [76] that stated that participant felt collaboration more efficient with SDG. The most reported coordination issue with *Desktops* was the difficulty to communicate (6/16 participants), which often led them to start interacting without having formed a concrete plan. On the *SharedDisplay*, the most reported issue was physical conflicts with their partner in front of the display (5/16). Video coding allowed us to see that there were 35 physical conflicts and 54 position changes in the 80 *SharedDisplay* trials. This required extra coordination from our participants.

4.4 CONCLUSIONS

We conducted a quantitative study to assess collaboration differences when using a large shared display, compared to two desktops sharing the same view, in a sequence of path-planning tasks. We measured no difference in how fast pairs learn to perform the new task across setups. Nevertheless, with the large display, pairs adopted strategies that included more planning and coordination, which led them from the beginning to consistent, good quality results. It seems that when participants are faced with a new task, they do not adapt more quickly using the large display, but they can produce better results from the start. This observation may have important implications in situations like crisis management, and command and control centers, where collaboration on large displays could provide better quality solutions in unexpected crisis events.

However, on average, pairs took less time to solve the task with the desktops than with the large shared display. This finding is partially explained by the large amount of verbal communication when using the large display (even if this communication decreases as pairs become more accustomed to the task). This is surprising as shared displays provide more implicit ways to communicate and awareness of other's action, compared to the desktops were cursor movements and voice are the main communication channels. Due to these reduced communication channels, with desktops pairs often adopted loose collaboration strategies [206], that were nonetheless faster, with one participant making choices quickly for their path and the other working a solution around them. It would be interesting to see if these strategies change when more communication channels, such as video arms or viewports of one's partner, are available. On the other hand, participants using the large display planed with their partner ahead of time, before committing to actions on the display, a difference seen in the time spent before the first interaction. With the shared display participants were reluctant to start interacting before they had come to full agreement with their partner.

The adopted strategy and participant comments indicate that the large display eased communication and coordination, even if it was slower. This delay is in part due to planning discussions, but also due to the need for pairs to move around each other and avoid physical conflict while using the shared surface, a fact that likely encouraged tighter coordination. It would be interesting to investigate if similar planning discussions occur in intermediate situations, such as around smaller shared displays, e.g., a common desktop.

In our experiment, we studied a single task and attempted to maintain a similar task difficulty, as we studied learning. In the future, it is necessary to verify if our findings hold for other tasks and to vary task difficulty to see if it has an impact on the strategy used. We expect loose collaboration will be even more error-prone.

This chapter showed that the use of a shared vertical display can encourage users to collaborate closely. This is important in situations, such as exceptional situations in command and control rooms, where close collaboration is desired. In the next chapter, I study how the interaction techniques can influence the collaboration used in front of this kind of display, in particular if it can promote even closer collaboration.

5 IMPACT OF THE INTERACTION TECHNIQUE ON COLLABORATION

In the previous chapter, I showed that a wall display facilitates communication and coordination compared to the use of separate desktops, an aspect that could aid in cases where close collaboration is needed such as during exceptional situations in command and control rooms.

However, as it was stated in chapter 2, inputs and interaction techniques have an influence on how users collaborate on a wall display. It is important to adopt the ones that encourage the type of collaboration we want. In this chapter, I study how two interaction techniques impact the collaboration for graph exploration.

Main portions of this chapter were previously published in [148][1].

5.1 INTRODUCTION

Wall displays support different types of input: remote inputs, like mice, or more direct inputs like touch. Both have their strengths and weaknesses, as mentioned in chapter 2. For collaboration, direct inputs like touch provides a better group awareness, allows an easy switch between close and loose collaboration and is preferred by users [97, 99]. However, because of the proximity to the screen, users tend to lose awareness of collaborators who are interacting further away [218]. Thus, to collaborate closely, people tend to work close to each other [204]. But for some tasks this is not possible, as users need to work on different areas of the wall.

However, the use of elaborate interaction techniques could influence how closely people collaborate. For instance, Liu et al. developed a set of shared gesture which allows close collaboration at a distance when classifying data on a wall display. In this chapter, we study selection techniques for graph exploration on a wall display, and we study how their characteristics impact collaboration.

We focus on graph exploration as it doesn't require specific domain-knowledge (contrary to control rooms) so experiments can be done with many non-expert subjects. It also allows us first to control the different factors of the tasks removing noise due to the context, and thus have result that are more generalizable, and at the same time to have multiple repetitions. However, it is relevant to command and control as graphs are widely used in control rooms, for example, to

1 Thus any use of "we" in this chapter refers to me, Anastasia Bezerianos and Olivier Chapuis

represent road networks. Moreover, some of the common topological tasks are also done in the control room context, like in road traffic control rooms, finding the shortest path between two locations to plan routes for ambulances.

We present a systematic study of how pairs use a wall-display to solve topology based tasks, that are common components of more complex graph analysis tasks [113]. We study how the interaction technique supports or hinders pairs collaborating on these tasks. We focus on techniques for selection, a fundamental visualization task, as it is a pre-requisite to many interactions such as filtering, comparisons, details on demand, etc.

We adapt two general purpose graph selection techniques for use by multiple users on a touch-enabled wall-display. Our baseline is an extension of basic node/edge selection for multiple users. It is easy to master, and has a limited, and thus fairly localized, visual footprint on the wall display, that does not interfere with colleagues' work. The propagated selection extends for multiple users the idea of transmitting a selection to neighboring nodes/edges [80, 127]. It highlights the connectivity structure of the graph (See Figure 52), but may have a large visual footprint that should help for awareness, but can also disturb colleagues.

We first assess the impact of selection technique on pairs conducting a specific topology analysis task, namely identifying a shortest path. As there is no work on pairs working on such tasks on wall-displays, we tease out effects due to the technique or due to collaboration, by also studying single user selections. We then examine how propagation, the most promising technique, is used by pairs on other graph analysis tasks [113].

5.2 RELATED WORK

Chapter 2 presented the related work with regards to the benefits of wall displays on collaborative use. In this part, we focus on their use to explore graphs and on the idea of transmission (as one technique is based on this notion).

5.2.1 *Graph Exploration on Large Surfaces*

Collaborative analysis is one of the next challenges of the analysis of graphs [202]. Existing systems support mainly remote collaboration (e.g. [221]). Less work has targeted co-located analysis, like that by Isenberg et al. [92] that retrofitted an existing graph visualization application for use by multiple analysts with mice and keyboards.

Although work on graph exploration using wall-displays is limited, researchers have identified their potential early on. For example, Abello et al. [2] used a wall display to visualize communication network data. Later, Mueller et al. [134] designed an algorithm to interactively layout graphs optimized for tiled displays and distributed environments, while Marner et al. [125] let users interactively adapt the layout on the wall using a mouse and keyboard. Lehmann et al. [115] leverage physical navigation as an implicit interaction, using the viewer's distance from the wall to adjusted the level of detail of a graph, and Kister et al. [105] use it to move a lens with contextual information. More recently, Kister et al. [106] developed GRASP, a set of interaction techniques to explore graphs on a large display using mobile devices. This past work on wall displays does not study the use of explicit interactions (e.g., selections) during collaboration, as we do. Finally, although not explicitly testing collaboration, researchers have introduced multi-touch techniques for manipulating graphs on interactive tabletops. For example, Henry Riche et al. [83] use multi-touch interactions to fan out links leaving a node, to bundle them, or use link magnets to attract certain types of links. Schmidt et al. [166] alter link trajectories, pin, or make them vibrate by plucking them. These works introduce multi-touch techniques on tabletops for different purposes. While we also use touch, we focus specifically on selection and study how pairs use it to perform graph topology tasks on wall-displays.

5.2.2 *Graph Exploration using Transmission*

Visual analysis of graphs is a long standing field, with numerous research questions (see [84, 202] for reviews). We focus on techniques related to our propagation selection (section 5.3.2), that use the idea of propagating/transmitting information to neighboring nodes or links that is central to graph analysis (e.g., [159]).

As graph structures can be very large, exploration is often localized on interesting nodes and their neighbors. For example, van Ham and Perer [75] designed a Degree-of-Interest function for graph exploration that first proposes interesting nodes, and lets the user indicate interesting nodes to expand to. Archambault et al. [9] use specifically the notion of distance to progressively reveal and render nodes proximal to a node of interest from within a larger graph hierarchy. Moscovich et al. [133] propose interaction techniques for panning within a graph, or bringing neighbors closer, based on the graph's connectivity. Similarly, Tominsky et al. [191] developed lenses that bring neighbors nodes closer. Finally, egocentric techniques (e.g., [215]) re-layout graphs by focusing around one node and laying out the rest based on their distance from it; or focus on two nodes [50] and highlight their common neighbors. This work can lead to a user-driven re-layout of the graph, that may disrupt the work of other viewers in a multi-user setting.

Other techniques related to propagation preserve the layout. Heer et al. [79, 80], allow users to highlight the contour of the 1st or 2nd degree neighbors, or the connected component of a node, by hovering over it or by using repeated mouse clicks. McGuffin and Jurisica [127] propose techniques to locally select and manipulate nodes, including a menu option that selects a node's neighbors of increasing distance progressively. Ware and Bobrow [210] evaluate different means of highlighting connections to neighbors of arbitrary degrees specified by a text field, and found that motion representations are not better than static highlighting. We extend this notion of propagated selection to multiple origin nodes, providing appropriate input and visual design, to support such selections by multiple users.

5.3 INTERACTION TECHNIQUES

Our goal is to investigate how interaction techniques affect multiple users working on graphs. We focus on selection, as it is a required first step for many other visualization tasks, such as filtering, comparison, details on demand, etc. Two techniques were considered, a simple selection (*Basic*), and one based on the graph's connectivity structure (*Propagation*). These techniques were chosen due to their properties: they can benefit graph exploration differently but also face different challenges when adapted for multiple users on wall-displays. We describe next how we adapted the techniques for touch interaction on wall-displays, and for collaborative use. Each description finishes with a summary of the technique's properties, motivation for their use, and possible challenges when used in a multi-user context on wall displays.

5.3.1 *Basic Selection*

Basic is inspired by colored selections available in graph visualization software extended for multiple users. We chose it to investigate the limits of basic selections in collaborative settings.

5.3.1.1 *Interaction and Visual Design*

A node (or link) is selected by tapping on it once, and deselected if tapped again. Inspired by previous work [9, 80], we also highlight the links (or nodes) attached to it so as to demonstrate its connections, but do not re-layout the graph to avoid disrupting collaborators. Given that we do not have keyboard modifiers, and wanted to keep the touch input vocabulary simple, we decided to allow users to modify this selection in the following way: if the user taps on a node adjacent to an existing selection (direct neighbor), then this node is added to the selection and it, and its links, are highlighted with the selection's color. If the node is adjacent to more than one existing selections it takes the color of the last edited selection. Tapping on a selected node removes it from the selection. This way users can edit their selections with simple taps, keeping the input vocabulary very simple. We chose to not use lasso-type selections that require dragging to select multiple items, as they are not well suited to large interactive surfaces, such as walls, where prolonged dragging is inaccurate, fatiguing [85], and often disrupted by bezels in tiled walls.

Our wall, similar to many touch enabled surfaces, does not differentiate between users. Nevertheless, it is important for colleagues to differentiate their work. Thus, if users tap on nodes that are not adjacent to existing selections, we assume a new selection is being made (potentially by a different user) and assign it a new color, chosen randomly from a set that is easily distinguishable.

5.3.1.2 *Summary*

Basic extends the simple selection available in graph visualization software to selection of multiple nodes/edges by multiple users. It is familiar, easy to understand, and our design ensures it relies on simple taps. It has a small visual footprint as it selects a single node and its edges at a time, and thus will likely not disrupt collaborators when used in a multi-user context on wall displays. Nevertheless, it may require extensive physical movements if users need to select multiple nodes that are far away on the wall.

5.3.2 *Propagation Selection*

As an alternative, we investigate *Propagation* selection, based on the idea of progressive transmission of a selection to neighboring nodes. Propagation allows local interaction on a node that can highlight its influence across a larger area on the graph (and wall), without requiring extensive physical movement that can be tiring. Because of its large footprint, it can improve awareness of interactions that are out of the area of actions of users, but it can also be disrupting.

Variations of the propagation selection from past work (e.g. [80, 127]) allow a single user to either highlight neighboring nodes up-to a specific degree only [80], usually 2, or use a menu or text option to select a node and its neighbors of a certain degree [104, 127]. We explain how we adapted the technique allowing multiple users to easily expand the selection to the n-th degree using simple touch interactions. We finally describe its properties and how it can be used to perform topology-based tasks [113] when analyzing graphs.

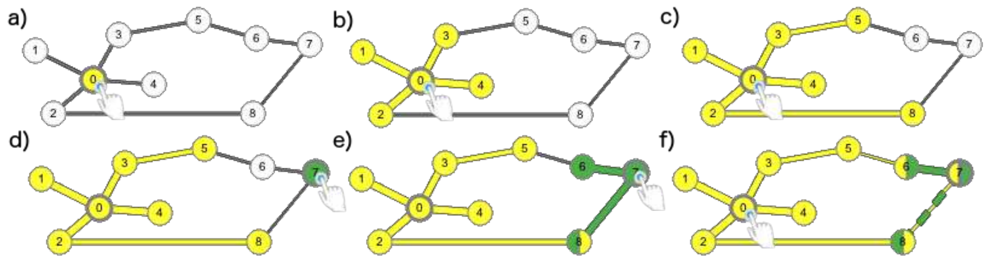


Figure 41: Multiple propagations: (a) a first tap on node 0 selects it; (b) a second tap propagates the selection to immediate neighbors; (c) and a third tap to 2nd degree neighbors (notice the difference in link width according to distance); (d) a tap on node 7 selects it with a new color; (e) a second tap selects its neighbors, one of which (node 8) is shared with the first propagation and has both colors; (f) a fourth tap on node 0 propagates the first selection a third time, resulting in nodes 6,7,8, and link 8-7 being shared between propagations, with the color and width on shared link 8-7 alternating.

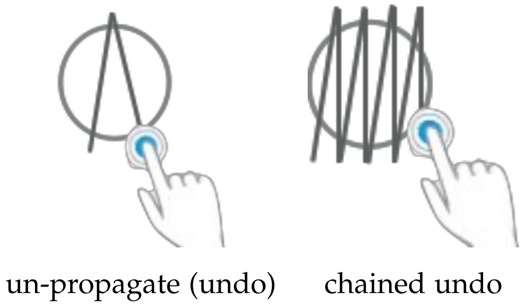


Figure 42: Gesture to undo one propagation step on a node (left) and chained undo for backtracking multiple steps (right).

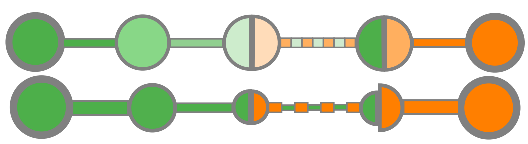


Figure 43: Design variations for displaying propagation distance using color intensity (top) and node-link size (bottom).

5.3.2.1 *Interaction*

Propagation allows users to select a node, which we will refer to as the *origin*, and then propagate the selection first to its neighbors, then to their neighbors, and so on. Propagation of a selection is done through a series of taps (clicks) on a node. The first tap selects the node itself (Figure 41-a), and the following taps propagate the selection progressively to the neighboring edges and nodes: the second tap adds to the selection outgoing links and first-degree neighbors of the origin (Figure 41-b), and so on for all following taps[2] (Figure 41-c). If users continue tapping, propagation continues until no more nodes can be reached from (are connected to) the origin node. Thus a propagated selection is a progressive query selection, that adds elements connected to the origin node at progressively increasing distances.

We note that the first step of propagation (selecting only the node) is not the same as *Basic* (selecting the node and its edges). We made this design choice as initial feedback indicated that the metaphor of transmission is better served if we consider that each tap opens the flow of transmission from the selected nodes to their neighborhood (both links and nodes).

To accommodate multiple users working in parallel, when users select a node that is not part of an existing propagated query, it becomes the origin of a new propagation selection (Figure 41-d). If they select a node already inside a propagation query (but not its origin), the query expands to also include propagations from this new origin. Thus one propagation query can have multiple origins.

As we designed the technique for touch surfaces, we chose a simple crossing zig-zag gesture to undo propagation steps. When performed on the origin, it backtracks the propagation by one step (See Figure 42). The gesture can be chained to perform multiple backtracks without lifting a finger, undoing quickly several propagation steps in one interaction. When the selection is reduced to a single node (the origin), this gesture unselects the node.

A crossing gesture on an element (node or link) that is not the origin of a propagation, removes this node from the selection and blocks future propagation paths of this selection to go through it.

5.3.2.2 *Visual design*

Nodes and links in a propagated selection share a common color (as traditional color queries). Propagation origins stand out with a thicker border (Figure 41-a), and new propagations are assigned a different color, similar to *Basic* (Figure 41-d).

2 Propagation starts either from a node or a link. To simplify the discussion we talk about node propagation, but we use a similar selection pattern for links: link selected first, adjacent nodes and their links next, and so on.

Due to the propagation of selections, a node can be selected by two or more colors. The node in question is divided visually into slices equal to the number of selections, and given the respective colors (Figure 41-e).

Links can similarly be part of several selections. Dividing them in segments equal to the number of selection colors (similar to nodes) could lead to few, but long, colored segments if links are long. Thus the multiple colors could be hard to see locally on a wall display. We decided instead to streak (dashing pattern) the links with the selection colors (Figure 41-f). We fixed the number of streaks to seven, as we observed that on our wall they were still visible locally, even on long links. Moreover, as the fixed number of streaks have different length depending on the total length of the link, they give locally an indication of its overall length.

We explored different design variations to emphasize the distance of elements (nodes and links) from the origin. This is of interest both within a single selection (to identify the farthest elements), but also for elements that are part of multiple selections to identify which origin is closest. As color is already used in selections, we considered other visual variables (Figure 43). Color intensity that drops with distance was considered, but rejected, as the perception of intensity may be affected by viewing distance and angle across the wall-display, and color intensity may vary across screens in tiled wall-displays [179]. We thus chose the size of elements, i.e., the thickness for the links and the radius for the node slices. While testing our prototype, we observed that as nodes have multiple incoming links, it is hard to identify which path and origin is responsible for the shortest distance that determines their size. Thus to avoid confusion and reduce clutter, we chose to only display distance information on the links.

As the thickness of selected links indicates their distance to the propagation origin node, the thicker the link the closer to the origin it is. We chose to display three visual levels of thickness: links with maximum thickness are linked to first-degree neighbors, ones of medium thickness link first and second-degree neighbors, and all remaining links selected through propagation have a similar minimum thickness. We found that more levels led to small variations in thickness that were hard to perceive in dense graphs. When a link is traversed multiple ways inside a selection (e.g., there are multiple origins in a selection, or the link belongs to multiple paths of different length), the link thickness is determined by the smallest distance to the closest origin in the selection.

5.3.2.3 *Propagation Properties, Support for Graph Analysis*

Multiple propagations allow multiple users to simultaneously explore different parts of the graph with their own color, examining connectivity relationships in different areas, as well as interactions between their selections made visible by the combined colors in nodes and links when propagations coincide. They also highlight relationships that may span large distances on wall displays, without the need for extensive physical movement.

Multiple propagations can also aid a single user to visually conduct basic set operations between selections. For example, the union of two or more propagation selections is the set of all the colored nodes. Their intersection are the nodes and edges colored by all respective colors simultaneously. The difference of two selections (i.e. elements in one but not in the other), are all nodes and edges that are colored by a single color.

Thus propagation from multiple nodes could be used to answer fairly complex topological questions, such as identifying all common neighbors of N-degree or less of multiple actors in a social network (union of N-level propagations), all the co-authors of one researcher that are not co-authors of her colleagues in a co-authorship network (difference of 1st level propagations), etc. We consider next topological tasks, such as the ones described by Lee et al. [113], that are well supported by propagation.

- Adjacency (direct connections): It is trivial to find and highlight the neighbors of a node by propagating one level. Nevertheless, there is no clear strategy for how to identify the node with most neighbors (highest degree) using the propagation technique.

- Accessibility (direct or indirect connections): This set of tasks are well supported by propagation. Nodes accessible from an origin are colored by the propagation. And the propagation level highlights nodes at distances less or equal to that level.

- Common Connections: To find the common neighbors of two or more nodes, we can propagate from each of these origin nodes and identify nodes that have both colors (i.e. belong to both propagation selections). And as before we control the distance of neighbors.

- Connected Components: To identify discrete connected components, i.e. subgraphs not connected to each other, we can choose a node and propagate until no more nodes are added, thus identifying a connected component. Repeating the process with uncolored nodes will identify the remaining connected components.

- Shortest distance between two nodes: The length of the shortest distance between two nodes can be found by propagating from one node and counting the number of propagation steps to reach the second. Nevertheless, determining the *actual shortest path* is more challenging: although the path is part of the propagated selection, it can be hard to identify it within all the selected elements, particularly in dense graphs.

This is a non exhaustive list of tasks well supported by propagation, and tested later on. More complex strategies could be devised for other tasks, to find for example articulation points or bridges (a node or link that is the only connection between two subgraphs).

5.3.2.4 *Summary*

Our adapted *Propagation* technique for interactive surfaces uses fast taps to expand, and a crossing gesture to backtrack. We support multiple propagations that can aid with several graph topology tasks. By design, propagation can select several nodes quickly, based on the connectivity structure of the graph, without requiring extensive moving around the wall-display. Its large visual footprint can be beneficial for awareness of each other's actions, but it may cause visual disturbance in well connected graphs, as it will quickly span the entire graph and may disrupt the work of colleagues if links cross their workspace.

5.4 EXPERIMENT 1: PROPAGATION VS. BASIC

It is unclear how *Propagation* and *Basic* selection will affect multiple users working on a wall-display. As there is little work on graph analysis on wall-displays in general, we also studied an individual user context, to tease out effects due to collaboration and ones due to the techniques.

As an instrument for this exploration we chose a well-defined topology task, the identification of the shortest path between two nodes, for several reasons. First, identifying the shortest path, or variations thereof, is a task used often in controlled graph evaluation studies (e.g. [55, 186]) and can be fairly involved in complex graphs. It requires an understanding of both the local context of nodes (identifying neighbors), as well as more global structure information, as a shortest path is not necessarily small in absolute distance. And as it is a well-defined, closed task, with an objective solution, it is well suited for controlled experiments.

Second, the task is not clearly divisible, as a more global understanding of the graph structure is required. Thus it is unclear if multiple users working together would fare better than single users. As it can be performed individually, it gives us the opportunity to compare individual vs. multiple user work. Finally, and very importantly for our purposes, the task does not bias against *Basic* as it is not trivial to do with *Propagation*. As *Propagation* highlights a large number of possible paths (explained in section 5.3.2.3), this task could reveal issues with visual clutter caused by *Propagation*. The task is different from the one in chapter 4 in which we wanted to force coordination. Here we want to let users freely coordinate their actions (or not) to study if the techniques promotes coordination of not.

Based on the design and properties of the two techniques, we formulate the following general hypotheses:

H1 In both *Individual* and *Multi-user* contexts, performance (time & accuracy) will be better with *Propagation* than *Basic*.

H2 With both techniques, performance will be better in the *Multi-user* context than in the *Individual* context.

H3 *Propagation* will result in less participant movement, but will cause higher visual disturbance.

5.4.1 *Experimental Design*

5.4.1.1 *Participants*

We recruited 16 participants in pairs (6 females, 10 males), aged 23 to 39, with normal or corrected-to-normal vision. Pairs knew each other beforehand. Participants were HCI and visualization researchers or graduate students, with experience in reading graphs. Most (15/16) reported using at least once a day a device with touch interaction, and having already used a wall-display (13/16).

5.4.1.2 *Apparatus*

We used an interactive wall made of 75 LCD displays (21.6 inches, 3mm bezels each), composing a 5.9m × 1.96m wide wall, with a resolution of 14 400 × 4800 pixels (Figure52). The wall was driven by a rendering cluster of 10 computers. A PQ labs[3] multi-touch layer allowed for direct touch over the wall. Participants' positions were tracked by a VICON motion-capture system[4].

The experimental software ran on a master machine connected to the cluster through 1Gbit ethernet, and was implemented in Java using the ZVTM[5] Cluster toolkit [146]. The operator controlled the experiment progression using a smartphone running an android application implemented with the Smarties[6] toolkit [39].

5.4.1.3 *Graph Types*

We considered two different Graph types:

- *Planar*: These graphs can be drawn without edge crossings. Transport networks (e.g. subway or air-routing networks) are often

3 pqlabs.com
4 vicon.com
5 zvtm.sourceforge.net
6 smarties.lri.fr

planar. We generated them using an algorithm inspired by Mehadhebi [128] to design air route networks.

- *SmallWorld*: These illustrate the small-world phenomenon identified by Milgram [132] in social networks, where most actors are linked by short chains of acquaintances. Social networks, communication networks, and airline networks are often Small-world graphs. We generated them using Kleinberg's algorithm in the Java Universal Network/Graph Framework (JUNG) toolkit [141].

In a pilot study (2 pairs) we tested three types of generated graphs: *Planar* and *SmallWorld* ones, as well as randomly generated ones inspired by Ware and Mitchell's [212] algorithm. Participants' performance with the random graphs was very similar (time, errors, subjective comments) to *SmallWorld* ones, and we thus removed them from the experiment.

5.4.1.4 *Complexity*

To explore graphs of different complexity, we created two variations for each graph type, *Low* and *High* Complexity. We generated them by varying structural characteristics, such as number of nodes and edges and mean shortest path, and visual aesthetic criteria that can affect readability, such as visual density and number of edge crossings [152]. Visual density is calculated as the ratio of pixels occupied by nodes and links, over the entire surface used to calculate the layout (discussed later).

Graph	Complexity	#Nodes	#Edges	$\overline{\text{Shortest Path}}$	Visual Density	#Crossings
Planar	*Low*	100	288	4.27	0.06	179
	High	200	582	5.69	0.10	627
SmallWorld	*Low*	36	103	2.27	0.02	249
	High	196	588	3.55	0.12	4879

Table 1: Mean metrics of the graphs used in the experiments.

Table 1 reports mean values for the metrics of graphs used in the experiment. We note that our purpose was not to equate all metrics across graph types, but rather to create "difficult" and "easy" variations for each type (Figure 44). For high complexity graphs of all types (*Planar* and *SmallWorld*), we chose high complexity graphs with similar visual density, i.e. the amount of ink or clutter, and number of nodes and edges. For low complexity graphs we found in a pilot (1 pair) that tasks on *Planar* graphs with less than 100 nodes were trivial and did not require interaction. Thus for the low complexity variation of *Planar* we chose higher visual density than for *SmallWorld* ones.[7]

7 In our pilot we considered a no-interaction condition, but found that for our graphs (both *Low* and *High* complexities), tasks were respectively either very hard (double

Density and crossings depend on the layout used to draw the graph. To ensure consistent drawing across graph types, we used for all graphs the Inverted Self-Organizing Map (ISOM) layout [131]. We tested several layout algorithms, such as classic force directed ones [56, 67], that position neighboring nodes close together and minimize edge crossings. Nevertheless, the tested force directed layouts [67] generated larger number of edge crossings compared to ISOM, a metric associated with readability [152], and did not uniformly fill our wall space. We thus moved to the ISOM layout that optimizes similar quantities to force directed layouts, while ensuring best coverage of our wall surface, and resulting into a smaller number of crossings. The ISOM layout is well adapted to planar graphs, but as other layout algorithms, it can lead to layout calculations that break somewhat the visual planarity of structurally planar graphs, as can be seen in Table 1. The same graphs and layouts were seen in both techniques (see Procedure), to keep this experimental factor consistent across techniques.

5.4.1.5 *Task*

Participants were asked to identify the shortest path between two target nodes. Target nodes were positioned in height at the middle 60% of the wall, thus not too high or too low to reach; and were spaced by a distance of at least 50% and 75% of the width of the wall to ensure paths were not too localized.

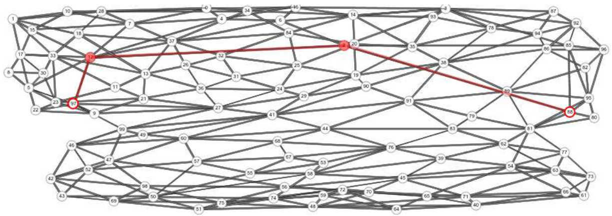
For each graph type and complexity we generated three variations to be used as "replications". In each of the three variations, we selected a path of LENGTH 3,4 and 5 respectively[8]. Paths of the given length were chosen automatically (using exhaustive search) to fulfill the following criteria: (i) the first and last node, that would become the "target nodes", met the above placement criteria; and (ii) all nodes in the path similarly fell into the middle 60% of the wall to ensure they were easily selectable.

5.4.1.6 *Procedure and Design*

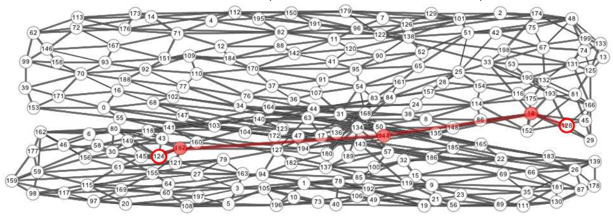
The experiment was divided in two sessions, an *Individual* and a *Multi-user* one. To counterbalance these conditions, half of the participants did the *Individual* session first and half the *Multi-user* session first. In the *Multi-user* session, pairs saw both techniques (within-subject design), and the order of presentation was counterbalanced across groups. To end-up with an equal sample of group and individual sessions, in the *Individual* sessions each participant only saw

the time) or impossible to do without interaction to help trace one's process. Thus we did not test the "no interaction" condition further.

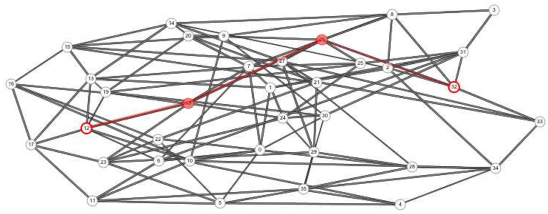
8 The use of LENGTH as a replication factor was justified, as there was no interaction between LENGTH and TECH, CONTEXT, GRAPH (see Results).



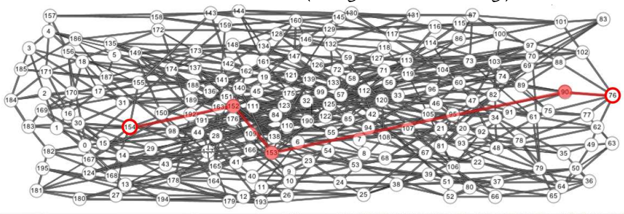
Planar-Low (N: 100 and L: 288)



Planar-High (N: 200 and L: 582)



SmallWorld-Low (N: 36 and L: 103)



SmallWorld-High (N: 196 and L: 588)

Figure 44: Graph examples used in Experiment 1 with their number of nodes (N) and links (L). Colored paths are for illustration purposes only, and highlight the shortest path between the two target nodes. During the experiment participants were only shown the first and last node (target nodes).

one technique (between-subject design), chosen at random. *Individual* sessions lasted approximately 25 min, and *Multi-user* ones 40 min. Overall our mixed experiment design consisted of: 8 sessions (pairs or individuals) $\times$ 2 CONTEXTS (*Individual*, *Multi-user*) $\times$ 2 TECHS (*Basic*, *Propagation*) $\times$ 2 GRAPHS (*SmallWorld*, *Planar*) $\times$ 2 COMPLEXITIES (*Low*, *High*) $\times$ 3 LENGTHS (3, 4 and 5) = 384 measured trials.

For each TECH in both contexts, participants conducted 7 training trials before proceeding to the main experiment. Trials began with a screen indicating the position of the two target nodes, to ensure visual search was not required. Participants were then shown the actual graph with the target nodes highlighted. They then interacted with the wall display to find a shortest path, and when they had an answer they verbally indicated to the experimenter to stop the timer, and showed their solution. An experimenter followed the discussion to ensure they did not "cheat", i.e. report done before finding all nodes. No such cases were observed. If their answer was correct, they would proceed to the next trial. If their answer was wrong, the trial was marked as an error. Nevertheless, the task resumed and participants had to continue the trial until they found the correct answer. This ensured participants did not rush to give partially formed answers. At the end of the sessions participants filled a questionnaire on the perceived load and visual disturbance, and provided general preferences and subjective comments.

We chose a verbal indication of when pairs had reached a consensus, because in a third pilot (1 pair) we found that other procedures did not always ensure a consensus. We first provided each participant with a mobile device with a "done" button. We observed that choosing as a trial completion the first time one of the two participants pressed "done" was problematic, as they often did so while the other was still working. We also considered the time both participants had pressed "done", but found that some would occasionally forget to press their button while discussing with their partner. We next provided a single mobile device to only one participant. Although in most cases a very clear verbal agreement would take place before they pressed "done", occasionally the participant holding the mobile would forget getting verbal agreement and would press the button too soon. Thus we decided to enforce verbal agreement between participants, by asking them to instead tell the experimenter together when they were done, a process they practiced during training. When the two verbal indications were given the experimenter would log the time.

For each technique and context, participants were shown the *Low* complexity graphs first to ease them into the task, while the order of graph type and path length was randomized, but consistent, across participants. The same graphs were seen across techniques and collaboration contexts, but to avoid learning we used mirrored versions of the graphs on the x and/or y axis (resulting in 4 variations per graph).

Participants were instructed to be as fast as possible while avoiding errors. We recorded the time to the first given answer as our task completion time (*Time*), and the count of incorrect answers. We logged kinematic data of participants' movements using a motion tracking system, and video recorded the sessions.

5.4.2 *Results*

We report on the measures: (i) *Time* taken by participants to state for the first time that they completed the task, approximating expert behavior. When the first answer was wrong trials were marked as errors and the task would resume to discourage participants from rushing through trials (but the extra timing was not logged). (ii) *ErrorRate*, i.e. the percent of trials where participants provided incorrect answers. (iii) *TraveledDistance* by participants in front of the wall. (iv) Subjective *rating* of visual disruption.

STATISTICAL METHOD – Following recommendations from the American Psychological Association (APA) [1], our analysis and discussion on continuous measures (*Time*, *TraveledDistance*) are based on estimation, i.e., effect sizes with 95% CI. Our confidence intervals were computed using BCa bootstrapping. Error bars in our images reporting means, are computed using all data for a given condition.

When comparing means, we average the data by participants/-groups (random variable) and compare the two conditions globally using a $(-1, 1)$ contrast (between-subject case), or by computing the CI of the set of differences by participants/groups (within-subject case). In our images we display the computed CI of the differences, and report the corresponding Cohen's d effect size, that roughly expresses the difference in standard deviation units. Finally, for completeness, we also report p values. These are computed as an approximation of the smallest $p \geqslant 0.001$ such that the $100.(1-p)\%$ CI interval does not contain 0 (i.e., we compute the "largest" I-levels that lead to a "significant" result)[9].

To compare errors and Likert results we use non-parametric tests (Wilcoxon rank sum), which are more adapted to bi-valued and ordinal measures.

As mentioned, LENGTH was used as a replication factor, and as such is not considered as part of the analysis. Nevertheless, we conducted a-posteriori tests and verified that although there was a difference between the 3 length variations in time and errors, there were *no interaction* effects between length and interaction technique, context, or

9 A CI of a difference that does not cross 0, can be read as "significant".

graph type. We also did not find any learning effects due to technique presentation order.

5.4.2.1 *Time*

INDIVIDUAL When working individually, participants were faster with *Propagation* (29.3 s) than *Basic* (54.1 s). To better understand the nature of this difference, we looked separately at each COMPLEXITY and GRAPH. Our analysis (Figure 45) shows *Propagation* consistently outperforming *Basic*, with the effect being stronger in *SmallWorld-High* (most complex graphs).

MULTI-USER Similarly, *Propagation* (22 s) was measurably faster than *Basic* (30 s) for pairs, even though the difference was not as pronounced. Looking at conditions in detail (Figure 46), the effect mainly exists in the *High* complexity graphs.

INDIVIDUAL VS. MULTI-USER Individuals were slower with *Basic* (almost double the time) than with *Propagation*. This tendency was also visible in the *Multi-user* condition, although mainly for the larger graph sizes. This indicates that *Propagation* is more efficient, in particular for larger and complex graphs.

When we compare the *Individual* and *Multi-user* condition, mean times for both *Basic* and *Propagation* were better for pairs, but this difference was not measurable (Figure 47-left). However, examining the different complexities, we found a measurable time improvement for *Basic* when collaborating on *Low* complexity graphs, and a measurable improvement for *Propagation* when collaborating on *High* complexity graphs (Figure 47-right). This indicates that collaboration does not compensate for the weakness of *Basic* for complex graphs (in particular the *SmallWorld-High* ones). While with *Propagation*, one user is as effective as pairs for simple graphs, but that the collaboration benefit is seen in more complex graphs.

5.4.2.2 *Error Rate*

INDIVIDUAL We observed no measurable difference in *ErrorRate* between *Propagation* (9%) and *Basic* (13%), even if mean error rate was

	aggregated		*Planar*				*SmallWorld*			
			Low		*High*		*Low*		*High*	
	Basic	*Prop*	*Basic*	*Prop*	*Basic*	*Prop*	*Basic*	*Prop*	*Basic*	*Prop*
Indiv.	13.5%	9.4%	0%	4.2%	0%	0%	16.7%	8.3%	37.5%	25.0%
Collab.	16.7%	3.1%	8.3%	0%	12.5%	0%	4.2%	4.2%	41.7%	8.3%

Table 2: Error rate per TECH, aggregated and by GRAPH × COMPLEXITY conditions, in the individual user case and in the multi-user case.

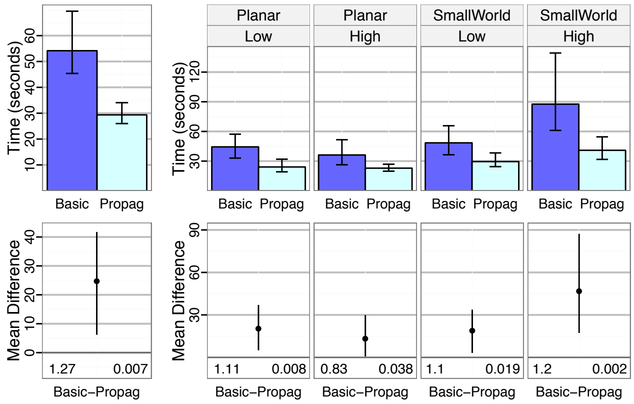


Figure 45: (Top) Average time to complet the task per TECH in the individual user case, aggregated on the left, and by GRAPH × COMPLEXITY conditions on the right. (Bottom) Corresponding 95% CI for the mean differences *Basic* − *Propagation* used in analysis: bottom left numbers show the Cohen's d effect size and the right ones the p values. This convention is followed in all images.

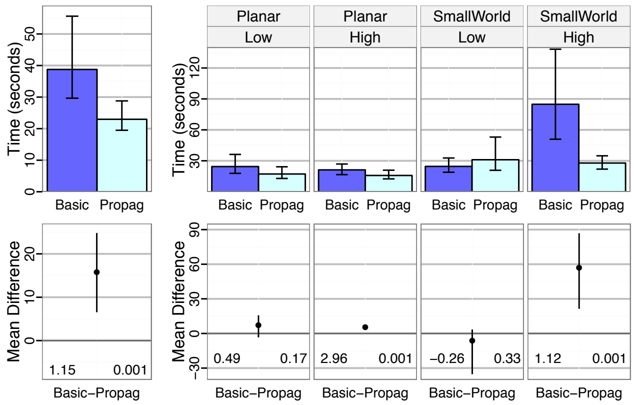


Figure 46: (Top) Average time to complet the task per TECH in the multi-user case, aggregated on the left, and by GRAPH × COMPLEXITY conditions on the right. (Bottom) Corresponding 95% CI for the mean differences *Propagation* − *Basic*.

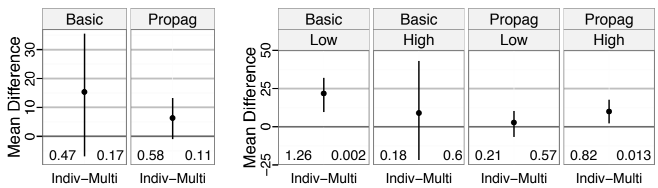


Figure 47: 95% CIs for mean time differences *Individual* − *Multi-user*, by TECH and by TECH × COMPLEXITY.

lower for *Propagation*. Table 2 shows the error rate for the different conditions. We can observe that almost all errors (95%) occurred with *SmallWorld* graphs irrespective of TECH.

MULTI-USER On the contrary, we measured a difference in *ErrorRate* between *Propagation* (3.1%) and *Basic* (16.7%) in the collaborative case (p's $< .01$). We observed that *Propagation* led to less errors in all conditions (p's $< .05$), except in the *SmallWorld-Low*. Figure 2 gives a break down for the different conditions.

INDIVIDUAL VS. MULTI-USER Overall, the effect of *ErrorRate* was different for each technique across the individual and multi-user case. For *Propagation* there are marginally less errors when working in pairs (3.1%) compared to individuals (9.4%) ($p = 0.066$), with a very marked drop in error rate in the hardest graph *SmallWorld-High*, where pairs had an error rate of 8% compared to the 25% error rate for individuals.

We do not have such an effect for *Basic*, where error rate increased when pairs worked together (16.7%) compared to individuals (13.5%). When looking at different conditions, the trend was measurable for the *Planar* graphs ($p = 0.023$), but mean error rates were indeed higher for all conditions apart from *SmallWorld-Low*. We come back to this result in our discussion section.

5.4.2.3 *Distance Traveled*

INDIVIDUAL The amount of movement in the individual case was higher for *Basic* (17.9m) than for *Propagation* (9.2m), almost twice as much (three times in complex graphs), and the effect exists for all GRAPH × COMPLEXITY conditions (Figure 48).

MULTI-USER Similarly, the distance covered by each participant when working in pairs was less with *Propagation* (4.6m) than *Basic* (9.3m), in all conditions (Figure 49).

INDIVIDUAL VS. MULTI-USER As expected the distance traveled by participants in individual sessions is about twice that traveled by each participant in *Multi-user* sessions for both techniques (Figure 50-left). However, as shown in Figure 50-right, this effect is strong for *Propagation* for both *Low* and *High* complexity graphs, but only for *Low* complexity ones for *Basic*. This reinforces that the gain of working in pairs is less with *Basic* in complex graphs.

Figure 51 illustrates these results with examples of participant trajectories in front of the wall. Pairs tend to divide their work spatially, with the exception of using *Basic* in *SmallWorld-High*. Nevertheless, video recording indicates that even here participants start the task by dividing the space, but as they cannot reach a solution, they start

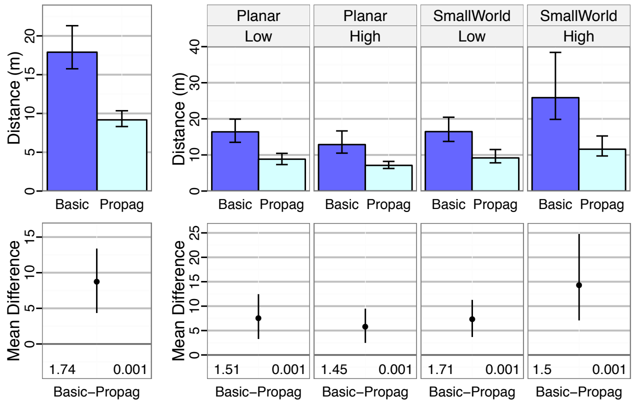


Figure 48: (Top) Average distance traveled by participant per TECH in the individual user case, aggregated on the left, and for each GRAPH × COMPLEXITY conditions on the right. (Bottom) Difference CI for the analysis.

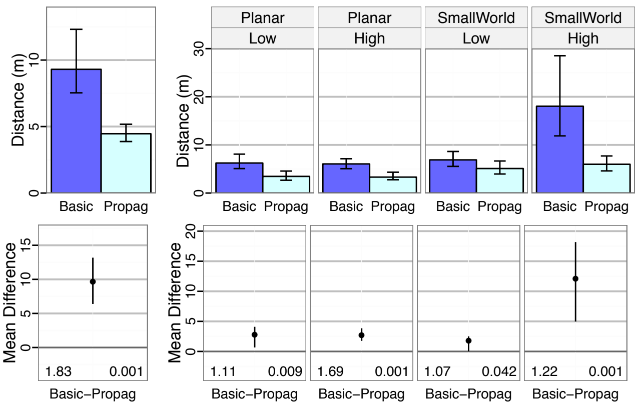


Figure 49: (Top) Average distance traveled by each participant per TECH in the multi-user case, aggregated on the left, and for each GRAPH × COMPLEXITY conditions on the right. (Bottom) Difference CI for the analysis.

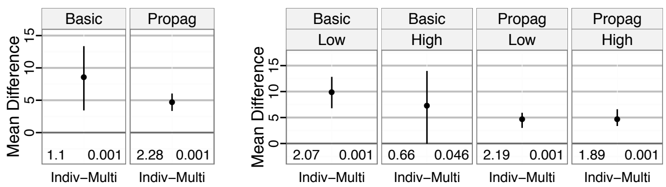


Figure 50: 95% CI for mean differences of the traveled distance *Individual — Multi-user*, by TECH and TECH × COMPLEXITY.

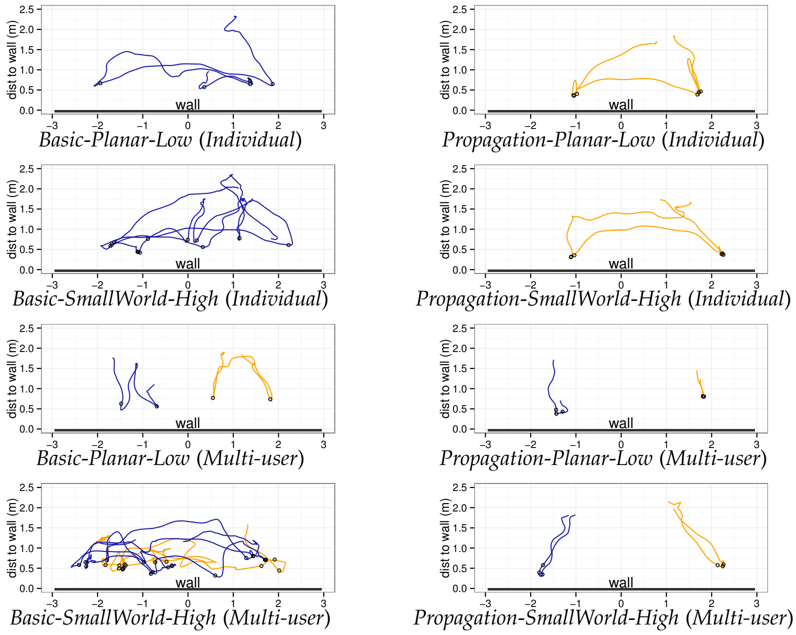


Figure 51: Bird's eye views of the movement of participants in trials for individual (2 top lines) and pairs (2 bottom lines), under the condition *Planar-Low* (easiest) and *SmallWorld-High* (hardest). *Basic* is seen in the left column, and *Propagation* in the right column. The wall is at the bottom of each graph, the unit is the meter, and the black little circles (∘) indicate a touch interaction.

moving more around the space to verify their work, stepping back likely to get an overview. Thus, these patterns are not just due to the need to reach nodes to interact with, but also due to the nature of collaboration using *Basic* in complex graphs.

5.4.2.4 *Observed Strategies*

INDIVIDUAL Instead of propagating from a single node, all individuals using *Propagation* selected one node, propagated typically one time (sometimes two), and then moved to the second to propagate, alternating between the two until they saw an intersection (two-color node). This strategy reduced the number of selected nodes and visual clutter (less propagation steps), helping them identify the shortest path as intersection points are inside it.

The strategy used for *Basic* was different. Participants consistently selected a subset of neighbors that seem to be between the two nodes, trying to reconstruct short paths moving from one node to the other. This was successful for the smaller and less complex graphs, but did not work well for the hardest condition *SmallWorld-High*, where participants had to consider a large number of nodes, as seen by the high error rate in this condition.

MULTI-USER When performing the task in pairs, participants were again consistent in their strategy. With *Propagation* it was similar to the individual sessions, but now each participant took charge of one of the two nodes, and propagated alternatively (but not concurrently) until they found intersecting nodes. They coordinated this asynchronous double-propagation using verbal communication. Then, both participants reconstructed together a shorter path candidate, each taking responsibility of their own end of the propagation. In more complex graphs, they occasionally checked each other's work (6 groups).

For *Basic*, participants again took charge of one node each, and tried to define paths using selections towards their partner, until they reached each other's work area. They worked more or less independently, and in parallel, until they started finding intersection nodes. After that, for the more complex *SmallWorld* graphs, they tried checking together candidate paths before making their choice (e.g. Figure 51 bottom-left graph, notice movement overlap). But, pairs did not double check each other's work in the easier *Planar* graphs (e.g. in Figure 51, 3rd row on the left, we see no movement overlap), which may explain the increased error rate. There was one notable strategy exception, one group decided to propagate systematically, simulating on their own the *Propagation* technique (which they had seen first).

5.4.2.5 *Subjective Comments*

INDIVIDUAL USERS Answers to the quantitative questions of the questionnaire (physical demand, visual disturbance, enjoyment) was very similar between the two TECH (p's $= 1$). This is not very surprising given that we used a between-subject design for TECH.

MULTI-USERS After the collaborative session participants were able to directly compare the two techniques. All 16 preferred *Propagation*. On a 7-point Likert scale participants found that *Propagation* was less physically demanding (Avg=2.5, SD=1.2) than *Basic* (Avg=4, SD=1.6) since they were required to walk less (p's < 0.05). They also found *Propagation* more enjoyable (Avg=5.3, SD=1.1) than *Basic* (Avg=4.1, SD=1.2).

Surprisingly, they also found *Propagation* to be *less* visually disturbing (Avg=2.9, SD=1.6) than *Basic* (Avg=4.8, SD=1.8) (p's < 0.05), contrary to our hypothesis. When asked to explain why they found *Propagation* less visually disturbing, they explained that *Propagation* helped highlight paths of interest *"helps to see how many possible shortest paths there are, which is very convenient"*. Although four mentioned explicitly in their comments the existence of visual disturbance in *Propagation*, they commented that the visual footprint was desirable for tracking their work *"it gets visually disturbing very quickly after a few propagations, but it is good to be able to see the changes when we can go back and forth with the propagation easily."*.

When asked if they preferred conducting the task individually or collaborating with a partner, participants had mixed opinions. Six out of the eight that run the individual session with *Propagation* preferred to run the experiment in pairs with *Propagation*, instead of alone. As one explained *"having a partner is easier because there's someone to help check whether the answer is correct or not and I don't have to move around. However I'm not sure if doing it together is faster because sometimes communicating takes time"*. Five out of eight participants that run the individual session with *Basic* preferred to do the task in pairs with *Basic*. But, as one participant explained *"it happens that the other was exploring different solutions than me* [parallel work], *so he was disturbing me"*. Thus, overall the multi-user context was been only slightly preferred than the individual context.

5.4.2.6 *Discussion*

Propagation was faster than *Basic* selection when identifying shortest paths, particularly in the more complex small-world graphs (confirming *H1* on time). This can be explained by participants moving more with *Basic*, twice as much overall and three times for complex graphs (confirming *H3* on movement). This is backed by subjective comments reporting less fatigue and higher preference for *Propagation*.

When moving from individuals to pairs, the mean time of both *Propagation* and *Basic* was faster, although this difference was not measurable overall. But there is a clear speed-up for complex graphs with *Propagation*, and for easy graphs with *Basic* (partially confirming *H2* on time). These differences are likely due to participant strategies. Individuals were fast with *Propagation* to begin with, and since pairs spent time coordinating and taking turns propagating, speedup due to collaboration is not visible. But as we move to more complex tasks, the cost of coordination drops compared to that of the task. On the other hand, individuals were slow with *Basic*, and as pairs worked in parallel first and combined their results later, this accelerated the work with simple graphs. But in more complex graphs this strategy was not effective, and collaboration did not compensate for the weakness of *Basic* when dealing with complex graphs.

Collaboration had an effect on accuracy. It increased when passing from individuals to pairs in *Propagation* (partially confirming *H2* on accuracy), particularly in the most complex graphs. Participants chose to closely coordinate their actions taking turns to avoid visual interference (supporting *H3* on visual disturbance). Thus it is possible they had increased workspace awareness [53], a fact supported by the ease with which they double checked each other's work. The colored propagation queries provided a filter to the interesting areas of the graph, that also helped participants focus more effectively on both their partner's and their own work, leading to the unexpected subjective feeling that propagation was less visually disturbing (subjective feel contrary to *H3* on visual disturbance). Surprisingly, accuracy decreased for *Basic* when moving to the collaborative setting. This can be explained by the adopted strategy of conducting part of the task independently, thus lacking a "big picture", that participants were forced to adopt in the individual case. This big picture is crucial for tasks such as shortest path identification, where dividing the task into spatial subtasks is not straightforward[10].

5.4.2.7 *Summary*

The two techniques, *Propagation* and *Basic*, support collaboration and wall display interaction differently:

• *Propagation* is promising for individual work for the shortest path finding task, requiring little physical movement. In group work it leads to increased accuracy, but no measurable increase in speed as there is an overhead related to coordination due to its visual footprint. Thus tight coordination, combined with the technique's highlighting of areas of interest, helped maintain an understanding of partners' work and increased accuracy.

• The *Basic* technique is as accurate when dealing with simple graphs for individuals, but considerably slower. And its performance degrades with more complex graphs. More importantly, when pairs divide tasks spatially, it can lead to loss of awareness of partners' work, resulting in loss of accuracy in collaborative work (compared to individual) when task division is not straightforward.

5.5 EXPERIMENT 2: OBSERVATIONAL STUDY

In the previous study we focused on a single controlled task that is not clearly divisible and parallelizable in its nature. Although pairs naturally took responsibility of one node, an overview of a larger area of the graph is required to correctly address the task. This is true for most low level graph analysis tasks suggested in the literature [113]. Nevertheless, studying them gives us insight as to how users can appropriate existing techniques in a collaborative manner. For example, *Propagation*, which quickly affected a large part of the graph, required explicit coordination. We examine, now, if this is true for other low level tasks.

More specifically, we are interested in assessing *Propagation*, that proved more promising, as a general graph exploration technique, observing if pairs can "discover" on their own how to perform new tasks without task specific training. And in whether they adopt similar coordination strategies as in Exp 1. Thus we are less interested in recording time, and more in observing if and how pairs collaborated.

10 For example, when choosing among shortest path candidates, considering only the left half of paths is not enough to identify good candidates.

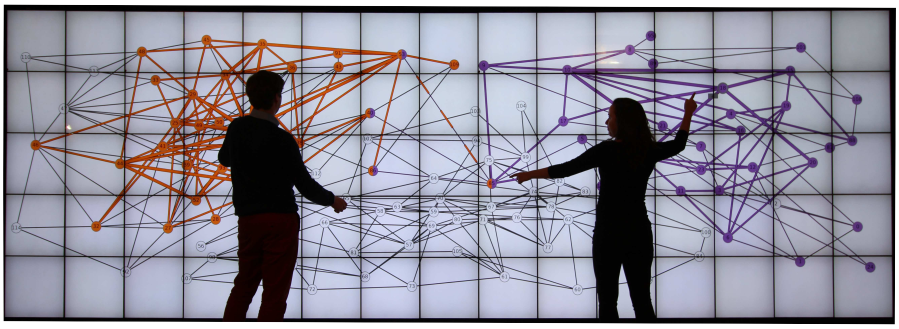


Figure 52: A pair using the propagation technique to perform the open exploration task. They discuss two communities, in orange and purple, selected using the propagation technique. The communities are linked by a specific node shown by the right user. The remaining 3 orange-purple nodes show how by propagating the purple community, it flows into the orange one through this node.

5.5.1 *Experimental Design*

5.5.1.1 *Participants & Apparatus*

We recruited 8 volunteers (4 females, 4 males) in pairs, aged 23 to 39, with normal or corrected-to-normal vision. Pairs knew each other and had taken part in Exp 1. Sessions lasted 30min, using the same apparatus as in the first experiment.

5.5.1.2 *Tasks*

Groups performed the following topology tasks [113]:

T1 Find the shortest distance between two nodes (as opposed to the shortest path as in Exp 1).

T2 Find the common neighbors of degree 2 between two nodes.

T3 Find all connected components.

T4 Find an articulation point between connected components.

T5 Open exploration, reporting interesting observations.

5.5.1.3 *Graph Types*

In *T1* and *T2* we used high complexity small-world graphs similar to Exp 1. In *T1* the shortest distance was 6 and the two target nodes were separated by a physical distance of about 75% of the wall width. In *T2* the two target nodes were closer (about 50% of the wall width) and had 5 common neighbors.

In *T3* and *T4*, we combined unconnected small-world graphs (20 nodes each) of high complexity: three in *T3* (60 nodes in total) and two fin *T4* (40 nodes). To complicate the tasks, we tweaked the layout

Tasks	Discovered	Avg.Time (SD)	Correct
shortest distance	✓ (4/4)	63.5s (SD=21.9)	✓ (4/4)
2nd degree neighbors	✓ (4/4)	77.6s (SD=90.3)	✓ (4/4)
connected components	✓ (4/4)	47.6s (SD=22.4)	✓ (4/4)
articulation point	X (0/4)	timeout (3000s)	2nd try (3/4)
			3rd try (1/4)

Table 3: Summary of findings for specific Tasks T1-4, indicating whether our pairs were able to discover how to perform a task, and the time it took them to do so (mean and SD). If they did not discover a strategy on their own within the timeout period, column Correct indicates on what try they succeeded.

to get overlap between subgraphs. And in *T4* we hid the articulation point connecting the subgraphs inside one of them.

The graph used in the open task *T5* (similar to Figure 52) consisted of three subgraphs of different densities, and two unconnected nodes. Two subgraphs where connected through an articulation point, hidden within the third subgraph. These were the insights we wanted our participants to identify. The layout was tweaked so that subgraphs were not easy to separate visually.

5.5.1.4 *Procedure*

Participants were first reminded of the propagation technique, but no task specific training was given. Then the experimenter introduced the task without giving instructions on how to solve it, and participants performed the five tasks in order. Participants indicated they were done verbally, in a way similar to Experiment 1. If participants succeeded on their first trial within a timeout limit of 3000sec (5min), they moved on to the next task. If they failed, a strategy to solve the task was explained to them, and they were presented with another trial for that task. If they failed again, they were given a final trial, and then moved to the next task.

The experiment was recorded, and one experimenter took notes. A second experimenter gave instructions and logged the time (as in Exp 1). At the end, we asked participants if they had any suggestions for improving the technique, their thoughts on collaboration, and how confident they were in their answers.

5.5.2 *Results*

We report next participants' success in discovering a correct strategy and time averages logged during the experiment, as well as the strategies they adopted based on video log analysis and notes taken in the experiment.

5.5.2.1 *Discovering*

All pairs discovered without any training correct strategies for identifying the shortest distance between two points, the common neighbors of degree two, and the connected components (*T1-3*). No pair was able to develop a correct strategy for finding an articulation point (*T4*), but three pairs understood how to identify possible candidates. After instruction, three pairs were able to perform a new *T4* trial, and one pair on their third attempt.

All pairs conducted *T1-T3* within the time limit, with connected component completed faster 47.6s (SD=22.4), followed by shortest distance 63.5s (SD=21.9) and 2nd degree neighbors 77.6s (SD=90.3). The larger mean time and standard deviation of 2nd degree neighbors is due to one pair that did an extensive verification of their answer (described next in strategies). We note that the times reported here include both the discussion of strategy and the actual interaction to find the solution. Table 3 summarizes the discoverability of strategies and the time taken by our pairs.

In the open task, three pairs found four out of five possible insights, and one pair found all insights within the time limit. All pairs found two connected subgraphs and identified an articulation point between them. They also verified that the third subgraph was disconnected, and identified the extra disconnected nodes. One pair noticed the differences in the density of the subgraphs by calculating shortest paths.

5.5.2.2 *Observed Strategies*

We describe next the strategies adopted by participants, focusing on how they coordinated, and report their subjective comments.

SHORTEST DISTANCE In all pairs, each participant propagated from one of the two target nodes, until one or more nodes were selected by both their colors. They took turns propagating and observed each other's work so as not to loose count of the total propagation steps performed. One pair also used the thickness of edges to confirm that bi-selected nodes were at a distance of 3 from each target node.

COMMON NEIGHBORS OF DEGREE 2 All pairs propagated two levels from both target nodes and then counted the number of nodes selected in both colors. Two pairs worked independently first (propagated in parallel) and checked later the bi-colored nodes together. Of these pairs, one backtracked their propagation to verify all bi-colored nodes were neighbors of degree two exactly, rather than neighbors of degree two or less for one of the nodes. The other two took turns propagating and looking at their partner's work, ensuring they considered neighbors of exactly degree two.

CONNECTED COMPONENTS All pairs discovered that the best strategy was to start propagating from nodes that seem distant, and if one propagation no longer had an effect (no more nodes added) they had identified and fully selected a connected component. Two pairs worked in parallel, propagating in different areas simultaneously. While the other two took turns propagating and observing. One such pair had a discussion at the end of the task, noting they could have interacted in parallel to be more efficient.

ARTICULATION POINT This task was more complex, even if the concept of articulation was easy to understand by all participants. No pair managed to find a correct strategy on their own. Nevertheless, three identified several possible candidates using propagation (including the actual one), although they were unsure how to proceed with proving it. The strategy of all pairs consisted of propagating from nodes in different areas in the graph and consider bi-colored nodes. But they did not verify that all following propagation steps between subgraphs passed through their candidates. After this strategy was explained, three pairs succeeded in their next try, while the last pair ran out of time and succeeded in its third attempt.

OPEN EXPLORATION TASK Being inspired by the previous tasks, all pairs began by propagating from far away nodes and found the subgraphs connected by an articulation point, and the third disconnected subgraph. Pairs mixed their strategies, propagating in parallel at the very beginning of the exploration, and then coming together to discuss hypothesis and taking turns propagating and observing.

5.5.2.3 *Subjective comments*

All participants felt confident in their answers and strategies, especially for the first three tasks. Six commented that collaboration increased their confidence in their solutions. When prompted about their coordination strategy, four explained that taking turns helped them be more aware of each other's work, while two mentioned that sometimes they still lacked awareness of each other's work when working at distant locations. Three participants also commented on the visual footprint of propagation: occasionally the colored query of their partner would enter their work area, causing some visual disturbance, while rarely they also missed the effects of their own propagation when it was far away from their location. Nevertheless, these participants also mentioned that these colors helped them verify their partner's work.

They all felt the articulation point task was difficult, and three users independently suggested extending the propagation selection to better support this task, for example by being able to "block" a node and prevent propagation from going through it, or removing nodes temporarily. Four participants commented that it was sometimes hard to tell how many propagation steps they had performed, and suggested adding it as a small number close to the propagation origin. These last two features were implemented. Two participants requested the possibility to collapse and bookmark propagation queries for later use, and another two suggested the option to propagate using a different color within an existing propagation.

5.5.2.4 *Summary*

Participants were able to devise correct strategies for the majority of tested tasks, and in the articulation point task identify good candidates, demonstrating that the extended *Propagation* is an interesting general purpose technique for graph exploration. As in Exp1, participants divided the space and mostly took turns propagating (with few exceptions). We got several comments indicating that the reason for this turn taking was to coordinate and keep awareness of others' work, but also to avoid visual disruption due to the global footprint of the technique. Nevertheless, this global footprint also helped them check each other's work quickly.

5.6 DISCUSSION AND DESIGN IMPLICATIONS

We examined how pairs and individuals work on wall-displays to solve low-level graph topology tasks. Our findings indicate that:

Exploring complex graphs individually requires interaction that highlights the structure of the graph, while basic interaction is enough for simple graphs. Wall-displays can comfortably display large graphs, nevertheless it is still challenging for individuals to explore complex graphs such as large small-world ones. Here we observed a significant benefit in using advanced interaction techniques, such as *Propagation* selection. For individuals, *Basic* selection did not scale well for complex graphs, nevertheless it performed reasonably well for simpler planar graphs.

Collaboration improves accuracy only *if techniques allow verification of partners' work.* Pairs were more confident in their responses than individuals with both techniques. Nevertheless, their actual accuracy improved only for *Propagation*. On the contrary, pairs using *Basic* were more error prone than individuals. Our observations and participants' comments indicate that this is because with basic selection it is difficult to acquire an overview of all choices considered by one's partner, and thus maintain a global view of the work and identify possible errors. On the contrary, with propagation selection it was easier to verify at a glance the work of one's partner and check for errors. In collaborative graph exploration, lack of workspace awareness [53, 72] can decrease accuracy, compared to individual work.

Even when tasks are not clearly divisible, pairs divide the wall spatially. For many topology tasks identified in the literature, and used in our experiments, there is no clear strategy to divide them in space, as they may require a global understanding of subgraphs that extend across the display. Nevertheless, irrespective of task and technique, pairs divided the wall spatially. Even when not optimal, they each took responsibility of one part of the wall and then combined their work, with mixed results. This division was observed in tasks that are clearly spatially divisible [97, 119, 193], but not in tasks that are not clearly spatially divisible, such as route planning tasks [186]. Designers should anticipate this division of space and encourage tighter collaboration (discussed next) when tasks are not spatially divisible.

If a technique has a global footprint, tight coordination is adopted. Although pairs occasionally worked in parallel with *Propagation*, they mostly took turns, working on different sections of the wall. They commented that this tight coordination was needed because the technique had a visual footprint that could reach all areas of the wall, risking disturbing the partner's work. Theoretical work on automated graph exploration using a variation of propagation [48] has shown that automated agents with full knowledge of others' exploration (i.e. high awareness) tend to explore the graph fully more quickly. Given our findings on propagation accuracy and the theoretical result on efficiency, designers could use techniques with large visual footprints to *encourage* close collaboration that can increase accuracy and efficiency. This is complementary to findings that when collaborating loosely, participants *chose* techniques with local visual footprints [186].

Consider awareness vs. disruption tradeoff in techniques. Participants' comments indicate there is a clear tradeoff between awareness and visual disruption. *Propagation* can be visually disrupting and affect the partner's work, but it also provides higher degree of workspace awareness [53, 72]. While *Basic* has a small visual footprint and is less disturbing, but pairs can loose track of their partner's work due to the wall size and graph complexity. Both types of techniques should be supported, and collaborators should be able to transition between them depending on how tight their work coupling is [186], and how divisible their task is.

Provide techniques that do not require extensive walking. Free walking is beneficial in wall displays [15, 21]. Nevertheless, techniques that require users to repeatedly walk to interact with different areas of visualizations (such as *Basic*) are fatiguing. Designers should provide interaction alternatives that can be activated locally but act globally, such as *Propagation* or ones proposed in the HCI literature for remote reaching [19, 172] and data manipulation [119]. Alternatively, designers could provide a combination of touch and distant interaction (e.g.

using mobile devices) to ensure users can perform large scale or remote interactions across distances [106].

5.7 CONCLUSION

In this chapter, we studied the impact that interaction techniques can have on the collaboration. We focused on a specific use case and studied two selection techniques for graph exploration on wall-displays. To isolate the effect of the techniques on collaborations, rather than general use, we also studied them in individual context. We adapted two existing techniques for use by multiple users on a touch enabled display, a basic selection, and a propagation selection using the idea of transmission.

We performed a user study that showed *Propagation* to be faster in both individual and multi-user contexts, to be more accurate for multiple users, and to require less movement than *Basic* in a shortest path identification task. It is also versatile enough to be used in a series of topology tasks, observed in a second study.

Nevertheless, as *Propagation* has a large visual footprint, it requires higher coordination when used by multiple users. When working in pairs, propagation selection increases accuracy overall, but due to a coordination cost it improves time only for complex graphs. When using basic selection, that has a small visual footprint, accuracy dropped for pairs, most noticeably in complex graphs. Indeed, we observed that using basic selections, participants tended to work independently and lose awareness of each other's work, which proved detrimental for the task we consider, that is not clearly divisible. We conclude with design implications, stressing the tradeoffs of techniques with global vs. local visual footprints, and the need to allow users to switch between such techniques depending on whether the task is spatially divisible, and on the nature of collaboration (loose or tight).

It would be interesting to investigate design variations for propagation that reduce this global footprint, and so reduce the disturbance while keeping a high awareness of other's actions. An example would be to re-layout the graph to move selected nodes closer together. A focus on a more open ended exploration tasks would also be interesting to see if the task division encouraged by the techniques in our low level task also takes place in more complex tasks.

Finally, it is unclear if the collaboration style will be the same with this technique but used with distant inputs, given that users would have a better overview of the graph if standing further away this would need to be investigated further.

In the next chapter, I get back on the main use-case of this thesis and I study how to use wall displays in control rooms, more particularly in road traffic control rooms. Inspired by the difference of performance between local and global techniques found in this chapter, I design two visualization techniques for traffic forecasting.

6 APPLICATION TO ROAD TRAFFIC MANAGEMENT

In the previous chapter, I showed that the visual footprint of an interaction technique has an impact on the degree of collaboration on a large display. A large footprint encourages coordination and cross-checking, while a small one encourages parallel work.

In this chapter, I focus on a particular use-case of command and control contexts: road traffic control rooms. As stated in Chapter 3 and demonstrated in Chapter 4, a wall display can encourage users to collaborate closely, which could be beneficial for exceptional situations in control rooms. Thus, I design a road traffic management system which runs on an interactive wall display. I then introduce two visualization techniques for forecast traffic, inspired by the different performance between local and global techniques showed in Chapter 5.

Main portions of this chapter were previously published in [149][1]

6.1 INTRODUCTION

Traffic congestion in major cities and highways is a growing problem in most countries. Perturbations such as accidents and breakdowns, or exceptional events such as demonstrations, can overload a road network that may already be operating at its limit, e.g. during rush hour. To prevent and to react efficiently to incidents and perturbations, road traffic in cities and highways is monitored in dedicated control centers.

Even for experienced operators, it is often challenging to evaluate the impact of an intervention on the network. While they are equipped with predefined traffic plans (sets of compatible interventions on a sector or area), it is still sometimes unclear which plan will work best for the current state of the network, in particular during exceptional events. This is where simulation models of road-traffic can help operators better understand and chose among possible intervention alternatives.

Road-traffic is a complex system with multiple agents (cars) that can behave in a non-deterministic manner. Researchers approximate road-traffic using methods from physics [82] or statistics and machine learning [200]. Their simulations can perform short-term traffic forecasting, identify problematic sectors with high-risk of traffic-congestion, and test new concepts to improve road-traffic such as

1 Thus any use of “we” in this chapter refers to me, Anastasia Bezerianos and Olivier Chapuis.

dynamic adjustment of speed limits. Nevertheless, there is little work that looks at incorporating these results visually in traffic control centers.

Following interviews and observations of road-traffic control centers (See Chapter 3), we extracted user needs and designed a prototype system for road-traffic monitoring that runs on a UHRIWD. Taking advantage of their high resolution and large real-estate, our prototype extends the visualizations currently used in road-traffic control centers, to allow operators to concurrently explore and visualize results from multiple simulations testing alternative interventions on the network, both in a local and global scale.

Inspired by the previous chapter, we propose two techniques for viewing multiple simulations in combination with real traffic: (i) *multiple views* [100, 194, 208] to show the global state of the network, and that has a global footprint; and (ii) *DragMagic*, a combination of DragMags [211] and magic lenses [23], to visualize localized sectors and that has a local footprint (Figure 54). We adapt and combine these techniques to visualize and compare several forecast visualizations using wall displays in control centers.

We focused on single users as we are unsure if the techniques are even appropriate to this task. Participants performed well in comparison tasks of up to 6 different simulations, contrary to previous findings [147] that predicted decreased performance with the increase of comparisons. Our results also suggest that DragMagic is easier to master and may be beneficial when the number of simulations to compare is high, but that both techniques are viable alternatives. Early feedback on our prototype from experts also indicates a preference for DragMagic.

6.2 BACKGROUND

Chapter 2 presented related work with regard to the use of large displays in control room contexts. In this part, we focus on the related work regarding techniques to focus and monitor areas of interest. We also focus on road traffic modeling and visualization.

6.2.1 *Techniques to focus and monitor areas of interest*

Irrespective of interaction platforms, this previous work often relies on general purpose interaction and visualization techniques related to focusing and monitoring one or more areas of interest, such as space folding [58], interactive lenses[190] like magic lenses [23], DragMags [211] and multi-focus techniques [101, 121]. This is due to the need in such contexts to monitor several specific areas in detail, while still having an overview of the situation. For example Ion et al. [91] use DragMags with attached cut-offs; Schwarz et al. [167] use local semantic magnification with a Manhattan lens or a deported view on the wall, and multiple space-folds to visualize multiple areas with context-sensitive information at higher resolution [32, 167].

Our work poses visualization challenges that go beyond those seen in previous work, as it not only needs to allow operators to monitor multiple areas of interest simultaneously, but it also combines real data with *simulation and forecasting* visualizations. Thus the progress and results of one or even more simulations need to be viewed and understood concurrently with the actual road traffic data on multiple areas of interest.

6.2.2 *Road Traffic Visualization*

Trajectory visualization [6] focuses often on vessel traffic, marine [110, 158, 164] and air [87, 163], and on an a-posteriori analysis of movement patterns over long time periods, using sophisticated interaction and visualization mechanisms such as aggregating paths, brushing and linking views, advanced statistics on selections, etc.

Similarly, most work on *road traffic* focuses on a-posteriori analysis and visualization of traffic patterns. For example, Andrienko et al. [5] extract and visualize meaningful places within movement data, and cluster spatio-temporal events or trajectories. Tominski et al. [189] visualize trajectories at different points in time, by stacking them on the 3rd dimension.

For real time traffic data visualizations, Wang et al. [209] visualize macro-traffic data recorded by transportation cells, using a combination of aggregated trajectories and of individual views for each cell showing vehicle animations. Nevertheless, the majority of modern traffic control centers visualize real traffic data by coloring road segments based on traffic density or average vehicle speed, similarly to tools like Google Maps, Bing Maps, etc. As we saw, this visualization is often coupled with techniques that aid monitoring of different locations on wall displays, most notably variations of Magic lenses [23] and DragMags [147, 211].

We also use visualization lenses, but for a different purpose. As our goal is to augment real time traffic with results of simulations, lenses are used to provide side-by-side comparisons between the current situation and simulations in an area of interest. As an alternative to lenses, we also provide multiple juxtaposed views of the entire network [100, 194, 208], with real or simulated data. Another approach taken by Andrienko et al. [7] superimposed on a map the simulated results of road traffic bands in a time cube. Nevertheless, they focused on the simulation visualization and did not combine this visualization with real-time traffic. More recently, they presented a complete framework [8] to analyze road traffic, and model how additional cars will influence the network. To compare the impact of different possible interventions, they visualize results using difference maps, time cubes and statistics. Our work is orthogonal, as we focus on the user-centered design of a system to be incorporated in the shared wall of a control center, using visualizations to monitor multiple simulations and points of interest at a given time.

6.2.3 *Road Traffic Modeling*

There is considerable work on modeling and predicting traffic in general, and road traffic in particular. To our knowledge, there are two main approaches. One uses statistical physics and non-linear dynamics (e.g. fluid-dynamics, gas-kinetic theory, cellular automata) to model *self-driven many-particle systems* that simulate vehicle traffic (see [42, 82] for surveys). The other, starts from "real" data and uses statistical methods and machine learning (e.g., neural networks) to predict traffic and provide short-term forecasting models (see [102, 200] for surveys on "Intelligent Transportation Systems"). This community visualizes its results mostly in the form of statistic charts (e.g. mean traffic density over time) or static images comparing two or more simulation states.

In our work, we use a model developed by Chrobok et al. [43] that is based on the foundational work of Nagel & Schreckenberg [139] that uses cellular automata to model road traffic. Although the visualization and interaction techniques of our prototype work with either type of model, we chose a model that does not require real data.

6.3 MOTIVATION

In chapter 3, we reported on our visits of the PC Lutèce, the PC Berlier, and the PC Bédier. These road traffic control centres are in charge of monitoring the traffic in Paris (PC Lutèce) and on the Peripheric ring (formerly PC Berlier and now PC Bédier). Each time, we observed how operators worked and interviewed in depth. In this chapter, we re-use our findings, and explore a specific issue: the difficulty to forecast the impact of an operators' action.

GENERAL OBSERVATIONS Both control centers are furnished with a large shared visualization wall showing the monitored network, surrounded by smaller screens with live camera feeds from the streets in PC Lutèce, and from the Périphérique and its tunnels in PC Berlier and Bédier. Road segments are colored depending on traffic congestion from green (no congestion), to yellow, orange, and red (high congestion). Gray is used to indicate segments with faulty loop detectors. Arrows are used to highlight areas in which an intervention was done, either by the system (green arrow) or by an operator (yellow ar-

Figure 53: PC Lutèce and PC Berlier traffic control centers in Paris.

row if the system agrees with the intervention and red if it disagrees). Individual operator workstations are located in front of the wall, also displaying the network visualization (see Figure 53), alerts and other statistical information.

Due to the small scale and resolution of their monitors (w.r.t. the scale of the monitored network), operators tend to focus on localized areas of the network in their workstations, using mouse and keyboard to navigate. While they look at their individual workstations more, they all use the wall as an awareness monitor to acquire the "big picture" of the network state.

pc! (pc!) LUTÈCE An automated system (SURF3) manages the traffic lights for approximately 1500 Parisian intersections, with more than 800.000 cars and 2.5 million pedestrian movements daily. It includes a library of "Traffic Light Plans" (a collection of consistent traffic light durations), and automatically choses the most appropriate plan, depending on the current traffic situation, the day of the week and the time of day. Under normal conditions (outside special events) the priority is public transport and pedestrian flow.

Operators can switch plans for specific sectors, or change traffic light duration of individual intersections for specific events or when incidents occur. Our interviewees explained that operators have a lot of experience in handling incidents in the city and can very accurately predict the impact of their actions and interventions in a local scale, such as a crossroad. Nevertheless, they explained it is difficult to assess the impact of actions at a more global scale, e.g., it is often unclear how a change in a crossroad will impact other connected crossroads in the *local sector* or even the *entire network*.

pc! BERLIER AND BÉDIER The center manages the traffic flow in the Périphérique motorway (IPER-REPER system), that hosts daily approximately 1.2 million car movements of commuters between Paris and its suburbs (60% of traffic in the region, 2002). Operators have to constantly monitor traffic in the motorway and its tunnels in order to spot incidents and congestion. To optimize traffic flow, they can activate/deactivate lanes (only in PC Berlier) and reroute drivers using variable message signs, in particular since they face almost daily maintenance of lanes that requires reflow of traffic. To ensure safety in tunnels, operators can trigger and follow emergency plans, including evacuation, activation of smoke control systems, or closing tunnels in coordination with firefighter forces on the ground.

Our interviewees explained that a rerouting plan is in place for closing off sections of the motorway or tunnels, but they are hard-pressed to apply it as it is difficult to assess the impact of such a drastic measure in each traffic situation. They described an incident with a tunnel flooded in both directions for 11 hours, where they considered applying this plan but could not risk it without a clear picture of potential *global* effects on the rest of the network.

The operator supervisor organizes shifts, oversees the good operation of the center and is involved in training new operators. She added that operators also face the challenge of boredom: monitoring traffic feeds and messages from the public to detect incidents early is monotonous and operator attention can wander, and she felt that occasional task switching, such as forecast planning, could increase operator interest and focus.

OTHER CONTROL CENTERS Road-traffic control centers around the world use different technologies and methods. In Paris, the traffic light control cycle is controlled by timing plans, while dynamic modification of the green light duration is not allowed. Other centers, like in London (SCOOT system[2]) allow such modifications. Interestingly, some centers started using predictive modeling to assess the impact of incidents and to help decision-making, such as in the Piemont Control Center in Italy (PTV Optima[3] software). However, to our knowledge no control center combines forecasting and real-time traffic visualizations.

MOTIVATION AND USER NEEDS Our interviews and knowledge of existing centers suggest that: (i) It would be beneficial to incorporate *visualization of predictive models* with real-time monitoring tools, as the impact of actions is often hard to predict. (ii) Operators should be provided with likely outcomes of their interventions both *globally* on the entire network, and *locally* on specific sectors or intersections. (iii) Forecast visualizations increase the amount of information to be displayed, but are needed *periodically*, not on a constant basis. Given the advances in wall displays, i.e., their interactive support and their ability to display a large amount of information, wall displays can be a good platform for the next generation of road traffic systems, going beyond awareness monitors to also incorporate forecast analysis and visualization when needed.

Current control center setups also suffer from divided attention issues [167], with operators monitoring live camera feeds, the entire

2 http://www.scoot-utc.com/
3 http://vision-traffic.ptvgroup.com

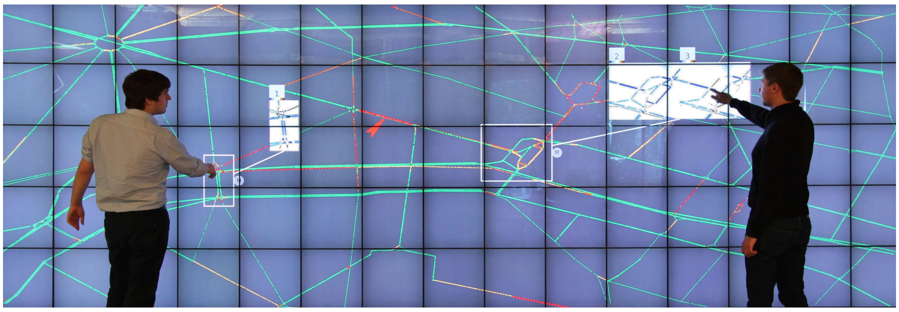


Figure 54: Visualization of traffic in a city with two "DragMagics" (white rectangles) showing one (left) and two (right) simulations associated with different possible interventions on the traffic. The simulation visualizations use difference color maps to highlight differences with the real traffic.

network on the visualization wall, and interacting through their individual workstations. If we consider additionally visually displaying the results of predictive models, the already challenging task of monitoring real-time traffic can become increasingly difficult. As such, for our prototype we decided to show the visualization of the prediction models on the main visualization, and test the limits of how many such prediction models users can comfortably monitor.

6.4 PROTOTYPE

In order to explore solutions for integrating the results of forecasting models to real-time traffic monitoring, we implemented a set of visualizations and interaction techniques within a functional prototype. The prototype is developed using Java and the ZVTM Cluster library [146] that allows it to run simultaneously on desktops and on a wall driven by a computer cluster (See Figure 54). Several desktop computers can share the view seen on the wall, but at different scales, as is currently done in control centers. On desktops, operators interact with mice and keyboard and their actions are mirrored on the wall.

On the wall we support two types of inputs: direct touch, and indirect touch using mobiles and tablets via the Smarties toolkit [39]. This dual input enables implicit zooming and context switching through movement [17, 21], leverages the benefits of wall displays in high information density tasks [118], and provides new opportunities for collaborative data analysis [97]. Such interaction requires physical navigation [17], that could fatigue operators working long hours. We instead envision they will be used occasionally: operators generally sit in front of their workstation, but when they address critical incidents or conduct planning sessions, they get up and interact with the wall. Focusing on a single shared screen could better support group work and awareness [72], and reduce the visual attention switch that occurs in MDE [154].

6.4.1 *Traffic data and modeling*

In our prototype, we represent each road network as a directed graph, with roads as links and intersections as nodes. The topography of existing road networks is extracted from OpenStreetMap data, or can be generated artificially (randomly) given a number of intersections and a desired road density.

Our system can process and display real-time streaming traffic-density data (e.g. data from the SURF3 system). To predict the evolution of current traffic, or of possible operator interventions, our prototype also models traffic. Roads are assigned speed limits, and intersection traffic-lights are assigned a duration. The duration of multiple lights (e.g. on a single road) can be synchronized as a group.

The current forecasting model is an extension of the Nagel and Schreckenberg one [139] developed by Chrobrok et al. [43]. It is based on cellular automata, and can model road networks with several lanes. At each intersection cars have a predefined probability of taking one of the available roads; this probability is calculated using real data, or the network topology favoring multi-lane roads.

A given state of the network can be cloned and used to run a forecasting model (accelerated) to (i) see a likely outcome of the current traffic, or (ii) see and compare the impact of possible interventions that adjust different parameters of the network (e.g. speed limit, lane closing, traffic light duration).

Our model is only a simplification of real road traffic, and more complex models have been developed in the field of traffic prediction using real-time data (e.g [8]). Nevertheless, our goal is not to develop a more accurate model, but rather to focus on the design of interaction and visualization techniques that can combine real time data and data from (multiple) forecasting simulations. Thus the traffic model is a plug-in in our prototype, so as to be able to incorporate and test different models in the future.

6.4.2 *Real Traffic, Visualization & Interaction*

To visualize real-time data, we follow the conventions used in traffic control that operators are familiar with. Traffic density is represented by a progressive color scale: green (fluid), yellow, orange and red (saturated). Depending on data availability, individual cars can also be displayed as circles with a line representing their direction and speed vector (Figure 55).

Operators can invoke context-aware tool palettes (left click for mouse, long tap for touch) to manage roads or intersections. For a road they can alter the speed limit, open or close individual (or all) lanes, and report accidents (Figure 56-left). For an intersection, they can act on light duration: change the proportion of red/green light time, change

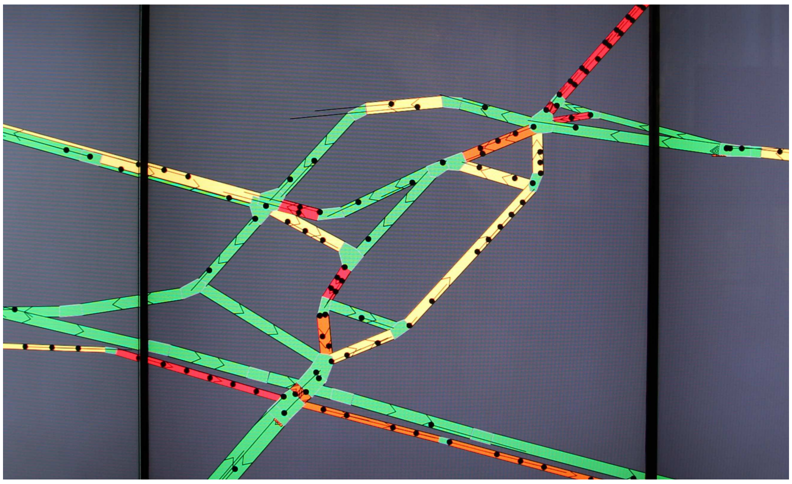


Figure 55: View of "Place de la Concorde" in Paris on our prototype.

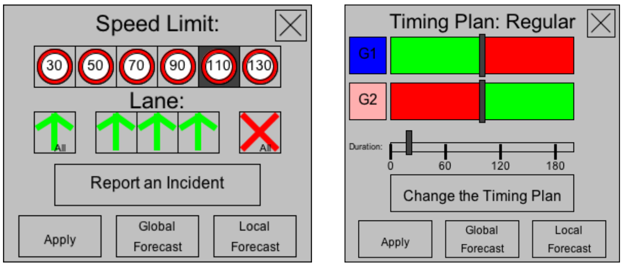


Figure 56: Context aware tool-palettes for modifying road (left) and intersection settings (right).

the cycle duration, or change the current timing plan with another (Figure 56-right). These changes can either be applied immediately to the traffic, or user can clone the traffic and create a forecast visualization (discussed next).

Operator interventions on real traffic are reported on the map with arrows. By selecting an intervention arrow they can undo the action, or "lock" it so that it cannot be undone, suppressing the marker.

6.4.3 *Forecasts, Visualization & Interaction*

We are interested in combining real traffic visualization, with likely *forecasts* of the potential future of this traffic, or of the impact of an intervention (e.g., closing a lane or changing light duration), calculated by traffic models. When operators invoke the tool palette to intervene on real traffic, instead of applying their changes, they can choose to instead start a forecast simulation. This clones the state of the real traffic and models the possible outcome of applying the changes, or the predicted outcome of the current situation sped-up.

Operators can intervene further on a forecast visualization, by changing road or intersection settings in the same way they do in the real-time visualization. They can choose to apply their changes to this

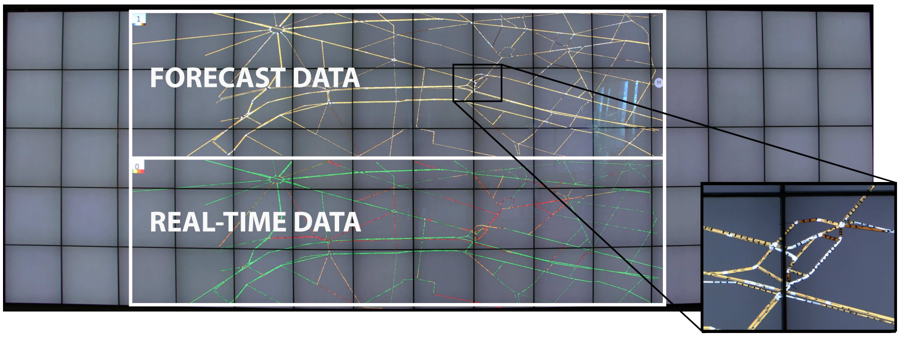


Figure 57: Global visualization of real traffic (bottom) and forecast (top) using MultiViews. A difference color map is used in forecast (cutout).

particular forecast visualization, to the real traffic, or even clone the forecast simulation and apply the changes to the clone. Thus, they can generate multiple branching alternative simulations if desired.

As operators often want to compare the result of forecasts to the baseline traffic to see if there is an improvement, we use difference maps (as Lampe et al. [110]): colors do not indicate an absolute measure (e.g. density), but rather a positive or negative distance from a baseline situation (real traffic). The selection of an appropriate color map is important to highlight differences [199]. We use a diverging color scheme, adapted to be clearly visible on a wall (Figure 57 top & Figure 58 DragMagic views). Three blue hues indicate improvement, three brown deterioration, and white color indicates a similar traffic density. These 7 colors represent all the possible amplitudes of the difference between real traffic and forecasts.

Based on our interviews, operators need to see two types of forecast results: *Global*, that show the forecast for the entire network; or *Local*, that are focused on a few neighboring roads and intersections, that we call an "area of interest".

GLOBAL (*multiviews*) When operators are interested in forecast visualizations focusing on global outcomes, they can create a new view of the entire network for each simulation, following the idea of small multiples [100]. One view always represents the real time traffic, while the others are forecasts calculated by the predictive model (Figure 57). The visual footprint of this technique is large as it has a visual impact on the entire display. Even though not tested, a creation of a *MultiViews* by one operator can possibly disturb others operators working on another part of the display.

Apart from using the tool palette, operators can also create new global forecast visualizations by tracing a vertical line inside a simulation to "split" its view, and create a perfect clone of it. Simulations are laid out on the wall using a grid optimization algorithm.

On the top left corner, global forecast visualizations have a unique identification number based on the order in which they were spawned,

Figure 58: A DragMagic with two forecast visualizations (top left) linked to its area of focus (inside white rectangle), and its menu open (right).

and a legend explaining the color range used in the view. They also have a button for invoking a tool palette, through which operators can change simulation settings, such as setting the prediction time frame with a slider from 0 to 30 minutes (a time duration considered to provide reliable results for our forecasting algorithm).

LOCAL (*dragmagic*) When operators want to focus on particular areas of interest, they can invoke a *DragMagic*, a variation of magic lenses [23, 121, 190] that displays the forecast only for that area. This local view is placed at an offset position to avoid obscuring the real traffic at this area. A DragMagic can also be created by tracing a corner shaped gesture to define the area to be cloned in the DragMagic. As with a DragMag [211], the forecast visualization can be dragged, and is linked visually to the area of interest that is itself highlighted. Several forecast visualizations of different intervention simulations, focusing on the same area of interest, can be displayed side-by-side to show the possible outcomes (Figure 58). The visual footprint of this technique is local as it concerns only a few roads. Although not tested, it likely won't disturb another operator working on another part of the display.

Similarly to the global forecast visualization, DragMagics have a number identifying the simulation they are displaying, and a button to invoke the settings palette (Figure 58). This can be useful if operators want to monitor the results of a single simulation on more than one area of interest. It can be used for example to aid operators visualize the impact of an action on critical areas not directly linked to the location of the action, that may be far away. Such areas include vital pathways for access to hospitals, sensitive locations such as long tunnels, or central traffic hubs.

6.5 MULTIPLE VIEWS VS. DRAGMAGIC

An important and novel functionality of our prototype is the visualization of forecasts in combination with real traffic, using *MultiViews* to provide a global view of the models' prediction for the entire network, and *DragMagic* to visualize locally the predictions for specific areas.

MultiViews are well adapted for situations where operators need to see the impact for the entire network, as they show global forecasts. When they are interested in a single small area of the network, *DragMagic*s are better for showing local effects. However, the situation is more complex when operators need to consider several areas of interest (critical areas) on the network. Due to the higher number and sparsity of areas of interest, this task is neither clearly local nor global, and thus it is unclear which technique fares best. *DragMagic* likely works well for few areas of interest, but as their number increases they approximate the entire network, and as such *MultiViews* may be better. Moreover, it is unclear how hard it is to follow multiple simulations running at the same time in order to decide between alternatives, using either technique. We thus designed an experiment to compare viewers' performance using *DragMagic* and *MultiViews* for this intermediate case, varying the number of simulations and areas of interest. As trade-offs between techniques are unclear, we focus this experiment on single users.

Our factors are: two techniques TECH, *DragMagic* and *MultiViews*; number of simulations #SIMU, with 3 values {2,4,6} (to simplify, we consider real-time traffic as a simulation); and number of areas of interest #AoI, with 3 values {3,5,7}.

In a trial, we showed participants several traffic simulations, where one ("simulation 0") is considered the reality and is coded with the classic red to green color coding. The rest use difference maps with simulation 0 (see Prototype). In *MultiViews*, on each simulation the areas of interest are highlighted using white rectangles. In *DragMagic* only simulation 0 is shown fully, and a DragMagic per area of interest is used to display the remaining simulations. For consistency, in the experiment all areas of interest contained exactly two roads, and simulations were updated every 10 seconds.

The layout of *MultiViews* was such that simulations had the same size, and were as big as possible while fitting on the wall. *DragMagic*s were positioned such that they were as close as possible of their area of interest, while not overlapping with other areas of interest or *DragMagic*.

In each trial, participants were asked four questions, separated by intervals of about 30 sec. Two questions were on the present state of the areas of interest, and two on their past history (inspired by tests accessing situation awareness that alternate and repeat questions on present and past, as in [91]):

Q_{pres} "At the present moment, which simulation is the best for the areas of interest?". Asked 1st and 3rd.

Q_{hist} "From the beginning of this trial, which simulation was the best for the areas of interest?". Asked 2nd and 4th.

When it was time for a question, an alarm rung, the simulations paused, and the question was displayed at the top of the wall. Participants gave their answer (the simulation number) using a smartphone. They were instructed to be as fast as possible while minimizing errors. We explicitly told participants not to perform a detailed comparison, but to give us their overall impression, especially for Q_{pres} where a detailed comparison is tedious but possible. Trials lasted 2 minutes plus the time taken by participants to answer the questions.

Our first working hypothesis is that:

H1 *DragMagic* will perform better than *MultiViews*, as viewers have to monitor a smaller area.

Following Plumlee and Ware [147] that link performance with the number of visual comparisons in a task, it is reasonable to hypothesize that increasing the number of simulations #SIMU and areas of interest #AOI will decrease performance overall. However, our experiment was not designed to evaluate the effects of #SIMU and #AOI, but rather to evaluate a possible interaction of TECH with #SIMU and #AOI. According to Plumlee and Ware [147] distance between comparisons can also deteriorate performance:

H2 *DragMagic* will perform better with a larger number of simulations #SIMU as the distance of the areas being compared is reduced; while *MultiViews* will perform better with more areas of interest #AOI, as its global view will be a good approximation of all the #AOI's.

6.5.1 *Experimental Design*

PARTICIPANTS Sixteen volunteers took part in the experiment (8 female, 8 male), aged 23 to 32, with normal or corrected-to-normal vision. As participants needed to tell the difference between several shades of the same color, they took the Ishihara Color Blindness test before the experiment to ensure they did not suffer from colorblindness. As our experiment is perceptual in nature (tracking of color changes over time) with no domain knowledge requirements, we believe that designing with experts and experimenting initially with non-experts is valid for measuring perceptual situation awareness (similarly to previous work, e.g., [91]).

APPARATUS We used an interactive wall (5.9m × 1.96m wide, with a resolution of 14 400 × 4800 pixels), made of 75 LCD displays (21.6 inches, 3mm bezels each), seen in Figure 54. The wall was driven by a rendering cluster of 10 computers. The experimental software, built on our prototype, ran on a master machine connected to the cluster through 1Gbit Ethernet. Participants answered questions using a smartphone.

PROCEDURE AND DESIGN The experiment is a $[2 \times 3 \times 3]$ within-participants design with factors TECH (*MultiViews* and *DragMagic*), #SIMU (2, 4 and 6) and #AoI (3, 5 and 7). We blocked by TECH and the order was counter-balanced between participants: half started with *DragMagic* and half with *MultiViews*. For each TECH, a first trial was used to explain the task, questions and the visualization (e.g., color code, areas of interest, simulation). Then participants conducted 3 training trials before proceeding to the 9 (=3×3) measured trials. For these 9 trials, the #SIMU increased gradually (first 2, then 4 and 6). And for each simulation number condition, the #AoI also increases gradually (3, then 5 and 7). We started with the a-priori easier tasks to try to reduce learning effects.

The network used are the main roads in Paris city center. Using our prototype we built 13 sets of simulations (4 for the training and 9 for the measured trials), by generating a large number of 2 min simulations and selecting ones with a similar number of color changes (about 1000 per simulation). Real traffic (sim 0) was also generated this way for consistency. To ensure a fair comparison across techniques, we took the original simulation sets, and built another 13 ones by changing the simulations order. TECH presentation order was counter-balanced consistently with the sets.

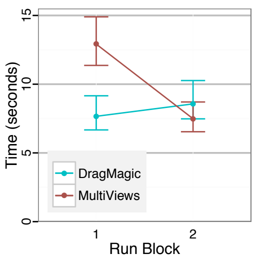
Sessions lasted 1 hour, and at the end participants completed a questionnaire on strategy, workload (customized NASA Task Load Index (NASA TLX) questionnaire) and preference.

MEASURES We recorded the time to answer the questions *Time*, and participants' answers. Time is important in a control room context, as operators need to evaluate situations and act quickly. In our experiment, slower answer times can indicate that in some conditions assessing a situation is harder and requires more reflection. When two or more simulations are displayed, a given imperfect answer could be better than another, as simulations have an order when it comes to improvement over the real situation. Thus, we define NError as: $(\mathsf{R}-1)/(\#\mathsf{Simu}-1)$ where R is the rank of the simulation when ordered from best to worst. Using #SIMU ensures we normalize the error per number of simulations. We also report on absolute number of errors per condition (Err).

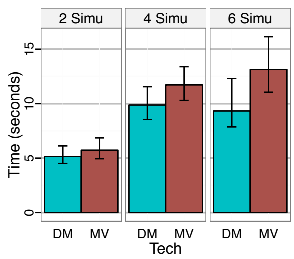
6.5.2 *Results*

Effect for *Time*	n, d	$F_{n,d}$	p	
TechOrder	1,14	2.48	0.137	
Tech	1,14	5.28	0.038	⋆
#Simu	2,28	31.8	<0.001	⋆
#AoI	2,28	3.77	0.036	⋆
TechOrder × Tech	1,14	6.44	0.024	⋆
TechOrder × #Simu	2,28	4.20	0.025	⋆
TechOrder × #AoI	2,28	0.56	0.565	
Tech × #Simu	2,28	2.61	0.091	·
Tech × #AoI	2,28	0.44	0.650	
#Simu × #AoI	4,56	5.38	<0.001	⋆

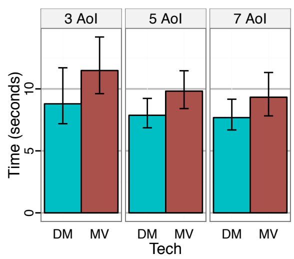
(a)



(b)



(c)



(d)

Figure 59: *Time* to answer for question Q_{pres}: (a) Results of the degree 2 ANOVA in the mixed model TechOrder × Tech × #Simu × #AoI × Rand(participant) (there is no significant interaction of degree > 2, all p's > 0.4); statistically significant results ($p < .05$) are starred, whereas a dot marks statistical trends ($p < .1$). (b) Time by Tech depending on whether a technique was run in the 1^{st} block or in the 2^{nd} one. (c) Time for each Tech by #Simu. (d) Time for each Tech by #AoI. In (c) and (d), DM stands for *DragMagic* and MV for *MultiViews*.

We first look at the results for Q_{pres}, the results for Q_{hist} are similar and discussed next. We noticed that the presentation order of Tech has an impact on the results, thus we report on the between-subject factor TechOrder. Error bars in our images represent 95% CI computed with all the data points using BCa bootstrapping. For post-hoc tests we use paired t-test with Holm correction.

6.5.2.1 *Time*

Figure 59-a shows the detailed ANOVA for *Time*. Tech has a significant effect on *Time* (*DragMagic* being faster), but we also have a significant Tech × TechOrder interaction. A post-hoc test shows that

DragMagic is significantly faster than *MultiViews* ($p = 0.007$, a speed-up of 33%) for participants starting with *MultiViews*, but not for participants starting with *DragMagic* ($p = 0.753$, almost the same mean *Time*). See Figure 59-b. Thus, *H1* is only satisfied when participants are mastering the techniques and task.

Note that the *Time* for *DragMagic* for both TECHORDERS, and for *MultiViews* when seen second are very similar, and all three significantly faster than *MultiViews* when seen first ($p\text{'s} < 0.009$). We see a positive learning transfer from *DragMagic* to *MultiViews*, while the time for *DragMagic* is similar irrespective of order indicating it is easier to master.

There is a significant effect of #SIMU and #AOI on *Time*, with significant interactions TECHORDER × #SIMU and #SIMU × #AOI, but no significant interaction with TECH (next paragraph). Post-hoc tests show that participants were overall faster with 2 simulations than with 4 and 6 ($p\text{'s} < 0.001$, no significant difference between 4 and 6 simulations, $p = 0.648$; see Figure 59-c). When starting with *MultiViews* this difference between 2 simulations and 4 or 6 simulations are bigger than when starting with *DragMagic* (the TECHORDER × #SIMU interaction). Surprisingly, when it comes to #AOI, participants were overall significantly slower with 3 AoIs than with 7 AoIs ($p = 0.025$; no other significant difference between the AoIs; see Figure 59-d). This difference is mainly caused by the case of 6 simulations (the #SIMU × #AOI interaction) and suggests that participants were able to use the time in between questions to select and focus on a few promising simulations, reducing the number of comparisons at answer time.

The TECH × #SIMU interaction is not significant ($p = 0.091$). However, the difference between the better performance of *DragMagic* over *MultiViews* grows with #SIMU and becomes significant with 6 simulations: $5.1s$ vs. $5.7s$ for 2 simulations ($p = 0.466$), $9.9s$ vs. $11.7s$ for 4 ($p = 0.146$), and $9.3s$ vs. $13.1s$ for 6 simulations ($p = 0.038$). Thus, the first part of *H2* is partially confirmed. Results do not confirm the second part of *H2*, as there is no effect of #AOI on TECH.

6.5.2.2 *Normalized Errors*

Regarding normalized errors, the only significant result is an effect of #SIMU ($F_{2,28} = 7.48$, $p = 0.002$). Participants made significantly more errors with 4 simulations (on average 0.13) than with 2 simulations (on average 0.06, $p = 0.02$. There also exists a trend for more errors with 4 simulations than with 6 simulations (average of 0.08, $p = 0.065$). We note that statistical trends with absolute number of errors are similar, with the additional difference between 2 and 6 simulations ($p < .001$). Mean absolute error was $0.06, 0.27, 0.20$ for 2,4, and 6 simulations respectively.

An important remark is that *DragMagic* and *MultiViews* exhibit very similar average normalized error, overall (0.087 vs. 0.086), and also depending on whether they are seen first or second (0.106 vs. 0.097 for block one and 0.068 vs. 0.076 for block two). The same holds for absolute error (0.18 vs. 0.185). Thus, the above results on *Time* cannot be attributed to a speed-accuracy trade-off.

6.5.2.3 *The $Q_{\mathtt{hist}}$ Question vs. the $Q_{\mathtt{pres}}$ Question*

Result trends for $Q_{\mathtt{hist}}$ are very similar to $Q_{\mathtt{pres}}$, we thus omit a detailed presentation of the results. For instance, we have a significant TECHORDER × TECH interaction ($F_{1,14} = 5.43$, $p = 0.035$), *DragMagic* is significantly faster than *MultiViews* for the participants starting with *MultiViews* ($p = 0.002$, a 26% speed-up), but not for the participants starting with *DragMagic*. Moreover, the *Time* for *DragMagic* for both TECHORDER and *MultiViews* for the participants starting with *DragMagic* are very close. Average errors are almost the same for the 4 conditions considered above.

Participants were overall significantly faster with $Q_{\mathtt{pres}}$ than with $Q_{\mathtt{hist}}$ ($p < 0.001$, 6.5s vs. 9.2s), and made significantly less errors ($p < 0.001$, 0.09 vs. 0.25). This is a reasonable result as $Q_{\mathtt{hist}}$ is more complex since it relies more heavily on memory.

6.5.2.4 *Subjective Results*

Eleven out of sixteen participants preferred to use *DragMagic* over *MultiViews*, a slight – non significant – preference for *DragMagic* ($\chi^2_{1,16} = 2.25$, $p = 0.134$). Seven out of the eight participants that started with *MultiViews* preferred *DragMagic* ($\chi^2_{1,8} = 4.5$, $p = 0.034$), while from the participants that started with *DragMagic*, four indicate a preference for *DragMagic* and four for *MultiViews*. Thus, TECH preference matches closely the results on time.

Regarding subjective mental workload, a TECHORDER × TECH interaction is again present. Participants starting with *MultiViews* reported a significantly higher mental workload for *MultiViews* than for *DragMagic* ($p = 0.008$, 4.8 vs. 3.9 on a $1-7$ scale), while for participants starting with *DragMagic* reported mental workload was similar between *MultiViews* (4.2) and *DragMagic* (4.1).

When reporting strategies, 10 participants explicitly mentioned they always chose 2-3 promising simulations to focus on, even when more simulations were actually visible.

6.5.2.5 *Summary and Discussion*

Participants starting with *MultiViews* were slower with this technique (without making less errors): participants starting with *DragMagic* were 33% faster with both *DragMagic* and with *MultiViews*, when compared to participants that started with *MultiViews*. The speed of *DragMagic* was fairly consistent across ordering conditions. The subjective results (preference and mental workload) show a similar trend.

Even if there is a learning effect on *MultiViews*, there is no such effect on *DragMagic*, which suggests that participants mastered the use of *DragMagic* faster than *MultiViews*. Moreover, using *DragMagic* has a positive learning impact on *MultiViews*.

DragMagic exhibits slightly better performance than *MultiViews* as the number of simulations increases, indicating that, as expected, reducing the distance between the simulations to be compared can be beneficial. Nevertheless, we did not measure any difference between *MultiViews* and *DragMagic* when the number of areas of interest increased.

Contrary to the model of Plumlee and Ware [147], we do not have a clear growing relation between *Time* and the number of comparisons needed to perform the task, in particular when it comes to the increase of areas of interests and number of simulations. This can be explained by the temporal nature of our task. Based on their comments, participants continuously compared simulations in the time between questions, not just at question time, and were thus able to identify and ignore ahead of time non-promising simulations, providing answers more quickly. Thus, the Plumlee and Ware model was not explicitly tested with tasks that have a temporal continuity.

When considering the traffic control context, our results indicate that both techniques can be effective for comparison of simulation results of possible interventions, without a strong performance difference once users become familiar with them. We feel this shows both designs as viable alternatives in terms of performance, and thus designers can choose based on other criteria, like space requirements, positioning of operators in the control room, areas to be monitored, etc.

Our study is perceptual in nature, thus we felt 16 non-expert participants were appropriate. Nevertheless, a larger number of participants could have provided more power to our results. Moreover, our study did not evaluate the interactive aspect of creating, managing and rearranging the *DragMagic* or the *MultiViews*. Finally, to ensure a realistic experiment duration, we fixed the time interval and changes between questions, but verifying that our results hold under varying intervals would strengthen our findings. These remain future work.

6.6 EARLY FEEDBACK FROM EXPERTS

A first user feedback session was conducted with three of our original interviewed users, using a combination of a desktop demo and a video of the prototype used on the wall.

Our interviewees found the idea of interleaving the results of real time traffic data and model predictions very useful. However, all explained that these visualizations would not be used constantly, rather occasionally in situations when the results of possible actions are hard to predict. Operators mentioned they would most likely interact with them from their workstations. Nevertheless, the operations manager explained that the setup of the walk-up and use wall (away from their workstation) could benefit operators in two ways: first by helping them focus on the task at hand without distractions such as camera feeds, etc. And second it could shift their attention away from the monotonous monitoring tasks, and thus alleviating boredom and improving overall performance.

All interviewees seemed to be more interested in the DragMagic visualization for comparing real and forecast data, as they give operators the information they need in the areas of interest "and also the state of the traffic around it".

Two operators thought separately of another use for our system not envisioned before. They felt our techniques can help them diagnose and predict problematic situations by comparing "benchmark" traffic data (past data recorded under normal conditions) with current traffic. As one explained, the system could suggest to operators to open the comparative visualizations when a big enough difference is detected. The visualizations could then provide context and help operators determine if the unusual behavior is a potential unreported incident that requires further investigation, or if the traffic situation is deteriorating and requires intervention.

They also highlighted the need to incorporate some additional functionality, such as the ability to update messages on electronic signs around the city and motorway for the public, and to integrate multiple global traffic light timing plans used currently in the city that we did not have access to initially.

One operator and the operations engineer are currently involved in the development of new systems that may include predictive models (without visualization). Both explained that our setup could also be very useful to their colleagues that work on improving traffic modeling for control centers. Their algorithms require careful tuning and they often need to run multiple small variations of them, that are hard to visualize concurrently on desktop screens.

A second user feedback session was organized later with the three control room managers of the PC Bédier, including one former road traffic operator, during which we demonstrated them the prototype running on our wall display. They confirmed the findings of the first session and discussed about the applications of the techniques in the PC Bédier control room.

With the opportunity of being the host of the Olympic Games either in 2024 or in 2028, Paris plans to modernize the management of its traffic, especially in the péripherique ring. Examples of modernization could be the use of ramp metering, giving the possibility to operators to close and open lanes and to modify speed limits. It will lead operators to act more on the traffic, and they will need to assess the impact of these actions, but most importantly, they will need to learn how to assess this impact. The managers though that the techniques could help operators to assess this impact, at least in the beginning, and help them familiarize themselves with the effect of these new actions.

6.7 CONCLUSION

In this chapter we propose using interactive wall displays in road-traffic control centers for interacting with real-time and simulated traffic data. After visiting three such centers, we designed a prototype that allows to monitor and act on the traffic (or on simulations) and, more importantly, to compare real traffic and several forecast simulations. To this end, we use two visualization techniques: Multi-Views and DragMagic, that were inspired by the findings of chapter 5, the first one with a global visual footprint and the second with a local one. We compared both in a laboratory experiment in terms of situation awareness.

The results show that DragMagic is easier to master, but that both techniques are reasonable design options for control centers, even for several simulations and areas of interest. It seems that the speed of monitoring tasks, that are temporal in nature, is not drastically affected by the number of comparisons in multiple views (predicted by the Plumlee and Ware model [147]). Viewers can identify and ignore non-promising forecasts, reducing the number of effective comparisons. Revising such models is interesting future work.

Expert users provided encouraging feedback and suggestions after seeing the prototype, appreciating in particular the use of DragMagic to follow forecast simulations while keeping the context of real traffic. They also found the prototype useful to compare real and past data to help identify possible problematic situations.

In this work, we only focused on the use of a wall display. However, as we stated in this chapter, the use of only a wall display, in that case, is not realistic, as the operators can't stand up for a long time due to fatigue. In the next chapter, we will study the collaborative use of a wall display integrated with several individual workstations. The different types of display fit the different types of collaboration needed (see Chapter 4). I will then present techniques to help operators to switch between the different collaboration styles, and so the different available displays.

7 INTEGRATION OF A UHRIWD IN A MULTI-DISPLAY ENVIRONMENT: APPLICATION TO CRISIS MANAGEMENT

In the three previous chapters, I focused on benefits of using wall displays in collaboration, and how the visual footprint of interaction or visualization techniques on such a display can influence monitoring and collaboration. However, complex collaborative tasks can take time, and continuously standing in front of the wall and walking to reach different areas of the workspace can cause fatigue. Additionally, in control room situations that have motivated our design, close collaboration is not always necessary: users sometimes have to work in parallel on different subtasks. For these reasons, UHRIWD, used for close collaboration can be combined with personal displays for users to work in parallel on different subtasks.

In this chapter, I give an example of how we could use a UHRIWD combined with workstations in crisis management situation rooms. I design techniques to help operators switch between loose and close collaboration phases, and implement them in a prototype of a crisis management system. For each technique, design rationale is grounded in earlier prototypes in this thesis and in related work.

7.1 INTRODUCTION

Shared surfaces, such as wall displays or tabletops, require, most of the time, users to stand in front of them. Complex collaborative tasks, such as brainstorming, data sense-making or emergency planning, can be time-consuming and constantly standing is not a viable option. Moreover, such tasks can be decomposed into many sub-tasks, some that require close collaboration and others that can be done by users in parallel. A way to handle such tasks and reduce fatigue from standing up is to combine personal displays, in front of which users can sit, with shared surfaces. We go from a SDG to a MDG system.

MDG systems, when they are composed of private and shared displays, allow for mixed-focus collaboration [71]: users can work in parallel on sub-tasks on their private displays (loose collaboration), or together on the same task on shared displays (close collaboration).

Mixed-focus collaboration requires several transitions between loose and close collaboration [186]. These transitions are well supported when everyone is working on the same shared surface, such as a tabletop, as all data are accessible on that surface and the work of one's colleagues is visible. However, in the case of MDG, these transitions are not straightforward. First, colleagues working in parallel in their private displays need to be aware of the activities of others to be able to identify opportunities for close collaboration. And second, when they decide to collaborate closely together and move to a shared display, they need to transfer their personal data from their private displays to the shared one.

In this chapter, we propose interaction techniques to aid these transitions in a MDE composed of a very high resolution interactive wall-sized display, several workstations, and other peripheral displays. We designed three techniques to aid workspace awareness and help identify opportunities for close collaboration, by displaying information about the activities of others. Our designs vary with respect to where this additional information is placed in the environment (superimposed with the data necessary for the task or displayed on the periphery), and with how long they are displayed (transiently or permanently). We additionally provided an interaction technique to transfer data from a private display to a shared display, it can be triggered directly from a workstation and from a tracked smartphone, to accommodate both seated and standing users.

We are motivated by crisis management situation rooms, which represent an extreme case of multi-display collaboration. Many operators (from 2 to 20), that come from different agencies involved in the crisis management, and thus have different roles and domains of expertise, need to effectively coordinate their plan of actions. We implemented our techniques within a larger prototype of a crisis management system that runs on a multi-display environment. We demonstrate their use on a use-case scenario based on a real crisis event: a helicopter crash in the city of London [12].

7.2 MOTIVATION

From Chapter 3, we learned that operators in control rooms, including situation rooms, faced two types of situation: *Normal situation*, during which operators focus on their own tasks (mostly monitoring) and work mostly in parallel, and *Exceptional situation*, during which, due to the complexity of the event, operators need to collaborate closely on the same tasks, they need more coordination and awareness of others' activities. This is a good example of mixed-focus collaboration, in which users need to switch between very loose collaboration to close collaboration.

In this chapter, we define several goals (G) for the design of crisis management systems using using data from Chapter 3 illustrated by concrete examples of crisis management situations. Examples include:

- The derailment of a freight train in a tunnel in Baltimore [182]

- The crash of a helicopter in the center of London [12]
- The flood of the Loire river in France [64]

G1: Colleagues can have different roles, and access to different information, in the collaborative environment.

The response team in a situation room is composed of highly specialized people from different agencies, who are each in charge of one aspect of the crisis management. The flood of the Loire required the involvement of more than 23 agencies in the crisis response, including police, fire brigade, first responders, water/power/communication/road network managers, public transportation managers and flood forecasting service. Each of these agencies had tasks to perform like monitoring road traffic, coordinating fire fighters and first responders, and managing public transportation.

G2: Operators should be able to share with their colleagues only data useful for the situation.

During close collaboration, operators need a very precise view of the whole situation, which means they need to have access to various data [111]. While sharing role-specific data between operators is important, access to role-specific data not relevant to the situation can confuse operators and alter their understanding of the situation [44]. For example, During the Baltimore accident, a main water pipe broke at the location of the crisis and started flooding the area. Firefighters had to work with public work administration officials to see how to access the train in these conditions. Eventually, both agencies had their own data and needed to share useful data: for the firefighters, it was the position of their units on site, and for public works it was the plan and information regarding the water network of the city.

G3: To serendipitously or actively seek out close opportunities for collaboration, colleagues need a good mutual awareness of where others are working on, and on what.

In situation rooms, close collaboration can be forced by the situation itself. For instance, when the first responders operator needs to collaborate with the road traffic operator to ensure ambulances avoid traffic jams caused by the situation. Or it can also be initiated by operators in a serendipitous manner, such as when they see their colleagues working in an area of interest to them. Due to the uncertainty of the situation, operators also often explore different strategies and possible outcomes to try and stay ahead of the evolving situation [111], actively seeking out colleagues working on their area of interest to discuss their plans. For example, weather reports are coming in, and as an area next to a hospital may be flooded soon, the first response operator seeks the road traffic operator responsible for that area to discuss re-routing alternatives. To initiate such collaboration, each member of the team needs to be aware of what others are currently working on, and where. This can be particularly challenging, as agencies and operators may be introduced late into a situation room.

G4: Colleagues need to have a good awareness of past activities in specific areas, or of specific operators.

During the transition to close and synchronous collaboration, colleagues leave a state of semi-synchronous collaboration where they worked concurrently on different sub-tasks [74], a situation where they partially lose awareness of others. So to start a close collaboration, operators may need some contextual information about recent work and the focus of their colleagues. For example, during the Loire flood, an operator of the power company needed to guide her team to a damaged power unit, saw that the traffic operator worked recently in her area of interest, so she knew she needed to provide less context for the situation in that area when she went to them to coordinate the best path for her team to take. A trace of recent activity of a specific colleague (not just activity in a specific area) can also be important, for example if the power company operator knows that the first responder operator has been focused on a specific area for the duration of the crisis, she can plan a path to damaged units that does not interfere with this area.

7.3 INTERACTION TECHNIQUES

In this section, we explain the techniques we developed to meet these goals in a multi display environment. Due to the criticality of the tasks performed by operators in situation rooms, it is important to make sure that the techniques don't disturb them, and don't hide important information. Disturbance is accepted and reserved for important alarms that require immediate attention from operators. Apart from operators' own data, any awareness information was presented following this constraint.

7.3.1 *Awareness Bars: persistent real-time awareness*

Goal 3 states that operators need good awareness of the current work of the others. More precisely, they often need to know who is working on which part of the workspace at any time (workspace awareness

Figure 60: Awareness bars. Top: Initially, the red and the blue operators are working on their workstation, they are both focusing at the same area, on the middle of the workspace. Middle: The blue operator pan to the left of the workspace. Bottom: The red operator zoom-out.

[72]). Because it is unclear when exactly they will need this awareness information, it has to be persistent in time (always visible).

7.3.1.1 *Related work*

In their work studying collaborative writing, Dourish and Belloti [52] studied issues of workspace awareness in a distributed environment. The authors present the concept of shared feedback, which consists in presenting feedback of users' activities in the shared workspace. Concrete examples of shared feedback were the representation of each user's cursor and of their text selection in the shared workspace. Gutwin and Greenberg [71] adapted this concept by displaying each user's pointer in the shared workspace: these pointers are called telepointers. This technique is problematic in multi-scale environments as users can be focused on different areas of the workspace and thus they cannot see each other's cursor.

For multi-scale environments, Gutwin and Greenberg [71] proposed the use of a radar view, that consisted of a small simplified map of the workspace that displayed the telepointers and of rectangles which represented each user's viewport. Finally, Gutwin et al. [73] also proposed to use multi-user scrollbars as workspace awareness widgets: on each user's screen. Additionally to their own scrollbar, there are also the position of others' scrollbars. These techniques provide information regarding the areas of the workspace on which others are focused and can help users see who is working on the same area as them.

The previous research focused on traditional distributed environments composed of several desktops. Roussel and Nouvel [161] suggested to replace traditional cursors with real-time videos of users' hand in order to ease gestural communication. Doucette et al. [51] compared different designs of virtual arm embodiments to represent the others' arms positions on distributed interactive tabletops and their impact on workspace awareness. They showed that virtual arm embodiments with a high level of occlusion provided a high level of workspace awareness. However, the higher the occlusion, the more awkward it was to interact and the less users crossed the embodiments.

To conclude, an efficient way to enhance workspace awareness, especially with distributed environments, is to provide shared feedback of users' locations. The shared feedback can be directly displayed on the shared workspace (e.g. telepointers and virtual arm embodiments), displayed at the edge of the screen (e.g. multi-user scrollbars), or on larger dedicated areas of the screen (e.g. minimaps) present on each user's screen. When displayed on the workspace, it is important to find a balance between awareness and occlusion of important information.

7.3.1.2 *Design choices*

Our environment is very different from the distributed ones presented in the related work. It is composed of several workstations (which can be considered as distributed) and of a large high resolution vertical shared display.

The workstations are dedicated to the role-specific tasks of the users. When using their personal workstation, users can be in the middle of a cognitively heavy task; and displaying information about others' activities (e.g. telepointers, multi-user scrollbars) needlessly could attract their attention. Additionally, it clutters the screen. The use of minimaps can restrict this type of information to a specific area of the screen. Users can avoid distraction as they can choose to look at it only when they need workspace awareness. However, minimaps may not scale well with a high number of collaborators and the large size of the workspace.

Because of its size and the fact that it displays the whole scene, the shared wall display makes a good alternative to display awareness information, even though this requires operators to split their focus occasionally. A possible awareness visualization is to display a telepointer for each operator on the wall display. However, the small size of the pointer make it difficult to spot [103], a situation that will become even more challenging if a high number of operators are present in the room. Moreover, telepointers show a single location and make it hard to determine the larger areas the operators are focusing on.

As an alternate to simple pointers, we first considered displaying the viewport of the workstations directly on the wall. This can be achieved by displaying directly colored rectangles on the wall which represent the area the operator is focusing on (as it is done in minimap). We implemented it in our prototype and observed that when more than 4 operators are working around the same area, it becomes hard to understand where each of them is working exactly and the screen becomes cluttered. It is also difficult to distinguish it from the background when the rectangle is large (because the workstation of the operator is very zoomed out). Finally, in anticipation for *Goal 2* where we want to use magic lenses, the lenses can be easily confused with this viewport rectangle.

Inspired by the multi-user scrollbars, we finally decided to display the same information (size and position of workstations' viewport), but in the form of bars at the edges of the wall display. Thus, it is possible to make the visualization of awareness visible without cluttering the screen. The x-position of the bars at the top and bottom edges of the display represent the x-location of the viewport, the y-position at the left and right edges represent y-location of the viewport (See Figure 60). The size of the bars change depending on the zoom level as the viewport covers different size areas. And their color matches the color attributed to the operator. When the operators pan and zoom in their workstation, the bars move and scale accordingly.

At first, we also mapped the y-location of the viewport to the y-position of the bar at the top/bottom edges (and same for the x-position for the right/left edges). But when several operators were working at the same area, the bars superimposed, which was confusing. We decided to give a fixed y-position to the bar at the top/bottom edges (and a fixed x-position for the right/left ones). This y-position depends on the order of connection of the operator's workstation to the application. Thus, when several operators are working at the same place, the bars are stacked in the same order and it is easy to distinguish between operators.

Finally, it is easy to notice when someone is working on the same area, because their bars will occupy the same location. The operators can see this information from their workstation (top edge) or when they stand in front of the wall (bottom edge). It can support a large number of operators as long as the colors assigned to their bars are distinct.

However, this technique displays information only about operators on the workstations, but not when they are standing in front of the wall. As we tracked the position and orientation of the head of a standing operator, it is possible to determinate the area on the wall at which she is focused [150]. We tried to display this area using the same technique, but as we tend to move our head continuously, it became quickly disturbing. The disturbance caused by updating bars using head tracking was too large, especially considering that it is easy to guess where a person standing in front of the wall is looking. So we did not include it in our final prototype.

7.3.1.3 *Summary of the Awareness bars technique*

- Position: Border of the wall display
- Temporality: Permanent
- Activation: None
- Visual representation: Colored bars
- Encoded information: Top and bottom bars represent the x-position and width of users' viewport. Similarly for right and left bars with y-position and height
- Concerned goal: Goal 3

7.3.2 *Focus Map: past & current focus awareness on-demand*

Following *Goal 4* we want operators to also know the past focus of other operators. We tried to address this by displaying a trace of the

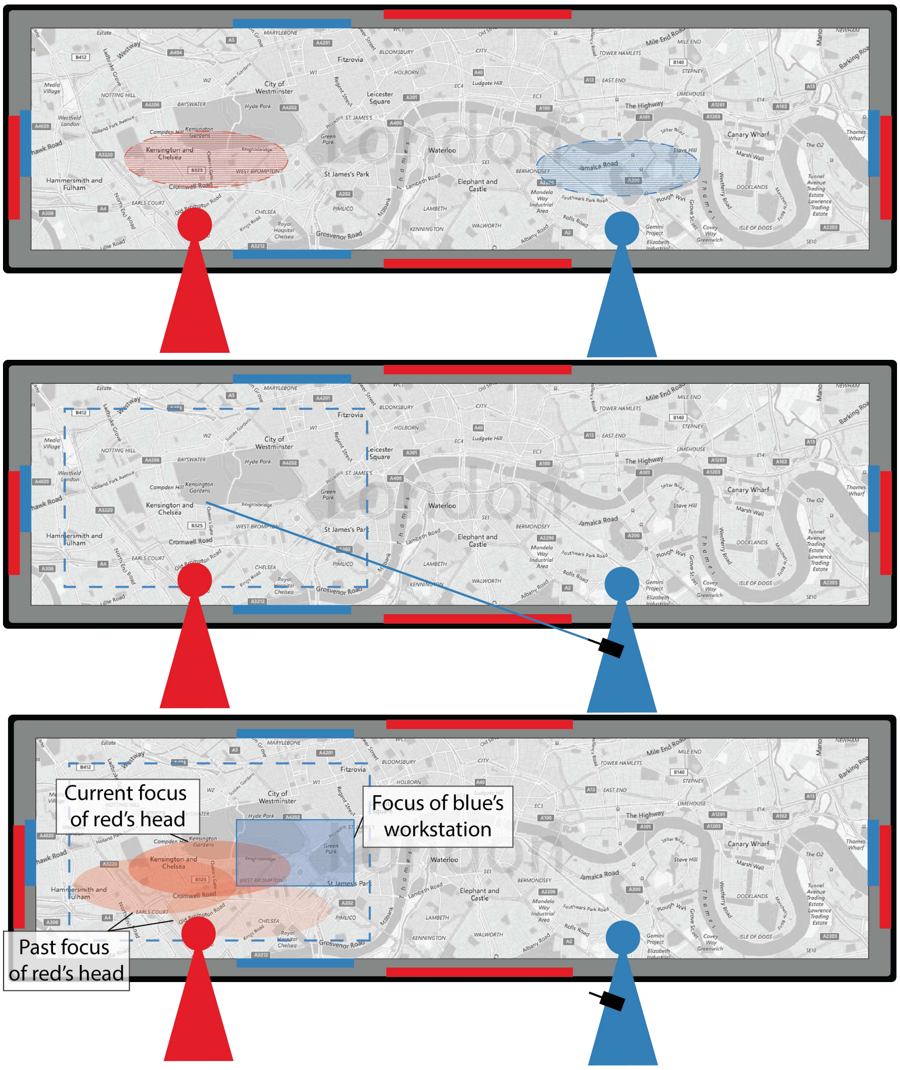


Figure 61: Use of the focus map technique on a specific area. Top: Initially, the red and the blue operators are working in front of the wall. Middle: The blue operator asks for a focus map for a specific area (dashed rectangle) by selecting the area using a tracked smartphone. Bottom: The history of focus of both operators is displayed for this area.

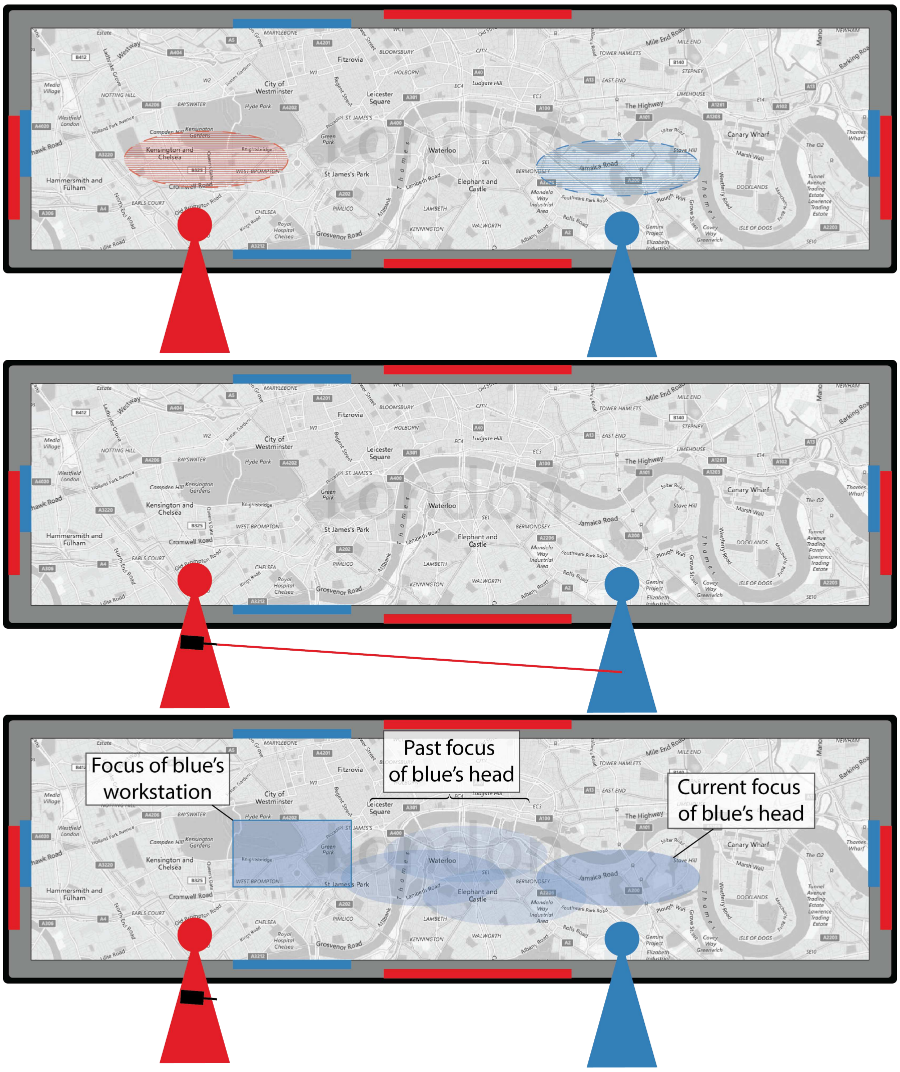


Figure 62: Use of the focus map technique on an operator. Top: Initially, the red and the blue operators are working in front of the wall. Middle: The red operator asks for a focus map for the blue operator by pointing at her with her tracked smartphone. Bottom: The focus map for the blue operator is displayed for the entire workspace.

movement of each awareness bar. This trace would fade away over time, giving an appropriate idea of both the time and location of areas of focus. But because of the constraint space in which bars move, it soon became crowded and illegible.

7.3.2.1 *Related work*

The awareness of past activities is mostly present in asynchronous or semi-synchronous collaborative systems. For instance, in git, the command *git diff* shows to the user the difference between commits. Dourish and Belloti [53] suggested that it could be done in their collaborative text editors using margin colored marks indicating text areas that had been changed. Both of these techniques automatically highlight changes, but it is also possible to let users decide what changes to highlight regarding their activities, for instance by allowing them to add annotations [35].

With large workspaces, even in a synchronous system, it could be difficult to keep track of all of each other's activities. One solution is to use a timeline that summarizes each user's activities. This solution has been adopted by Chang et al. [38] for a complex collaborative game on tabletop and by Kulyk et al. [107] for scientific exploration of data on a shared display. Another solution, designed by Bezerianos et al. [20], is Mnemonic Rendering. It consists in spatially representing a summary of changes of elements by superimposing a semi-transparent layer of the previous state of the interface.

7.3.2.2 *Design choices*

We could have designed a technique that visualizes all the actions done by the other operators, nevertheless, we think that the area on which operators worked before are more important than the performed action itself. First, operators spend an important amount of time monitoring the situation, during which they do not perform any actions. Further the actions performed are often role-specific, and so other operators are not always qualified to understand it. Finally, it is important to know in some situations where an operator has not looked (e.g., to see if an operator missed an important event). Thus, we decided not to display the actions of operators, only their area of focus.

Whether it is to grab a brief summary of the situation or to obtain context about the past focus of another operator before starting a close collaboration, the operators need information on past actions at a specific point in time and actively look for it at that time. It is thus possible to display this information on demand and for a limited amount of time.

Similarly to the previous technique, it seems difficult to display past actions only on the workstation. Plus, even the fact that an operator is requesting this information can be of interest to others. For example, if others are working on the requested area, they may be interested to see that someone else is interested in this area. We decided therefor to display it on the wall display.

We continuously record the focus of each operator. The focus is represented by the viewport of the operator's workstation when she is seated, and the area she sees when she is standing in front of the wall. In the later case, this area is calculated using the position and the orientation of the head of the user. Operators can invoke a focus map for the entire wall and for all operators.

It is also possible, for an operator, to invoke a focus map for:

- A specific area, she can select this area directly on the wall, and a colored heatmap will display for each operator who focused on this (See Figure 61). The color saturation represents the amount of time spent at each position. Once the area is selected, the operator can modify its size (see Section 7.4).

- A specific operator to see where she has focused. In that case, the activation is done either by selecting the operator on a menu on the workstation or by pointing at her with a tracked smartphone [117] (See Figure 62).

With this technique, we can take into account head movement information, since we display the density of time spent focused at each location, movements will contribute very little to the overall color density.

By default, the technique displays the history of focus since the start of the system, but we decided to allow the user to filter time ranges in this history when it is displayed. This allows users to focus on shorter time periods that could be of interest for them, but also to observe the evolution of focus for one user or one area since the start of the crisis. When users ask for a focus map, a range slider appears either on the smartphone or on the workstation (it depends on the device of activation). The user can manipulate the period of displayed history by manipulating both cursors of this range slider.

This technique allows operators to explicitly get access to brief awareness information of the past on specific areas, with limited disturbance for their partners.

7.3.2.3 *Summary of the Focus map techniques*

- Position: On the wall display

- Temporality: Temporary

- Activation:

  - From a workstation: Select an area on the wall to display the activities of all the operators for this area. Or select an

Figure 63: Step Map. The red and blue operators work in front of the wall. Their identity is confirmed by the colored circle around them. The red operator was before directly at the left of the blue one but moved recently more to the left. It is shown by the fading away red circles.

operator on the menu on the workstation to display the activities of this operator

- With a tracked smartphone: Select an area on the wall to display the activities of all the operators for this area. Point to an operator to display the activities of this operator

- Visual representation: Colored heatmaps
- Encoded information:
  - For a selected area: For all operators, it displays a colored heatmap for the history of focus on this area (While on their workstation or standing up in front of the wall)
  - For an operator: It displays a colored heatmap of history of focus of this operator for the whole wall
- Concerned goal: Goal 4

7.3.3 *Step Map: transient operator's identity awareness*

With the two previous techniques, it can be hard to associate an operator with the color displayed on the wall, especially if she is standing in front of it (we can imagine that a workstation can be colored). *Goal 1* states the importance of being able to identify each operator and their role.

7.3.3.1 *Related work*

The tracking of users in front of a wall display is not something new; it has been done in the design of proxemics interaction, which is the use of the position and orientation of users to provide adapted interactions with available displays [69]. However, in proxemics research this information is only used by the computer and rarely displayed.

In remote collaboration in front of wall displays, real-time awareness of users' actions is difficult by definition. One solution is to represent the remote collaborators on the display, superimposing the workspace according to their positions. It is possible to do it with more or less fidelity. Kister et al. [105] represent the outline of the collaborators' figures. Zillner et al. [220] used kinects to scan and then reconstructed with high fidelity the body of the collaborators. Finally, Avellino et al. [10] used arrays of cameras to film the users in front of the walls and then displayed video streams of the collaborators.

7.3.3.2 *Design Choices*

Real-time awareness of users' actions needs to be persistent and thus shouldn't be superimposed with the main scene to avoid disturbing other operators. We choose to display this information on the ground: due to its peripherality, it is less disturbing for operators working on their workstation, and it is directly linked to the standing user.

Our technique consist of drawing a colored circle around the operator's feet, with the color associated to their role (See Figure 63). We also choose to provide some information on the past position of the user, as a persistent way to provide awareness of the past focus. Nevertheless, to avoid cluttering the ground with colors, this awareness of the past is limited in time: after a specified time, the trace fades away.

This technique provides a way to identify operators that are standing in front of the wall, and a rough history of their position, as awareness information of the past.

7.3.3.3 *Summary of Step map the techniques*

- Position: On the ground
- Temporality: Displayed when the operator is standing up in front of the wall
- Activation: When the operator arrives in front of the wall
- Visual representation: A plain colored circle for the position of the operator. It fades away slowly
- Encoded information: The plain circle show the identity of the operator. It fades away slowly which allow a mapping of past position
- Concerned goal: Goal 1

7.3.4 *Data-lenses: data transfer between workstations & wall*

Goal 2 states that operators should be able to transfer their data from their workstation to the wall. We will first talk about the previous

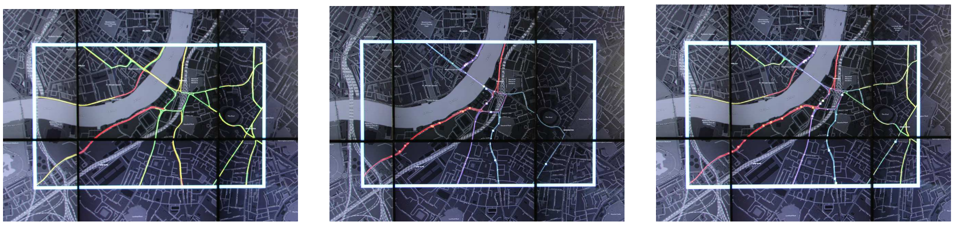


Figure 64: Data Lenses. Left: Data lens with traffic data. Middle: Data lens with public transportation data (network + buses position). Right: 2 lenses superimposed, one with traffic data, and one with public transportation data.

work done to do this and then explain how we adapted it to design our technique.

7.3.4.1 *Related work*

In collaborative MDE, it is necessary to be able to transfer data between the different displays. A first way to do this is to control what to display on each surface from a central display. In Multispace [62], Everitt et al. manage the transfer of data between the different displays using a tabletop. Similarly, Widgor et al. [213] used also a tabletop to manage the transfer in their interactive space for real-time collaboration.

Another solution, that depends largely on the type of display involved, is to design mechanisms to directly transfer from one display to another. For instance, Rekimoto and Saitoh [156] worked with an environment composed of a large display, a tabletop and a desktop. They tracked all the displays and designed a technique called Hyperdrag that allowed drag and drop between all of them using a mouse.

Direct transfer has been widely studied in multi display environments composed of an interactive shared display and several private displays. Two types of techniques stand out: virtual portal and physical proxy. The first consists of a matching pair of containers for each user, one in the private display of the user and one in the shared display. The users just need to put an object in one container to transfer it to the other container. The physical proxy is a physical object use to "stock" the object during the transfer. The proxy is also used to select the object to transfer and to select the position to which to transfer it. The physical proxy can be the hand of the user [168], or handheld devices[217].

Scott et al. [168] compared both types of techniques in a card game, using the hand of the user as a physical proxy. They showed that virtual portals required more physical efforts but felt simpler and more transparent to use. On the other hand, physical proxies was more efficient, but the lack of feedback during the transfer was disturbing for the user. Bachl et al. [13] also compared both types for a card sorting task, but they used a handheld device as physical proxy. They showed that the use of physical proxies was again more efficient, but the users found it more complex to use. Finally, Schmidt et al. [165] did a similar study but on a copy-paste task. Again, the use of physical proxies was a little faster. The use of a handheld device as a physical proxy can be a little more complex to use, but it is more efficient as you can select directly the object to transfer and place it at the location you want. Additionally it can easily provide feedback to the user during the transfer. On the contrary, the use of virtual portal is very easy to understand, but requires to move the object to the portal, and then to move it from the portal to the desire location. Several projects used a handheld devices directly to transfer. Sugimoto et al. [183] in Caretta and Seyed et al. [170] in SkyHunter show how they used it to transfer data from a tabletop to ipads. VonZadow et al. [217] and Langner et al. [112] used it to transfer objects between a smartphone and a wall display.

In this project, we decided to use handheld devices as physical proxies to transfer data between the workstation and the wall display. We also allowed users to transfer the data from their workstations using their mouse.

In order to reduce clutter on the shared display, a transfer of data to the wall display actually create a magic-lens which displays the data only for a specific area. Lenses have been used in the past on wall displays like in Bodylenses [105] where users created lenses on a wall display that could match their shape and their position; and Smarties [39] which allowed the control of lenses on a wall display using handheld devices. In our context, we want to allow both types of control: using the operator's position and a handheld device. We call this type of lens Data-lens in the rest of the chapter.

7.3.4.2 *Design choices*

A data-lens, with operator specific information, can be created either from the workstation, or directly in front of the wall display using a tracked smartphone. We can assume that lenses will often be created just before collaboration and so can be created from the operators' workstations. But operators can also decide to create a new lens during collaboration, so a way to create it without going back to the workstation is also important.

A data-lens belong to the operator who created it; only this operator can manipulate it, and when she moves away from it, it slowly fades away to disappear completely so as to not clutter the wall. The creator of the lens has access to a menu by clicking on the lens. Different action are possible:

- Destroy the lens

- Activate/Deactivate the "Follow me" mode: In the "Follow me" mode, the lens follows the operator when she moves in front of the wall.
- Activate/Deactivate the "Pin it" mode: In the "Pin it" mode, the lens will not fade away when the operator leaves the wall. When a lens is created from the workstations, this mode is automatically activated.
- Change permission: The creator can allow another operator to manipulate the lens

To create a data-lens, operators select an area using either a tracked smartphone or the workstation, and then select the data to display in this area.

Finally, it is possible for operators to stack several data-lenses in order to have different types of data for the same area (as it is done in MultiLens [104]).

The data-lenses allow operators to transfer easily the needed data to the wall for a close collaboration. Then, they can decide to let it on the wall for use by other operators, destroy it or let it fade away.

7.3.4.3 *Summary of the Data-lens technique*

- Position: On the wall
- Temporality: By default, a lens disappears slowly when its creator goes back to her workstation. However it is possible to pin it to make it always visible
- Activation:
  - In front of the wall: select the location and the size of the lens using the handheld device, then select the data to display
  - From a workstation: select the location and the size of the lens using the mouse, then select the data to display
- Visual representation: Data are displayed with a transparent background
- Encoded information: The data requested for the corresponding area
- Concerned goal: Goal 2

7.3.5 *Summary*

Table 4 proposes a summary of the main characteristics of the presented interaction techniques:

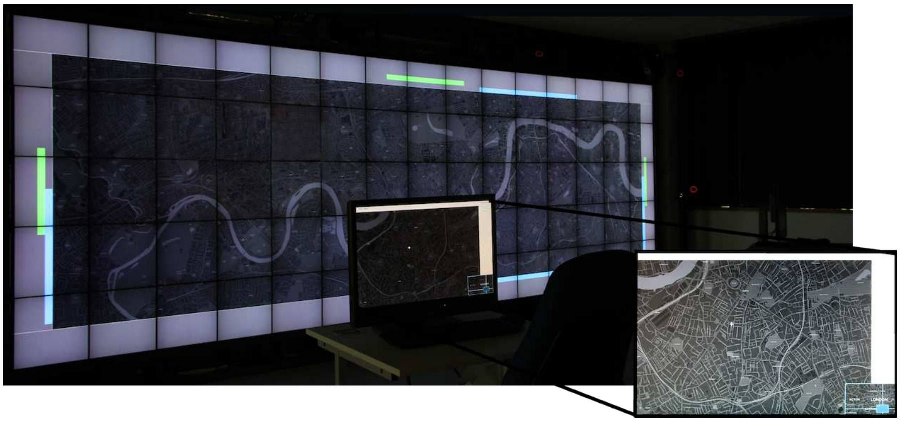


Figure 65: Prototype of the crisis management system running on a wall display and workstations

- The concerned goal
- The position
- The temporality

Technique	Awareness bars	Focus map	Step map	Data-lenses
Concerned goal	Goal 3	Goal 4	Goal 1 and Goal 4	Goal 2
Position	Periphery: Border of the wall display	In the focus: On the wall display	Periphery: On the ground	In the focus: On the wall
Temporality	Permanent	Temporary	Permanent	Permanent or Temporary

Table 4: Summary of the interaction techniques

7.4 PROTOTYPE

To help us design our interaction techniques, we implemented a broader prototype of a crisis management system, which runs on a multi-display environment (See Figure 65). The environment setup includes: a very high resolution wall-display made up of 75 LCD displays (in total 5.9m $\times$ 1.96m wide, with a resolution of 14 400 $\times$ 4800 pixels), driven by a computer cluster, and overlaid with a PQ Labs layer for multi-touch detection; six workstations; two mounted projectors for displaying operators' moving traces; and a VICON motion tracking system for tracking operators and devices.

The prototype is developed in Java using the Multi-Scale Scene Manager for ZVTM (ZUIST) Cluster library [146], which allows it to run seamlessly on the desktops and the visualization wall. On the desktop, operators interact using mice and keyboards. On the wall, they can interact directly using touch, or indirectly using mobile devices that are connected to the prototype via the Smarties toolkit [39] and whose position and orientation is tracked.

7.4.1 *Modeling the crisis scenario & role-specific data*

The basis of the visualizations on both workstations and the wall is a tiled map. On their workstations, operators can focus on a part of the map through pan and zoom. The shared wall shows a zoomed-out view of the map that is of fixed scale, similarly to what is done in actual control rooms, to avoid conflicts of operators requesting different zoom levels.

Our prototype reads a `graphml` file of the road network of the crisis area. We extracted the road network of London from OpenStreetMap and converted it in graphml, using the osmnx library [25]. On this network, the road traffic is simulated using the Lighthill-Whitman-Richards (LWR) model [116], which is a macroscopic traffic flow model. While our prototype can read streamed traffic data, we simulated the traffic for our scenario. The traffic density is then represented on the road network using a three color scale (green, yellow, red). This traffic data is accessible to the road traffic operator who can act on the network to reroute traffic (e.g., closing roads or lanes, changing traffic light duration, etc).

Public transportation companies often have an open data policy, making their transport network information available to third parties. Our prototype can read Comma-Separated Value (CSV) files with geographical position and order of all the stations on a public transport line, as well as its planned timetable. Bus line stations are positioned on the road network, and using the Dijkstra algorithm, we compute the path taken by buses between stations. We simulate the circulation of buses on the line using the departure time from the timetable, and the traffic density of the network. The paths of individual bus lines have a predefined color and buses are represented as small colored squares moving on them. These data are accessible to the public transport operator who can redirect buses.

Finally, we retrieve the position of important buildings for first-responders units (hospitals, fire stations, etc.). The prototype displays them with a red-cross glyph, and simulates first-responders vehicles (shown in white), that move on the road network. As with buses, the movement speed of these vehicles is impacted by the traffic density of roads it traverses. The first response operator has access to these data and can redirect the first-response vehicles.

The role-specific data are displayed on the workstation of the appropriate operator, but as we explained we do not display all of them on the wall. Nevertheless, parts of it can be displayed on the wall on demand using data-lenses (Section 7.3.4).

7.4.2 *Interaction*

There are two kinds of interactions: ones that act on the data and are role-specific; and general system control interactions that are available to all users want to interact with the shared display wall to activate the techniques described in the previous section.

7.4.2.1 *Activation of data-lenses and focus maps*

Users can chose to display a cursor on the wall, controlled either from desktops in a "wall mode" (for when operators are seated), using touch when operators are in-front of the display, or using tracked smartphones that can act as laser pointers when operators are moving.

When a user clicks, a dashed colored rectangle is displayed on the wall at the click position. The size depends on the area of focus of the workstation (if triggered from a workstation), or on the distance of the user from the wall (if she is standing in front of it, triggered either by touch or a mobile device). The rectangle can be dragged, and its size can be changed using the mouse wheel on the desktop, by a specific button on mobiles, and a pinch gesture for the wall touch. When the user clicks a second time, she validates the size and position of the rectangle (a click with any input outside of the rectangle will remove it). When the rectangle is validated, a pie-menu opens, and the user can either create a data-lens with their dataset, or they can request to activate a focus map to see others' activities for this area.

Instead of choosing an option in the pie menu, users can point at another user using the tracked smartphone (or select another operator in the menu on the workstation). A new pie-menu will be displayed with the dataset of the selected user. If they have the right permission, they can display the data of this selected user.

If users selects a data-lens (by clicking on it using the workstation or the mobile), they will see a pie-menu with several options. If they are the owner of the lens, they can delete it, enter in the "Pin it" mode, enter in the "Follow-me" mode, or access the "user menu" option to give right permission to others. Using drag and drop, they can also move the lens. If a user is given permission to manipulate someone else's lens, they have permission to manipulate it, enter in the follow-me mode (if the owner is not already using it), but can't modify permissions.

The "user menu" option of a lens, opens a display of colored circles that represent the operators registered in the system. A colored link is drawn between the owner's circle and the lens, and dashed links are drawn to the color of operator roles that have permission to manipulate it. The owner can click on operator colors to turn on/off manipulation permissions.

7.4.2.2 *Role-Specific Interaction on Data*

Role-specific interactions are accessible through menus that can be invoked by a long press if the operator is standing in front of the wall, or right mouse click on the workstation.

Each operators can do specific actions that have an impact on the situation. The road traffic operator can adapt speed limits, close roads or lanes, and change traffic light duration. The public transportation operator can reroute buses, either to a specific location or direct them to a station. The emergency services and the police can direct their vehicles in the city.

Additionally, all operators can put a specific symbol to mark a street that has been involved in the crisis.

7.5 scenario

To better illustrate the use of our techniques in a crisis management context, we walk through a potential scenario involving a helicopter crash, inspired by an actual event: the helicopter crash of Vauxhall in London [12].

A helicopter crashed in downtown London. Several pedestrian and drivers are injured, and the roads surrounding the crash site are blocked. This situation hinders the movement of the first responders vehicles.

At the beginning of the scenario, before the crisis starts, only the road traffic controllers, the bus operators and the room leader are present in the control room. The room leaders is in charge of the coordination between all agencies in the room and of the communication with the general public. He starts with a short briefing to the operators present in the room. They all stand up in front of the wall, the room leader adds the position of the debris and explains the main strategy to deal with this crisis.

Once he finishes, the operators go to their workstation and start doing their tasks. There is much uncertainty about the current situation. The road traffic controllers need to reroute the traffic to avoid drivers going to the dangerous area. The bus operators have to guide the buses trapped in the crash site out of it, and the other buses must circle around the area to limit delays and ensure passenger safety.

The leader contacts additional agencies, and medical dispatchers and police operators arrive later in the situation room. They first get a briefing of the situation by the room leader. Using a tracked smartphone, she selects the area around the location of the crash and asks for the history of focus using the Focus map method (*Goal 4*). The heatmap displayed shows where the other operators have been working, and allows a better understanding of the situation. For instance, they see that the road traffic controllers have focused a lot on the east side of the crash, which means that the roads on this side are or will be soon cleared of traffic, allowing first responders and police vehicles to pass. After that, they go to their own workstation and start deploying their units on site to respond to the situation.

Due to unreported debris, ambulance drivers need to take an alternative route using roads not cleared of traffic yet. They contact the control centre. As there are injured people on board, they need to get to the hospital quickly. The medical dispatcher looks at the awareness bars on the wall display and sees that a road traffic controller is working on the area that could provide an alternative route for the ambulances (*Goal 3*). She finds where she is seated by looking at the color of her workstation, goes to meet her, and explains the situation. They decide to work together to find the best way for the ambulances to arrive quickly at the hospital, by rerouting traffic if needed. They both transfer their data to the wall for the area in question by creating data lenses: the road traffic controller creates it from her workstation, the medical dispatcher uses her tracked smartphone to avoid going back to her workstation (*Goal 2*). They both move in front of the wall, and the step map shows their position with a history trace on the ground.

The two operators continue moving in front of the wall following the path taken by the ambulances. A police operator sees the trace they left on the step map and understands that they are working on an area of interest for her a few minutes earlier. The traces map also give her the identity of the operators in front of the wall (*Goal 1*). She needs to deploy police units in this area and wants to take advantage of the "free traffic" path just created for the ambulances, so she stands up and joins the two operators in front of the wall to discuss her plan and collaborate with them to make it happen.

7.6 CONCLUSION

In this chapter, we proposed designs to use in a MDE composed of a UHRIWD and several workstations for crisis management. Our three interaction techniques (awareness bars, focus map, and step map) help the transitions between parallel work and close collaboration in this environment. They provide additional information about operators' activities. They either display this information on demand (focus map), in which case it is displayed for a limited time on the wall, or it is displayed permanently at the periphery of the wall (awareness bars and step map). We also designed techniques to transfer data from personal workstations to data-lenses on the wall.

Using a scenario of a helicopter crash in the center of London (based on a real event), we show how these techniques can be used and help operators efficiently switch from parallel work to close collaboration.

As none of these techniques have been empirically evaluated, it would be interesting in the future to assess their performance in a laboratory experiment. The task used should be abstract enough to allow a generalization of the result. However, as in Chapter 4, it should be complex enough to require collaboration from the participants. Finally, the required collaboration should be mixed-focused, with subtasks that should be done in parallel and subtasks that should be done by all users together.

Another direction of future work would be to improve the techniques to display more information than just the position of areas of focus. It could be possible to display the detailed interaction done by users for example. Nevertheless, it could raise possible issues: too many details could clutter the visualization and slow down the understanding of the situation by other operators.

8 CONCLUSION

In this dissertation, I focus on the impact of an ultra high-resolution interactive wall display on collaboration. Due to its high resolution, users can work very close to the wall, and thanks to its size several people can interact simultaneously in front of it [144]. Thus wall displays are interesting collocated collaboration platforms, that support face-to-face communication and deictic gestures [119], awareness of others' activities, and allow for different styles of collaboration [204]. These, combined with the fact that users can use multi-touch input enhances group awareness[97].

However, research still needs to be done on how people collaborate in front of such a surface. This thesis takes a step in this direction by exploring a specific context: command and control, and more specifically control rooms. In such environments, collaboration is important, as operators have to make critical decisions in a short time.

I used this context to show that UHRIWD can be beneficial for collaboration, especially when people need to collaborate closely. These benefits can be magnified by interaction techniques with a large footprint, which also help cross-checking the work of others. Finally, I demonstrated how a wall display can be integrated in a multi-display environment and how to help people transition from individual displays to it.

8.1 SUMMARY

I started this dissertation with an overview of the benefits of a large display, first in an individual context and then in a collaborative one. I emphasized the need for further research in this area (e.g. about their benefits compared to collaboration on multiple desktops). I also presented previous research that showed the impact of the input and interaction techniques on collaboration in front of a wall display and showed that there were still unexplored areas (e.g. understanding the impact of different characteristics of interaction techniques on collaboration). Finally, I talked about the research done on the use of such displays in control rooms, that mainly considers them as passive overview displays, with some exceptions that envision their use as an interactive display.

I then studied the activities and the needs of operators in control rooms in different domains. This study was based on observations in different control rooms, interviews with operators and the current literature. I showed that close collaboration was needed in exceptional situations when operators' workload is already high, the situation is uncertain, and when there are no exact procedures to follow thus requiring operators to collaborate in order to find solutions. This study showed that the design of current control rooms can be improved when it comes to supporting close collaboration, and I suggest that UHRIWD can help in this respect.

With the idea of checking this hypothesis, I performed an experiment in which I compared collaboration in one large, shared, and vertical display with collaboration in a setup that doesn't possess these characteristics: several individual desktops. Results showed that the large shared display encouraged close collaboration and planning of the task before actually performing it. On the contrary, the desktops encouraged a loose collaboration with little communication, which is generally faster, but more error-prone.

Then, I focused on the UHRIWD and investigated the impact of the visual footprint of interaction techniques on collaboration. I designed two interaction techniques (basic and propagation) for multi-user selection on graphs, each with a different visual footprint. I compared the techniques in a laboratory experiment and found that the technique with a large visual footprint (propagation) led to a closer collaboration, and also to a crosscheck of each other's work.

Using this result I designed interaction techniques to help road traffic controllers assess the impact of their actions on the traffic (an issue highlighted in our observations and interviews). These techniques were adapted to be used in a UHRIWD. One had a small visual footprint, more adapted for parallel work, and the other had a large one, adapted for close collaboration. Both techniques were evaluated in a laboratory experiment first, and then shown to expert users for their feedback. Both were found to be viable options.

Finally, I showed how a UHRIWD can be used in a multi display environment in order to support mixed-focus collaboration. I developed a prototype which ran on a wall display and several workstations for a specific context: crisis management. I designed interactive techniques to enhance group awareness in such an environment (Awareness bars, Focus map, and Step map), and to transfer data from the workstations to the wall (Data-lens). These designs take into consideration where the information is placed and how long it is displayed.

Overall, this thesis contributes new insights on collaboration around wall displays. My work shows that with appropriate interaction and visualization techniques, and combined with other types of displays, UHRIWD can positively impact the performance of users in collaborative tasks. This is particularly true for command and control situations (i.e. control rooms) which represent an extreme case of mixed-focus collaboration, with both periods in which operators need to loosely collaborate and periods in which they need to collaborate closely. During loose collaboration, the UHRIWD could be used to display contextual information, but also awareness information. During close collaboration, operators could stand up and directly collaborate in front of the wall display.

8.2 PERSPECTIVES

8.2.1 *Evaluations with end-users*

I based my conclusions regarding the benefits of UHRIWD in control rooms on the laboratory experiments described in Chapter 4, 5 and 6, which were performed with non-expert users. However, it would be beneficial now to perform these evaluations with expert users: control room operators. It is quite difficult to gather enough expert users to perform strict laboratory experiments. To tackle this issue, I based the design of the techniques and their evaluation on observations and interviews with experts (see Chapter 3). Moreover, all the experiments were done on abstract tasks, which did not require domain knowledge, and allowed me to have non-expert participants. Finally, less formal evaluation regarding some techniques (see Chapter 6) were done with expert users, in order to confirm the results of the experiments.

Nevertheless, in the future, it would be interesting to evaluate formally some of the techniques with operators, as their experience could bring new insights. First, we could do the same controlled experiments with these experts in a laboratory context. Their cognitive performance might differ from what we have seen so far. Especially because they are more used to continuously monitor data, to handle critical situations in a time constrained environment, and to collaborate in such situations, they might handle the tasks differently.

Regarding the techniques I design, it could be, of course, very difficult to deploy them and to observe their use in real time. However, it would be possible to observe expert users using them in a prototype of a control rooms on a simulated situation. Simulation is a big part of operators' training, it confronts them to exceptional situation, which is rare in real control rooms. The use of simulation would allow us to observe how operators use the techniques in any situations, and assess their performance.

8.2.2 *The use of Microworld*

As we stated in section 8.2.1, evaluation with end users in command and control contexts are difficult to set up. Control rooms in general are considered as dynamic decision making environments [30]: their current state depends on their previous state and on decisions of the users. They are also complex, their future behavior is hard to predict because the links between the different elements of the system are not obvious. Finally, they are opaque, the decision maker doesn't have access to all the elements of the environment. Evaluating in a controlled manner interaction techniques for such environments is difficult, as traditional laboratory experiments cannot capture all nuances of the environment, and operationalizing real world tasks is challenging.

A solution is to use a microworld, a simulated environment that reproduces specific characteristics of a real world context [68]. Most of the time they are more abstract than the real world and require less domain-knowledge, and as a result they allow a better control of factors of the experiments and also to recruit non end-users. Several previous works already use microworld in command and control contexts. For instance, Convertino et al. [46] developed a simulation of a crisis management scenario based on ones developed by the FEMA but simplified it to be done by three participants without specific domain knowledge. Toups et al. [192] designed a game which recreated the collaboration condition of firefighters on an intervention. It was based on observation of real intervention and validated with firefighters. Fire Chief [142] is a microworld already used in single user studies, but which can be easily adapted for collaboration. The player in the game has to manage firefighters combating a large forest fire.

Fire Chief could be adapted to evaluate collaboration techniques for crisis management (such as the one in Chapter 7). To adapt it for collaboration, it would be possible to take the existing responsibilities in the game, and assign them to different roles in a collaborative context. For example one user could be in charge of fire-fighting units, and another of units evacuating the population. Each user would have access to different information (road traffic, position of the fire), and they would need to collaborate and exchange information to handle the fire without casualties. Taking already validated microworld scenarios, such as FireChief, and tailoring them for collaboration provides an interesting alternative means for early evaluation of techniques, in a somewhat more realistic context, without requiring experts.

8.2.3 *Tasks to study collaboration on a shared display*

In Chapter 4 I compared the use of a large shared display with the use of two separate desktops for a collaborative path-finding task. Because it was a first empirical comparison, I used a low level abstract task. The goal was to first control the difficulty of the task and to maintain it constant as we studied learning. I found that users used different types of collaboration depending on the setup.

To really understand other factors surrounding collaboration we need to replicate experiments studying collaboration under different conditions and with different tasks. The low level task presented in Chapter 4 could be a good starting point as it require both coordination and independent work. It would be possible to adapt the task in order to study more complex situations.

For example we could increase the difficulty of the task by adding constraints (that require coordination) to test if the performance is affected by difficulty. Or we could instruct participants to create longer paths in order to study navigation. My study so far doesn't take into account (on purpose) physical navigation, that is an important by-product of wall displays. The effects of physical navigation have been studied in an individual context (see Chapter 2), but not in a collaborative one. Physical navigation would likely positive impact collaboration as it enables a better group awareness: users' position gives information regarding their area of work. One way to test that is hypothesis is by adapting our task so that users have to construct longer paths. This way users would have to physically navigate on the wall display, and pan on the workstation.

Finally, it could be interesting to study quantitatively the transition between loose and close collaboration. In their study Jakobsen and Hornbæk [97] stated that users on a wall display could easily switch between loose and close collaboration. Most collaborative tasks, including the ones performed in control rooms, require mixed-focus collaboration (see Chapter 7). In Chapter 4, we only studied the impact of a shared display on collaboration for a task that requires coordination. By adapting the task, it would be possible to study the impact of a shared display on mixed-focus collaborative tasks. One way to adapt it would be to ask users to draw several paths in the same trial, some that require coordination, and some that don't (but still with some constraints, like a specific length). This would allow us to see the impact of a shared surface on collaboration, but also enable us to spot differences in patterns of transition between degrees of collaboration. For instance, with workstations, users may choose to start by solving their individual tasks before solving the collaborative one, and vice versa with the wall.

An example of using our suggested task as is under different situations, would be to study it under different communication conditions. Most control room situations require operators to speak with people outside the control room while doing other tasks (including collaborating with other operators). For instance, in air traffic control, controllers are frequently talking with pilots by radio. In road traffic control, operators receive phone calls from emergency services or drivers to inform them about incidents. This often leads to the use of non-verbal communication between operators, which has been observed and studied in air traffic control [31, 122] and in road traffic control (see Chapter 3). To see how a shared display impacts collaboration with limited verbal communication, it could be interesting to do the same experiment under different conditions of constraint communication: No verbal communication, verbal communication allowed only before the first interaction and a limited amount of verbal communication during the trial. It would also be interesting to study the task under conditions of disruptions (e.g. calls that require operators to switch to another task). In this case, it is unclear if workspace awareness in the wall could be preferred to an easy access to personal information needed to handle the call in the workstation.

8.2.4 *Collaboration with distant input*

In the experiments of this thesis, participants interacted with the wall display using touch. This choice was justified in Chapter 2: touch provides a better group awareness [97], while distant input like handheld devices and mice encourage loose collaboration and provide less group awareness [99].

However, distant inputs do have other interesting benefits, for example the use of mice to interact with the wall may be less fatiguing and can allow users to see and interact with a complete view of the workspace.

In Chapter 5, we showed that a technique with a large visual footprint could encourage a closer collaboration. Such an experiment could help us determine if by simply adding a technique with a large visual footprint, we could increase group awareness and close collaboration when using distant input. This would be an interesting finding, as lack of awareness and loose collaboration is one of the drawbacks of such inputs. And distant input comes with the aforementioned benefits of less fatigue, and reduced change blindness (missing events happening outside of users' visual field due to the closeness to the display [218]). While this question merits further investigation, clearly other factors would also need to be considered when studying distant input for collaboration, for example it is likely they make it more difficult for spectators to identify groups of users working together [11].

8.2.5 *Measure of group awareness*

In this thesis, we argued that one of the main benefits of wall displays is that they provide a better group awareness [99]. This was demonstrated through participants' subjective rating and comments. Other indirect methods we used to measure group awareness were the amount of communication (Chapter 4), and users' strategies of collaboration (Chapter 5). All these methods enable us to compare group awareness in different situations, nevertheless, they don't allow us to quantify it.

We could be inspired by the work that has been done to measure situation awareness [61], and adapt it for group awareness. The Situation Awareness Global Assessment Technique (SAGAT) test [60] provides an objective measure of situation awareness, and have been used in various domain including air traffic control. The development of similar type of test for group awareness could be beneficial, as it would provide a clear protocol to evaluate the impact of different interaction and visualization techniques on group awareness, but would also enable the comparison of results across experiments.

Such an adapted test could be intrusive (as is the case of the SAGAT test), in which case users would be interrupted during the task to answer questions about their partner's activities. The questions could be about low level aspects of group awareness (like where their partners are working on the workspace), or higher level ones (like what is their partners' goal, or on which area of the workspace are they going to work in the future - to check if they are aware enough of others' partners' activities to predict their next actions). Questions could concern specific areas of interaction, but also workspace artefacts, or other users their partners are likely to communicate with in the future. Such a questionnaire test would have to be extensively tested across multiple situations to ensure it is sensitive enough to capture differences in group awareness levels.

One way would be to measure group awareness using the questionnaire in different situations which we are able to classify a-priori regarding the level of group awareness, a task that is in itself challenging given that no such classification exists yet.

Then, using this methods we could actually revisit ours and other studies using these measures, in order to quantify group awareness in different situations.

BIBLIOGRAPHY

[1] APA. *Publication manual of the American Psychological Association (6th edition)*. Washigton DC, USA: APA, 2009.

[2] James Abello, Eleftherios Koutsofios, Emden Gansner, and Stephen North. "Large Networks present Visualization Challenge." In: *SIGGRAPH Computer Graphics Newsletter* 33.3 (Aug. 1999), pp. 13–15. DOI: 10.1145/330572.330576.

[3] R Amalberti. "The paradoxes of almost totally safe transportation systems." In: *Safety Science* 37.2 (2001), pp. 109 –126. ISSN: 0925-7535. DOI: http://dx.doi.org/10.1016/S0925-7535(00)00045-X.

[4] Christopher Andrews, Alex Endert, and Chris North. "Space to Think: Large High-resolution Displays for Sensemaking." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, 2010, pp. 55–64. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753336.

[5] Gennady Andrienko, Natalia Andrienko, Christophe Hurter, Salvatore Rinzivillo, and Stefan Wrobel. "From movement tracks through events to places: Extracting and characterizing significant places from mobility data." In: *IEEE Conference on Visual Analytics Science and Technology*. VAST '11. IEEE, 2011, pp. 161–170. DOI: 10.1109/VAST.2011.6102454.

[6] Natalia Andrienko and Gennady Andrienko. "Visual Analytics of Movement: An Overview of Methods, Tools and Procedures." In: *Information Visualization* 12.1 (Jan. 2013), pp. 3–24. ISSN: 1473-8716. DOI: 10.1177/1473871612457601.

[7] Natalia Andrienko, Gennady Andrienko, and Salvatore Rinzivillo. "Exploiting Spatial Abstraction in Predictive Analytics of Vehicle Traffic." In: *ISPRS International Journal of Geo-Information* 4.2 (2015), pp. 591–606. ISSN: 2220-9964. DOI: 10.3390/ijgi4020591.

[8] Natalia Andrienko, Gennady Andrienko, and Salvatore Rinzivillo. "Leveraging spatial abstraction in traffic analysis and forecasting with visual analytics." In: *Information Systems* 57 (2016), 172–194. ISSN: 0306-4379. DOI: http://dx.doi.org/10.1016/j.is.2015.08.007.

[9] Daniel Archambault, Tamara Munzner, and David Auber. "TugGraph: Path-Preserving Hierarchies for Browsing Proximity and Paths in Graphs." In: *IEEE Pacific Visualization Symposium*. PacificVis '09. Pekin, China: IEEE, Apr. 2009, pp. 113–121. URL: https://hal.inria.fr/inria-00413858.

[10] Ignacio Avellino, Cédric Fleury, Wendy E. Mackay, and Michel Beaudouin-Lafon. "CamRay: Camera Arrays Support Remote Collaboration on Wall-Sized Displays." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 6718–6729. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025604.

[11] Alec Azad, Jaime Ruiz, Daniel Vogel, Mark Hancock, and Edward Lank. "Territoriality and behaviour on and around large vertical publicly-shared displays." In: *Proceedings of the Designing Interactive Systems Conference*. DIS '12. Newcastle Upon Tyne, United Kingdom: ACM, 2012, pp. 468–477. ISBN: 978-1-4503-1210-3. DOI: 10.1145/2317956.2318025.

[12] *BBC - The Route Masters: Running London's Roads: Gridlock*. https://vimeo.com/1378 Accessed: 2017-01-17.

[13] Stefan Bachl, Martin Tomitsch, Karin Kappel, and Thomas Grechenig. "The Effects of Personal Displays and Transfer Techniques on Collaboration Strategies in Multi-touch Based Multi-Display Environments." In: *Proceedings of the 13th IFIP TC13 Conference in Human-Computer Interaction*. INTERACT '11. Lisbon, Portugal: Springer Berlin Heidelberg, 2011, pp. 373–390. ISBN: 978-3-642-23765-2. DOI: 10.1007/978-3-642-23765-2_26.

[14] S. K. Badam, F. Amini, N. Elmqvist, and P. Irani. "Proxemic Lens: Multi-User Visual Exploration using Proxemics and Gestural Interaction." In: *To appear in IEEE Transactions on Visualization and Computer Graphics*. VAST 2016. Lisbon, Portugal: IEEE, 2016, pp. XX–XX.

[15] Robert Ball and Chris North. "The Effects of Peripheral Vision and Physical Navigation on Large Scale Visualization." In: *Proceedings of Graphics Interface*. GI '08. Windsor, Ontario, Canada: CIPS, 2008, pp. 9–16. ISBN: 978-1-56881-423-0. URL: http://dl.acm.org/citation.cfm?id=1375714.1375717.

[16] Robert Ball, Chris North, and Doug A. Bowman. "Move to Improve: Promoting Physical Navigation to Increase User Performance with Large Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: ACM, 2007, pp. 191–200. ISBN: 978-1-59593-593-9. DOI: 10.1145/1240624.1240656.

[17] Robert Ball, Chris North, and Doug A. Bowman. "Move to improve: promoting physical navigation to increase user performance with large displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: ACM, 2007, pp. 191–200. ISBN: 978-1-59593-593-9. DOI: 10.1145/1240624.1240656.

[18] M. Beaudouin-Lafon et al. "Multi-surface Interaction in the WILD Room." In: *IEEE Computer* 45.4 (2012), pp. 48–56. DOI: http://dx.doi.org/10.1109/MC.2012.110.

[19] Anastasia Bezerianos and Ravin Balakrishnan. "The Vacuum: Facilitating the Manipulation of Distant Objects." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '05. Portland, Oregon, USA: ACM, 2005, pp. 361–370. ISBN: 1-58113-998-5. DOI: 10.1145/1054972.1055023.

[20] Anastasia Bezerianos, Pierre Dragicevic, and Ravin Balakrishnan. "Mnemonic Rendering: An Image-based Approach for Exposing Hidden Changes in Dynamic Displays." In: *Proc. UIST*. UIST '06. Montreux, Switzerland: ACM, 2006, pp. 159–168. ISBN: 1-59593-313-1. DOI: http://doi.acm.org/10.1145/1166253.1166279.

[21] Anastasia Bezerianos and Petra Isenberg. "Perception of Visual Variables on Tiled Wall-Sized Displays for Information Visualization Applications." In: *IEEE Transactions on Visualization and Computer Graphics* 18.12 (2012), pp. 2516–2525. ISSN: 1077-2626. DOI: http://doi.ieeecomputersociety.org/10.1109/TVCG.2012.251.

[22] Xiaojun Bi and Ravin Balakrishnan. "Comparing Usage of a Large High-resolution Display to Single or Dual Desktop Displays for Daily Work." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 1005–1014. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518855.

[23] Eric A. Bier, Maureen C. Stone, Ken Pier, William Buxton, and Tony D. DeRose. "Toolglass and Magic Lenses: The See-through Interface." In: *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*. SIGGRAPH '93. Anaheim, CA: ACM, 1993, pp. 73–80. ISBN: 0-89791-601-8. DOI: 10.1145/166117.166126.

[24] Jeremy P. Birnholtz, Tovi Grossman, Clarissa Mak, and Ravin Balakrishnan. "An Exploratory Study of Input Configuration and Group Process in a Negotiation Task Using a Large Display." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '07. San Jose, California, USA: ACM, 2007, pp. 91–100. ISBN: 978-1-59593-593-9. DOI: 10.1145/1240624.1240638.

[25] Geoff Boeing. *OSMnx: Python for Street Networks*. URL: http://geoffboeing.com/2016/11/osmnx-python-street-networks/.

[26] Christophe Bortolaso, Matthew Oskamp, Greg Phillips, Carl Gutwin, and T.C. Nicholas Graham. "The Effect of View Techniques on Collaboration and Awareness in Tabletop Map-Based

Tasks." In: *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces*. ITS '14. Dresden, Germany: ACM, 2014, pp. 79–88. ISBN: 978-1-4503-2587-5. DOI: 10.1145/2669485.2669504.

[27] Lauren Bradel, Alex Endert, Kristen Koch, Christopher Andrews, and Chris North. "Large High Resolution Displays for Co-located Collaborative Sensemaking: Display Usage and Territoriality." In: *Int. J. Hum.-Comput. Stud.* 71.11 (2013), pp. 1078–1088. ISSN: 1071-5819. DOI: 10.1016/j.ijhcs.2013.07.004.

[28] Alf Ove Braseth, oystein Veland, and Robin Welch. "Information Rich Display Design." In: *Proceedings of the Fourth American Nuclear Society International Tropical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies*. NPIC&HMIT 2004. Columbus, Ohio: American Nuclear Society, 2004, pp. 1–12.

[29] Alf Ove Braseth, Christer Nihlwing, Haakan Svengren, oystein Veland, Lars Hurlen, and Jon Kvalem. "Lessons learned from Halden project research on human system interfaces." In: *Nuclear Engineering and Technology* 41.3 (2009), pp. 215–224. DOI: 10.1145/331490.331491.

[30] Berndt Brehmer. "Dynamic Decision Making in Command and Control." In: *The Human in Command: Exploring the Modern Military Experience*. Ed. by Carol McCann and Ross Pigeau. Boston, MA: Springer US, 2000, pp. 233–248. ISBN: 978-1-4615-4229-2. DOI: 10.1007/978-1-4615-4229-2_16.

[31] Marie-Christine Bressolle, Bernard Pavard, and Marcel Leroux. "The Role of Multimodal Communication in Cooperation: The Cases of Air Traffic Control." In: *Multimodal Human-Computer Communication, Systems, Techniques, and Experiments*. London, UK, UK: Springer-Verlag, 1998, pp. 326–343. ISBN: 978-3-540-69764-0. DOI: 10.1007/BFb0052327.

[32] Simon Butscher, Kasper Hornbæk, and Harald Reiterer. "SpaceFold and PhysicLenses: Simultaneous Multifocus Navigation on Touch Surfaces." In: *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces*. AVI '14. Como, Italy: ACM, 2014, pp. 209–216. ISBN: 978-1-4503-2775-6. DOI: 10.1145/2598153.2598177.

[33] Simon Butscher, Jens Müller, Andreas Weiler, Roman Rädle, Harald Reiterer, and Marc H. Scholl. "Multi-user Twitter Analysis for Crisis Room Environments." In: *Collaborative Human-Computer Interaction with Big Wall Displays : BigWallHCI 2013 ; 3rd JRC ECML Crisis Management Technology Workshop on Human-Computer Interaction with Big Wall Displays for Situation Monitoring and Reporting in Crisis Management Centres*. Ed. by Markus

Rester. Luxembourg: Publications Office of the European Union, 2013, pp. 28–34. ISBN: 978-92-79-34935-5. DOI: 10.2788/50183.

[34] Bortolaso C., Graham N., Scott S.D., Oskamp M., Brown D., and Porter L. "Design of a multi-touch tabletop for simulation-based training." In: *Proceedings of the 19th International Command and Control Research and Technology Symposium*. ICCRTS '14. Alexandria, VA: ICCRTS, 2014, pp. 1–18.

[35] J. J. Cadiz, Anop Gupta, and Jonathan Grudin. "Using Web Annotations for Asynchronous Collaboration Around Documents." In: *Proceedings of the 2000 ACM Conference on Computer Supported Cooperative Work*. CSCW '00. Philadelphia, Pennsylvania, USA: ACM, 2000, pp. 309–318. ISBN: 1-58113-222-0. DOI: 10.1145/358916.359002.

[36] Paulo V.R. De Carvalho. "Ergonomic field studies in a nuclear power plant control room." In: *Progress in Nuclear Energy* 48.1 (2006), pp. 51 –69. ISSN: 0149-1970. DOI: https://doi.org/10.1016/j.pnucene.2005.04.001.

[37] Edwin Chan, Craig Anslow, Teddy Seyed, and Frank Maurer. "Envisioning the Emergency Operations Centre of the Future." In: *Collaboration Meets Interactive Spaces*. Cham: Springer, 2016, pp. 349–372. ISBN: 978-3-319-45853-3. DOI: 10.1007/978-3-319-45853-3_15.

[38] Y.-L. Betty Chang, Stacey D. Scott, and Mark Hancock. "Usage of Interactive Event Timelines in Collaborative Digital Tabletops Involving Automation." In: *Collaboration Meets Interactive Spaces*. Ed. by Craig Anslow, Pedro Campos, and Joaquim Jorge. Cham: Springer International Publishing, 2016, pp. 203–232. ISBN: 978-3-319-45853-3. DOI: 10.1007/978-3-319-45853-3_10.

[39] Olivier Chapuis, Anastasia Bezerianos, and Stelios Frantzeskakis. "Smarties: An Input System for Wall Display Development." In: *Proceedings of the 32nd international conference on Human factors in computing systems*. CHI '14. Toronto, CA: ACM, 2014, pp. 2763–2772. DOI: 10.1145/2556288.2556956.

[40] E. H. C. Choi, R. Taib, Y. Shi, and F. Chen. "Multimodal user interface for traffic incident management in control room." In: *IET Intelligent Transport Systems* 1.1 (2007), pp. 27–36. ISSN: 1751-956X. DOI: 10.1049/iet-its:20060038.

[41] Apoorve Chokshi, Teddy Seyed, Francisco Marinho Rodrigues, and Frank Maurer. "ePlan Multi-Surface: A Multi-Surface Environment for Emergency Response Planning Exercises." In: *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces*. ITS '14. Dresden, Germany: ACM,

2014, pp. 219–228. ISBN: 978-1-4503-2587-5. DOI: 10.1145/2669485.2669520.

[42] Debashish Chowdhury, Ludger Santen, and Andreas Schadschneider. "Statistical physics of vehicular traffic and some related systems." In: *Physics Reports* 329.4 (2000), pp. 199–329. DOI: 10.1016/S0370-1573(99)00117-9.

[43] Roland Chrobok, Sigurdur F. Hafstein, and Andreas Pottmeier. "Olsim: A new generation of traffic information systems." In: *Forschung und wissenschaftliches Rechnen, GWDG-Berichte* Nr. 63 (2004), pp. 11–25. URL: http://www.gwdg.de/fileadmin/inhaltsbilder/Pdf/Publikationen/GWDG-Berichte/gwdg-bericht-63.pdf.

[44] Sharolyn Converse. "Shared mental models in expert team decision making." In: *Individual and group decision making: Current issues* 221 (1993).

[45] Stéphane Conversy, Hélène Gaspard-Boulinc, Stéphane Chatty, Stéphane Valès, Carole Dupré, and Claire Ollagnon. "Supporting Air Traffic Control Collaboration with a TableTop System." In: *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work*. CSCW '11. Hangzhou, China: ACM, 2011, pp. 425–434. ISBN: 978-1-4503-0556-3. DOI: 10.1145/1958824.1958891.

[46] Gregorio Convertino, Helena M. Mentis, Aleksandra Slavkovic, Mary Beth Rosson, and John M. Carroll. "Supporting Common Ground and Awareness in Emergency Management Planning: A Design Research Project." In: *ACM Trans. Comput.-Hum. Interact.* 18.4 (Dec. 2011), 22:1–22:34. ISSN: 1073-0516. DOI: 10.1145/2063231.2063236.

[47] Mary Czerwinski, Greg Smith, Tim Regan, Brian Meyers, George Robertson, and Gary Starkweather. "Toward characterizing the productivity benefits of very large displays." In: *Proc. Interact*. INTERACT '03. IOS, 2003, pp. 9–16.

[48] Dariusz Dereniowski, Yann Disser, Adrian Kosowski, Dominik Pajak, and Przemyslaw Uznanski. "Fast Collaborative Graph Exploration." In: *ICALP - 40th International Colloquium on Automata, Languages and Programming*. Vol. 7966. ICALP '13. Riga, Latvia: Springer, 2013, pp. 520–532. DOI: 10.1007/978-3-642-39212-2_46.

[49] Paloma Diaz, Teresa Onorati, and Sergio del Olmo Pueblas. "Analyzing and Visualizing Emergency Information in a Multi Device Environment." In: *Information Systems for Crisis Response and Management in Mediterranean Countries: Third International Conference, ISCRAM-med 2016, Madrid, Spain, October 26-28, 2016, Proceedings*. Ed. by Paloma Díaz, Narjès Bellamine Ben Saoud,

Julie Dugdale, and Chihab Hanachi. Cham: Springer International Publishing, 2016, pp. 181–194. ISBN: 978-3-319-47093-1. DOI: 10.1007/978-3-319-47093-1_16.

[50] Marian Dork, Nathalie Henry Riche, Gonzalo Ramos, and Susuan Dumais. "PivotPaths: Strolling through Faceted Information Spaces." In: *IEEE Transactions on Visualization and Computer Graphics* 18.12 (2012), pp. 2709–2718. ISSN: 1077-2626. DOI: 10.1109/TVCG.2012.252.

[51] Andre Doucette, Carl Gutwin, Regan L. Mandryk, Miguel Nacenta, and Sunny Sharma. "Sometimes when We Touch: How Arm Embodiments Change Reaching and Collaboration on Digital Tables." In: *Proceedings of the 2013 Conference on Computer Supported Cooperative Work*. CSCW '13. San Antonio, Texas, USA: ACM, 2013, pp. 193–202. ISBN: 978-1-4503-1331-5. DOI: 10.1145/2441776.2441799.

[52] Paul Dourish and Victoria Bellotti. "Awareness and Coordination in Shared Workspaces." In: *Proceedings of the 1992 ACM Conference on Computer-supported Cooperative Work*. CSCW '92. Toronto, Ontario, Canada: ACM, 1992, pp. 107–114. ISBN: 0-89791-542-9. DOI: 10.1145/143457.143468.

[53] Paul Dourish and Victoria Bellotti. "Awareness and Coordination in Shared Workspaces." In: *Proceedings of the 1992 ACM Conference on Computer-supported Cooperative Work*. CSCW '92. Toronto, Ontario, Canada: ACM, 1992, pp. 107–114. ISBN: 0-89791-542-9. DOI: 10.1145/143457.143468.

[54] Pierre Duffé and Michel Marec. *Task Force for Technical Investigation of the 24 March 1999 Fire in the Mont blanc Vehicular Tunnel*. Tech. rep. of 30 june 1999. Paris: Ministry of Equipment, Transportation and Housing, 1999, p. 49.

[55] Tim Dwyer, Nathalie Henry Riche, Kim Marriott, and Christopher Mears. "Edge Compression Techniques for Visualization of Dense Directed Graphs." In: *IEEE Transactions on Visualization and Computer Graphics* 19.12 (2013), pp. 2596–2605. ISSN: 1077-2626. DOI: http://doi.ieeecomputersociety.org/10.1109/TVCG.2013.151.

[56] Peter Eades. "A Heuristic for Graph Drawing." In: *Congressus Numerantium* 42 (1984). Ed. by D. S. Meek and van G. H. J. Rees, pp. 149–160.

[57] Centre for Economics and Business Research. *The future economic and environmental costs of gridlock in 2030 - An assessment of the direct and indirect economic and environmental costs of idling in road traffic congestion to households in the UK, France, Germany and the USA*. Tech. rep. for INRIX. London: Centre for Economics and Business Research Ltd, 2014, p. 67.

[58] Niklas Elmqvist, Nathalie Henry, Yann Riche, and Jean-Daniel Fekete. "Melange: Space Folding for Multi-focus Interaction." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, 2008, pp. 1333–1342. ISBN: 978-1-60558-011-1. DOI: 10.1145/1357054.1357263.

[59] Alex Endert, Christopher Andrews, Yueh Lee, and Chris North. "Visual encodings that support physical navigation on large displays." In: *Proceedings of Graphics Interface 2011*. GI '11. St. John's, Newfoundland, Canada: CHCCS, 2011, pp. 103–110. ISBN: 978-1-4503-0693-5. URL: http://dl.acm.org.gate6.inist.fr/citation.cfm?id=1992917.1992935.

[60] M.R. Endsley. "Situation awareness global assessment technique (SAGAT)." In: *Proceedings of the IEEE National Aerospace and Electronics Conference*. IEEE, 1988, 789–795 vol.3. DOI: 10.1109/NAECON.1988.195097.

[61] Mica R. Endsley. "Toward a Theory of Situation Awareness in Dynamic Systems." In: *Human Factors* 37.1 (1995), pp. 32–64. eprint: http://dx.doi.org/10.1518/001872095779049543. DOI: 10.1518/001872095779049543.

[62] K. Everitt, Chia Shen, K. Ryall, and C. Forlines. "MultiSpace: enabling electronic document micro-mobility in table-centric, multi-device environments." In: *First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP '06)*. 2006, 8 pp.–. DOI: 10.1109/TABLETOP.2006.23.

[63] Andreas Rene Fender, Hrvoje Benko, and Andy Wilson. "MeetAlive: Room-Scale Omni-Directional Display System for Multi-User Content and Control Sharing." In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ISS '17. Brighton, United Kingdom: ACM, 2017, pp. 106–115. ISBN: 978-1-4503-4691-7. DOI: 10.1145/3132272.3134117.

[64] Audrey Fertier, Anne-Marie Barthe-Delanoë, Johan Manceau, Sébastien Truptil, and Frédérick Bénaben. "Towards a Support to Stakeholders' Collaboration During a Loire River Major Flooding." In: *Information Systems for Crisis Response and Management in Mediterranean Countries: Second International Conference, ISCRAM-med 2015, Tunis, Tunisia, October 28-30, 2015, Proceedings*. Ed. by Narjès Bellamine Ben Saoud, Carole Adam, and Chihab Hanachi. Cham: Springer International Publishing, 2015, pp. 183–193. ISBN: 978-3-319-24399-3. DOI: 10.1007/978-3-319-24399-3_16.

[65] Geneviève Filippi and Jacques Theureau. "Analyzing Cooperative Work in an Urban Traffic Control Room for the Design of a Coordination Support System." In: *Proceedings of the Third European Conference on Computer-Supported Cooperative Work 13–17 September 1993, Milan, Italy ECSCW '93*. ECSCW '93. Dor-

drecht: Springer, 1993, pp. 171–186. ISBN: 978-94-011-2094-4. DOI: 10.1007/978-94-011-2094-4_12.

[66] Joel E. Fischer, Stuart Reeves, Tom Rodden, Steve Reece, Sarvapali D. Ramchurn, and David Jones. "Building a Birds Eye View: Collaborative Work in Disaster Response." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 4103–4112. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702313.

[67] Thomas M. J. Fruchterman and Edward M. Reingold. "Graph Drawing by Force-directed Placement." In: *Software: Practice and Experience* 21.11 (Nov. 1991), pp. 1129–1164. ISSN: 0038-0644. DOI: 10.1002/spe.4380211102.

[68] Cleotilde Gonzalez, Polina Vanyukov, and Michael K. Martin. "The use of microworlds to study dynamic decision making." In: *Computers in Human Behavior* 21.2 (2005), pp. 273 –286. ISSN: 0747-5632. DOI: https://doi.org/10.1016/j.chb.2004.02.014.

[69] Saul Greenberg, Nicolai Marquardt, Till Ballendat, Rob Diaz-Marino, and Miaosen Wang. "Proxemic Interactions: The New Ubicomp?" In: *interactions* 18.1 (Jan. 2011), pp. 42–50. ISSN: 1072-5520. DOI: 10.1145/1897239.1897250.

[70] Stephen J. Guastello and Denise D. Guastello. "Origins of coordination and team effectiveness: A perspective from game theory and nonlinear dynamics." In: *Journal of Applied Psychology* 83.3 (1998), pp. 423–437. DOI: 10.1037/0021-9010.83.3.423.

[71] Carl Gutwin and Saul Greenberg. "Design for Individuals, Design for Groups: Tradeoffs Between Power and Workspace Awareness." In: *Proceedings of the 1998 ACM Conference on Computer Supported Cooperative Work*. CSCW '98. Seattle, Washington, USA: ACM, 1998, pp. 207–216. ISBN: 1-58113-009-0. DOI: 10.1145/289444.289495.

[72] Carl Gutwin and Saul Greenberg. "A Descriptive Framework of Workspace Awareness for Real-Time Groupware." In: *Computer Supported Cooperative Work* 11.3 (Nov. 2002), pp. 411–446. ISSN: 0925-9724. DOI: 10.1023/A:1021271517844.

[73] Carl Gutwin, Mark Roseman, and Saul Greenberg. "A Usability Study of Awareness Widgets in a Shared Workspace Groupware System." In: *Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*. CSCW '96. Boston, Massachusetts, USA: ACM, 1996, pp. 258–267. ISBN: 0-89791-765-0. DOI: 10.1145/240080.240298.

[74] Carl Gutwin, Carl Gutwin, Saul Greenberg, and Saul Greenberg. "Support for Group Awareness in Real-Time Desktop Conferences." In: *University of Waikato*. 1995, pp. 18–21.

[75] Frank van Ham and Adam Perer. ""Search, show context, expand on demand": supporting large graph exploration with degree-of-interest." In: *IEEE Transactions on Visualization and Computer Graphics* 15.6 (2009), pp. 953–60. ISSN: 1077-2626. DOI: 10.1109/TVCG.2009.108.

[76] Kirstie Hawkey, Melanie Kellar, Derek Reilly, Tara Whalen, and Kori M. Inkpen. "The Proximity Factor: Impact of Distance on Co-located Collaboration." In: *Proceedings of the 2005 International ACM SIGGROUP Conference on Supporting Group Work*. GROUP '05. Sanibel Island, Florida, USA: ACM, 2005, pp. 31–40. ISBN: 1-59593-223-2. DOI: 10.1145/1099203.1099209.

[77] Health and Safety Executive. *The explosion and fires at the Texaco Refinery, Milford Haven, 24 July 1994*. Tech. rep. HSE, 1997.

[78] Christian Heath and Paul Luff. "Collaboration and control: Crisis management and multimedia technology in London Underground Line Control Rooms." In: *Computer Supported Cooperative Work (CSCW)* 1.1 (1992), pp. 69–94. ISSN: 1573-7551. DOI: 10.1007/BF00752451.

[79] Jeffrey Heer, Maneesh Agrawala, and Wesley Willett. "Generalized Selection via Interactive Query Relaxation." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, 2008, pp. 959–968. ISBN: 978-1-60558-011-1. DOI: 10.1145/1357054.1357203.

[80] Jeffrey Heer and Danah Boyd. "Vizster: Visualizing Online Social Networks." In: *Proceedings of the Proceedings of the 2005 IEEE Symposium on Information Visualization*. InfoVis '05. Washington, DC, USA: IEEE, 2005, pp. 32–39. ISBN: 0-7803-9464-x. DOI: 10.1109/INFOVIS.2005.39.

[81] Tomi Heimonen, Jaakko Hakulinen, Sumita Sharma, Markku Turunen, Lauri Lehtikunnas, and Hannu Paunonen. "Multimodal Interaction in Process Control Rooms: Are We There Yet?" In: *Proceedings of the 5th ACM International Symposium on Pervasive Displays*. PerDis '16. Oulu, Finland: ACM, 2016, pp. 20–32. ISBN: 978-1-4503-4366-4. DOI: 10.1145/2914920.2915024.

[82] Dirk Helbing. "Traffic and related self-driven many-particle systems." In: *Reviews of modern physics* 73.4 (2001), pp. 1067–1141. DOI: 10.1103/RevModPhys.73.1067.

[83] Nathalie Henry Riche, Tim Dwyer, Bongshin Lee, and Sheelagh Carpendale. “Exploring the design space of interactive link curvature in network diagrams.” In: *Proceedings of the International Working Conference on Advanced Visual Interfaces*. AVI ’12. New York, New York, USA: ACM, 2012, pp. 506–513. ISBN: 9781450312875. DOI: 10.1145/2254556.2254652.

[84] Ivan Herman, Guy Melancon, and Scott Marshall. “Graph Visualization and Navigation in Information Visualization: A Survey.” In: *IEEE Transactions on Visualization and Computer Graphics* 6.1 (Jan. 2000), pp. 24–43. DOI: 10.1109/2945.841119.

[85] Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. “Consumed Endurance: A Metric to Quantify Arm Fatigue of Mid-air Interactions.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: ACM, 2014, pp. 1063–1072. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557130.

[86] Eva Hornecker, Paul Marshall, Nick Sheep Dalton, and Yvonne Rogers. “Collaboration and Interference: Awareness with Mice or Touch Input.” In: *Proceedings of the 2008 ACM Conference on Computer Supported Cooperative Work*. CSCW ’08. San Diego, CA, USA: ACM, 2008, pp. 167–176. ISBN: 978-1-60558-007-4. DOI: 10.1145/1460563.1460589.

[87] Christophe Hurter, Benjamin Tissoires, and Stéphane Conversy. “FromDaDy: Spreading Aircraft Trajectories Across Views to Support Iterative Queries.” In: *IEEE Transactions on Visualization and Computer Graphics* 15.6 (Nov. 2009), pp. 1017–1024. ISSN: 1077-2626. DOI: 10.1109/TVCG.2009.145.

[88] Christophe Hurter, Rémi Lesbordes, Catherine Letondal, Jean-Luc Vinot, and Stéphane Conversy. “Strip’TIC: Exploring Augmented Paper Strips for Air Traffic Controllers.” In: *Proceedings of the International Working Conference on Advanced Visual Interfaces*. AVI ’12. Capri Island, Italy: ACM, 2012, pp. 225–232. ISBN: 978-1-4503-1287-5. DOI: 10.1145/2254556.2254598.

[89] *ISO 9241-210:2010: Ergonomics of human-system interaction – Part 210: Human-centred design for interactive systems*. Standard. Geneva, CH: International Organization for Standardization, Mar. 2010.

[90] Kori Inkpen, Kirstie Hawkey, Melanie Kellar, Regan M, Karen Parker, Derek Reilly, Stacey Scott, and Tara Whalen. “Exploring display factors that influence co-located collaboration: angle, size, number, and user arrangement.” In: *Proceedings of HCI international*. HCII ’05. Erlbaum, 2005, 10 pages. URL: http://www.ece.ubc.ca/~hawkey/HCII2005_Inkpen.pdf.

[91] Alexandra Ion, Y.-L. Betty Chang, Michael Haller, Mark Hancock, and Stacey D. Scott. "Canyon: Providing Location Awareness of Multiple Moving Objects in a Detail View on Large Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: ACM, 2013, pp. 3149–3158. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466431.

[92] P. Isenberg, S. Carpendale, A. Bezerianos, N. Henry, and J. D. Fekete. "CoCoNutTrix: Collaborative Retrofitting for Information Visualization." In: *IEEE Computer Graphics and Applications* 29.5 (2009), pp. 44–57. ISSN: 0272-1716. DOI: 10.1109/MCG.2009.78.

[93] P. Isenberg, P. Dragicevic, W. Willett, A. Bezerianos, and J.-D. Fekete. "Hybrid-Image Visualization for Large Viewing Environments." In: *IEEE Transactions on Visualization and Computer Graphics* 19.12 (2013), pp. 2346–2355. ISSN: 1077-2626. DOI: 10.1109/TVCG.2013.163.

[94] Petra Isenberg, Sheelagh Carpendale, Anastasia Bezerianos, Nathalie Henry, and Jean-Daniel Fekete. "CoCoNutTrix: Collaborative Retrofitting for Information Visualization." In: *IEEE Computer Graphics and Applications* 29.5 (July 2009), pp. 44–57. DOI: 10.1109/MCG.2009.78.

[95] Shahram Izadi, Harry Brignull, Tom Rodden, Yvonne Rogers, and Mia Underwood. "Dynamo: A Public Interactive Surface Supporting the Cooperative Sharing and Exchange of Media." In: *Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology*. UIST '03. Vancouver, Canada: ACM, 2003, pp. 159–168. ISBN: 1-58113-636-6. DOI: 10.1145/964696.964714.

[96] Mikkel R. Jakobsen and Kasper Hornbæk. "Interactive Visualizations on Large and Small Displays: The Interrelation of Display Size, Information Space, and Scale." In: *IEEE Transactions on Visualization and Computer Graphics* 19.12 (2013), pp. 2336–2345. DOI: 10.1109/TVCG.2013.170.

[97] Mikkel R. Jakobsen and Kasper Hornbæk. "Up Close and Personal: Collaborative Work on a High-resolution Multitouch Wall Display." In: *ACM Transactions on Computer-Human Interaction* 21.2 (Feb. 2014), 11:1–11:34. ISSN: 1073-0516. DOI: 10.1145/2576099.

[98] Mikkel R. Jakobsen and Kasper Hornbæk. "Is Moving Improving?: Some Effects of Locomotion in Wall-Display Interaction." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 4169–4178. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702312.

[99] Mikkel R. Jakobsen and Kasper Hornbæk. "Negotiating for Space?: Collaborative Work Using a Wall Display with Mouse and Touch Input." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Santa Clara, California, USA: ACM, 2016, pp. 2050–2061. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858158.

[100] Waqas Javed and Niklas Elmqvist. "Exploring the Design Space of Composite Visualization." In: *Proceedings of the 2012 IEEE Pacific Visualization Symposium*. PacificVis '12. Washington, DC, USA: IEEE, 2012, pp. 1–8. ISBN: 978-1-4673-0863-2. DOI: 10.1109/PacificVis.2012.6183556.

[101] Waqas Javed, Sohaib Ghani, and Niklas Elmqvist. "Polyzoom: Multiscale and Multifocus Exploration in 2D Visual Spaces." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, 2012, pp. 287–296. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2207716.

[102] MG Karlaftis and EI Vlahogianni. "Statistical methods versus neural networks in transportation research: Differences, similarities and some insights." In: *Transportation Research Part C: Emerging Technologies* 19.3 (2011), pp. 387–399. DOI: 10.1016/j.trc.2010.10.004.

[103] Azam Khan, Justin Matejka, George Fitzmaurice, and Gordon Kurtenbach. "Spotlight: Directing Users' Attention on Large Displays." In: *Proc. CHI*. CHI '05. Portland, Oregon, USA: ACM, 2005, pp. 791–798. ISBN: 1-58113-998-5. DOI: http://doi.acm.org/10.1145/1054972.1055082.

[104] Ulrike Kister, Patrick Reipschläger, and Raimund Dachselt. "MultiLens: Fluent Interaction with Multi-Functional Multi-Touch Lenses for Information Visualization." In: *Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces*. Niagara Falls, ON, Canada: ACM, Nov. 2016, pp. 139–148. ISBN: 978-1-4503-4248-3. URL: http://dx.doi.org/10.1145/2992154.2992168.

[105] Ulrike Kister, Patrick Reipschläger, Fabrice Matulic, and Raimund Dachselt. "BodyLenses: Embodied Magic Lenses and Personal Territories for Wall Displays." In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. ITS '15. Madeira, Portugal: ACM, 2015, pp. 117–126. ISBN: 978-1-4503-3899-8. DOI: 10.1145/2817721.2817726.

[106] Ulrike Kister, Konstantin Klamka, Christian Tominski, and Raimund Dachselt. "GraSp: Combining Spatially-aware Mobile Devices and a Display Wall for Graph Visualization and Interaction." In: *Computer Graphics Forum* (2017). ISSN: 1467-8659. DOI: 10.1111/cgf.13206.

[107] Olga Kulyk, Gerrit van der Veer, and Betsy van Dijk. "Situational Awareness Support to Enhance Teamwork in Collaborative Environments." In: *Proceedings of the 15th European Conference on Cognitive Ergonomics: The Ergonomics of Cool Interaction*. ECCE '08. Funchal, Portugal: ACM, 2008, 5:1–5:5. ISBN: 978-1-60558-399-0. DOI: 10.1145/1473018.1473025.

[108] Jari Laarni, Hanna Koskinen, Leena Salo, and Leena Norros. "Evaluation of the fortum IRD pilot." In: *Proceedings of the Sixth American Nuclear Society International Tropical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies*. NPIC&HMIT 2009. Knoxville, Tennessee: American Nuclear Society, 2009, pp. 1–12.

[109] Jean-Paul Labarthe and Cecilia De la Garza. "The human factors evaluation program of a control room: The French EPR approach." In: *Human Factors and Ergonomics in Manufacturing & Service Industries* 21.4 (2011), pp. 331–349. ISSN: 1520-6564. DOI: 10.1002/hfm.20227.

[110] Ove Daae Lampe, Johannes Kehrer, and Helwig Hauser. "Visual Analysis of Multivariate Movement Data Using Interactive Difference Views." In: *Proceedings of Vision, Modeling, and Visualization*. VMV '10. Siegen, Germany: EG, 2010, pp. 315–322. DOI: 10.2312/PE/VMV/VMV10/315-322.

[111] Jonas Landgren and Fredrik Bergstrand. "Work Practice in Situation Rooms – An Ethnographic Study of Emergency Response Work in Governmental Organizations." In: *Information Systems for Crisis Response and Management in Mediterranean Countries: Third International Conference, ISCRAM-med 2016, Madrid, Spain, October 26-28, 2016, Proceedings*. Ed. by Paloma Díaz, Narjès Bellamine Ben Saoud, Julie Dugdale, and Chihab Hanachi. Cham: Springer International Publishing, 2016, pp. 157–171. ISBN: 978-3-319-47093-1. DOI: 10.1007/978-3-319-47093-1_14.

[112] Ricardo Langner, Ulrich von Zadow, Tom Horak, Annett Mitschick, and Raimund Dachselt. "Content Sharing Between Spatially-Aware Mobile Phones and Large Vertical Displays Supporting Collaborative Work." In: *Collaboration Meets Interactive Spaces*. Ed. by Craig Anslow, Pedro Campos, and Joaquim Jorge. Cham: Springer International Publishing, 2016, pp. 75–96. ISBN: 978-3-319-45853-3. DOI: 10.1007/978-3-319-45853-3_5.

[113] Bongshin Lee, Catherine Plaisant, Cynthia Sims Parr, Jean-Daniel Fekete, and Nathalie Henry. "Task Taxonomy for Graph Visualization." In: *Proceedings of the 2006 AVI Workshop on BEyond Time and Errors: Novel Evaluation Methods for Information Visualization*. BELIV '06. Venice, Italy: ACM, 2006, pp. 1–5. ISBN: 1-59593-562-2. DOI: 10.1145/1168149.1168168.

[114] Seung Woo Lee, Ar Ryum Kim, Jinkyun Park, Hyun Gook Kang, and Poong Hyun Seong. "Measuring Situation Awareness of Operating Team in Different Main Control Room Environments of Nuclear Power Plants." In: *Nuclear Engineering and Technology* 48.1 (2016), pp. 153 –163. ISSN: 1738-5733. DOI: http://dx.doi.org/10.1016/j.net.2015.09.008.

[115] Anke Lehmann, Heidrun Schumann, Oliver Staadt, and Christian Tominski. "Physical Navigation to Support Graph Exploration on a Large High-resolution Display." In: *Proceedings of the 7th International Conference on Advances in Visual Computing - Volume Part I*. ISVC '11. Las Vegas, NV: Springer-Verlag, 2011, pp. 496–507. ISBN: 978-3-642-24027-0. URL: http://dl.acm.org/citation.cfm?id=2045110.2045165.

[116] M. H. Lighthill and G. B. Whitham. "On Kinematic Waves II: A Theory of Traffic Flow on Long Crowded Roads." In: *Proc., Royal Society of London Series A* 229 (1955), pp. 317–345.

[117] Can Liu. "Leveraging Physical Human Actions in Large Interaction Spaces." In: *Proceedings of the Adjunct Publication of the 27th Annual ACM Symposium on User Interface Software and Technology*. UIST'14 Adjunct. Honolulu, Hawaii, USA: ACM, 2014, pp. 9–12. ISBN: 978-1-4503-3068-8. DOI: 10.1145/2658779.2661165.

[118] Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, Eric Lecolinet, and Wendy Mackay. "Effects of Display Size and Navigation Type on a Classification Task." In: *Proceedings of the 32nd international conference on Human factors in computing systems*. CHI '14. Toronto, CA: ACM, 2014, pp. 4147–4156. DOI: 10.1145/2556288.2557020.

[119] Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, and Eric Lecolinet. "Shared Interaction on a Wall-Sized Display in a Data Manipulation Task." In: *Proceedings of the 34th international conference on Human factors in computing systems*. CHI '16. San Jose, CA: ACM, 2016, pp. 2075–2086. DOI: 10.1145/2858036.2858039.

[120] Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, and Eric Lecolinet. "CoReach: Cooperative Gestures for Data Manipulation on Wall-sized Displays." In: *Proceedings of the 35th international conference on Human factors in computing systems*. CHI '17. Denver, CO, USA: ACM, 2017, to appear. DOI: 10.1145/3025453.3025594.

[121] María-Jesús Lobo, Emmanuel Pietriga, and Caroline Appert. "An Evaluation of Interactive Map Comparison Techniques." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Ko-

rea: ACM, 2015, pp. 3573–3582. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702130.

[122] Wendy E. MacKay. "Is Paper Safer? The Role of Paper Flight Strips in Air Traffic Control." In: *ACM Trans. Comput.-Hum. Interact.* 6.4 (Dec. 1999), pp. 311–340. ISSN: 1073-0516. DOI: 10.1145/331490.331491.

[123] Narges Mahyar and Melanie Tory. "Supporting communication and coordination in collaborative sensemaking." In: *IEEE Transactions on Visualization and Computer Graphics* 20.12 (2014), pp. 1633–1642. DOI: 10.1109/TVCG.2014.2346573.

[124] Narges Mahyar, Kelly J. Burke, Jialiang (Ernest) Xiang, Siyi (Cathy) Meng, Kellogg S. Booth, Cynthia L. Girling, and Ronald W. Kellett. "UD Co-Spaces: A Table-Centred Multi-Display Environment for Public Engagement in Urban Design Charrettes." In: *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces*. ISS '16. Niagara Falls, Ontario, Canada: ACM, 2016, pp. 109–118. ISBN: 978-1-4503-4248-3. DOI: 10.1145/2992154.2992163.

[125] Michael Marner, Ross Smith, Bruce Thomas, Karsten Klein, Peter Eades, and Seok-Hee Hong. "GION: Interactively Untangling Large Graphs on Wall-Sized Displays." In: *Proceedings of Graph Drawing*. GD '14. W¸rzburg, Germany: Springer-Verlag, 2014, pp. 113–124. ISBN: 978-3-662-45803-0. DOI: 10.1007/978-3-662-45803-7_10.

[126] Joseph Edward McGrath. *Groups: Interaction and Performance*. Vol. 14. Upper Saddle River, NJ, USA: Prentice-Hall Englewood Cliffs, 1984.

[127] Michael McGuffin and Igor Jurisica. "Interaction Techniques for Selecting and Manipulating Subgraphs in Network Visualization." In: *IEEE Transactions on Visualization and Computer Graphics* 15.6 (Nov. 2009), pp. 937–944. DOI: 10.1109/TVCG.2009.151.

[128] Karim Mehadhebi. "A methodology for the design of a route network." In: *3rd Air Traffic Management R&D Seminar*. Napoli, Italy: Eurocontrol & FAA, 2000. URL: http://atm2003.eurocontrol.fr/past-seminars/3rd-seminar-napoli-italy-june-2000/papers/paper_053/view.

[129] Johanna Merand, Francoise Darses, and Cecilia De La Garza. "The role of argumentation in the resolution of ambiguoug situations: an exploratory study in the field of supervision in the nuclear industry." In: *Proceedings of the 11th International Conference on Naturalistic Decision Making*. NDM 2013. Marseille, France: Arpege Science Publishing, 2013, pp. 289–296. ISBN: 979-10-92329-00-1. URL: http://arpege-recherche.org/ndm11/papers/ndm11-289.pdf.

[130] Najmedin Meshkati. "Safety and Human Factors Considerations in Control Rooms of Oil and Gas Pipeline Systems: Conceptual Issues and Practical Observations." In: *International Journal of Occupational Safety and Ergonomics* 12.1 (2006). PMID: 16554002, pp. 79–93. eprint: http://dx.doi.org/10.1080/10803548.2006.11076669. DOI: 10.1080/10803548.2006.11076669.

[131] Bernd Meyer. "Self-Organizing Graphs A Neural Network Perspective of Graph Layout." In: *Proceedings of Graph Drawing*. GD '98. Montreal, Canada: Springer-Verlag, 1998, pp. 246–262. DOI: 10.1007/3-540-37623-2_19.

[132] Stanley Milgram. "The small world problem." In: *Psychology Today* 1.1 (1967), pp. 61–67.

[133] Tomer Moscovich, Fanny Chevalier, Nathalie Henry, Emmanuel Pietriga, and Jean-Daniel Fekete. "Topology-aware Navigation in Large Networks." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 2319–2328. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1519056.

[134] Christopher Mueller, Douglas Gregor, and Andrew Lumsdaine. "Distributed Force-directed Graph Layout and Visualization." In: *Proceedings of the 6th Eurographics Conference on Parallel Graphics and Visualization*. EGPGV '06. Braga, Portugal: EA, 2006, pp. 83–90. ISBN: 3-905673-40-1. DOI: 10.2312/EGPGV/EGPGV06/083-090.

[135] Jens Müller, Tobias Schwarz, Simon Butscher, and Harald Reiterer. "Back to Tangibility: A post-WIMP Perspective on Control Room Design." In: *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces*. AVI '14. Como, Italy: ACM, 2014, pp. 57–64. ISBN: 978-1-4503-2775-6. DOI: 10.1145/2598153.2598161.

[136] Jörg Müller, Florian Alt, Daniel Michelis, and Albrecht Schmidt. "Requirements and Design Space for Interactive Public Displays." In: *Proceedings of the 18th ACM International Conference on Multimedia*. MM '10. Firenze, Italy: ACM, 2010, pp. 1285–1294. ISBN: 978-1-60558-933-6. DOI: 10.1145/1873951.1874203.

[137] William P. Myers and Greg A. Jamieson. "Rethinking groupview display alternatives." In: *Proceedings of the American Nuclear Society International Tropical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies*. NPIC&HMIT 2015. Charlotte, NC: American Nuclear Society, 2015, pp. 2570–2577.

[138] Miguel A. Nacenta, David Pinelle, Dane Stuckel, and Carl Gutwin. "The Effects of Interaction Technique on Coordination in Tabletop Groupware." In: *Proceedings of Graphics Interface 2007*. GI '07. Montreal, Canada: ACM, 2007, pp. 191–198. ISBN: 978-1-56881-337-0. DOI: 10.1145/1268517.1268550.

[139] Kai Nagel and Michael Schreckenberg. "A cellular automaton model for freeway traffic." In: *Journal de physique I* 2.12 (1992), pp. 2221–2229. DOI: 10.1051/jp1:1992277.

[140] Tao Ni, Doug A. Bowman, and Jian Chen. "Increased Display Size and Resolution Improve Task Performance in Information-Rich Virtual Environments." In: *Proceedings of Graphics Interface*. GI '06. Quebec, Canada: CIPS, 2006, pp. 139–146. ISBN: 1-56881-308-2. URL: http://dl.acm.org/citation.cfm?id=1143079.1143102.

[141] Joshua O'Madadhain, Danyel Fisher, Padhraic Smyth, Scott White, and Yan-Biao Boey. "Analysis and Visualization of Network Data using JUNG." In: *Journal of Statistical Software* 10.2 (2005), pp. 1–35.

[142] Mary M. Omodei and Alexander J. Wearing. "The Fire Chief microworld generating program: An illustration of computer-simulated microworlds as an experimental paradigm for studying complex decision-making behavior." In: *Behavior Research Methods, Instruments, & Computers* 27.3 (1995), pp. 303–316. DOI: 10.3758/BF03200423.

[143] Teresa Onorati, Petra Isenberg, Anastasia Bezerianos, Emmanuel Pietriga, and Paloma Diaz. *WallTweet: A Knowledge Ecosystem for Supporting Situation Awareness*. ITS Workshop on Data Exploration for Interactive Surfaces (DEXIS). Nov. 2015. URL: https://hal.inria.fr/hal-01237149.

[144] Peter Peltonen, Esko Kurvinen, Antti Salovaara, Giulio Jacucci, Tommi Ilmonen, John Evans, Antti Oulasvirta, and Petri Saarikko. "It's Mine, Don'T Touch!: Interactions at a Large Multi-touch Display in a City Centre." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, 2008, pp. 1285–1294. ISBN: 978-1-60558-011-1. DOI: 10.1145/1357054.1357255.

[145] E. Pietriga et al. "Interaction Design Challenges and Solutions for ALMA Operations Monitoring and Control." In: *SPIE 8451, Software and Cyberinfrastructure for Astronomy II*. SPIE, 2012, 10:1–10:16. DOI: 10.1117/12.925180.

[146] Emmanuel Pietriga, Stéphane Huot, Mathieu Nancel, and Romain Primet. "Rapid development of user interfaces on cluster-driven wall displays with jBricks." In: *Proceedings of the 3rd ACM SIGCHI symposium on Engineering interactive computing*

systems. EICS '11. Pisa, Italy: ACM, 2011, pp. 185–190. ISBN: 978-1-4503-0670-6. DOI: 10.1145/1996461.1996518.

[147] Matthew D. Plumlee and Colin Ware. "Zooming Versus Multiple Window Interfaces: Cognitive Costs of Visual Comparisons." In: *ACM Trans. Comput.-Hum. Interact.* 13.2 (June 2006), pp. 179–209. ISSN: 1073-0516. DOI: 10.1145/1165734.1165736.

[148] Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. "Evaluating Multi-User Selection for Exploring Graph Topology on Wall-Displays." In: *IEEE Transactions on Visualization and Computer Graphics* In Prescreening (2016), 14 pages. DOI: 10.1109/TVCG.2016.2592906.

[149] Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. "Towards Road Traffic Management with Forecasting on Wall Displays." In: *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces*. ISS '16. Niagara Falls, Ontario, Canada: ACM, 2016, pp. 119–128. ISBN: 978-1-4503-4248-3. DOI: 10.1145/2992154.2992158.

[150] Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. "Visual Immersion in the Context of Wall Displays." In: *Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*. ISS Companion '16. Niagara Falls, Ontario, Canada: ACM, 2016, pp. 33–39. ISBN: 978-1-4503-4530-9. DOI: 10.1145/3009939.3009945.

[151] Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. "Trade-offs Between a Vertical Shared Display and Two Desktops in a Collaborative Path-Finding Task." In: *Proceedings of Graphics Interface*. GI '17. Edmonton, Alberta, Canada: CHCCS, 2017. URL: http://graphicsinterface.org/proceedings/.

[152] Helen Purchase. "Metrics for Graph Drawing Aesthetics." In: *Journal of Visual Languages and Computing* 13 (2002), pp. 501–516. DOI: 10.1006/jvlc.2002.0232.

[153] Fateme Rajabiyazdi, Jagoda Walny, Carrie Mah, John Brosz, and Sheelagh Carpendale. "Understanding Researchers' Use of a Large, High-Resolution Display Across Disciplines." In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. ITS '15. Madeira, Portugal: ACM, 2015, pp. 107–116. ISBN: 978-1-4503-3899-8. DOI: 10.1145/2817721.2817735.

[154] Umar Rashid, Miguel A. Nacenta, and Aaron Quigley. "Factors Influencing Visual Attention Switch in Multi-display User Interfaces: A Survey." In: *Proceedings of the 2012 International Symposium on Pervasive Displays*. PerDis '12. Porto, Portugal: ACM, 2012, 1:1–1:6. ISBN: 978-1-4503-1414-5. DOI: 10.1145/2307798.2307799.

[155] Khairi Reda, Andrew E. Johnson, Michael E. Papka, and Jason Leigh. "Effects of Display Size and Resolution on User Behavior and Insight Acquisition in Visual Exploration." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 2759–2768. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702406.

[156] Jun Rekimoto and Masanori Saitoh. "Augmented Surfaces: A Spatially Continuous Work Space for Hybrid Computing Environments." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '99. Pittsburgh, Pennsylvania, USA: ACM, 1999, pp. 378–385. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303113.

[157] Meredith Ringel Morris, Kathy Ryall, Chia Shen, Clifton Forlines, and Frederic Vernier. "Beyond "Social Protocols": Multiuser Coordination Policies for Co-located Groupware." In: *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*. CSCW '04. Chicago, Illinois, USA: ACM, 2004, pp. 262–265. ISBN: 1-58113-810-5. DOI: 10.1145/1031607.1031648.

[158] Maria Riveiro. "Evaluation of Normal Model Visualization for Anomaly Detection in Maritime Traffic." In: *ACM Trans. Interact. Intell. Syst.* 4.1 (Apr. 2014), 5:1–5:24. ISSN: 2160-6455. DOI: 10.1145/2591511.

[159] Everett M. Rogers. *Diffusion of Innovations*. 5th ed. Free Press, 2003, pp. 1–453.

[160] Yvonne Rogers and Siân Lindley. "Collaborating around large interactive displays: which way is best to meet?" In: *Interacting with Computers* 16.6 (Jan. 2004), pp. 1133–1152. ISSN: 00419907.

[161] Nicolas Roussel and Ghislain Nouvel. "La main comme télépointeur." In: *Tome 2 des actes des 11ème journées francophones sur l'Interaction Homme Machine (IHM'99)*. 1999, pp. 33–36. URL: http://insitu.lri.fr/~roussel/publications/IHM99.pdf.

[162] Enrico Rukzio, Michael Müller, and Robert Hardy. "Design, Implementation and Evaluation of a Novel Public Display for Pedestrian Navigation: The Rotating Compass." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 113–122. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518722.

[163] R. Scheepens, C. Hurter, H. van de Wetering, and J.J. van Wijk. "Visualization, Selection, and Analysis of Traffic Flows." In: *IEEE Transactions on Visualization and Computer Graphics* 22.1 (2016), pp. 379–388. ISSN: 1077-2626. DOI: 10.1109/TVCG.2015.2467112.

[164] Roeland Scheepens, Niels Willems, Huub van de Wetering, Gennady Andrienko, Natalia Andrienko, and Jarke J. van Wijk. "Composite Density Maps for Multivariate Trajectories." In: *IEEE Transactions on Visualization and Computer Graphics* 17.12 (Dec. 2011), pp. 2518–2527. ISSN: 1077-2626. DOI: 10.1109/TVCG.2011.181.

[165] Dominik Schmidt, Corina Sas, and Hans Gellersen. "Personal Clipboards for Individual Copy-and-paste on Shared Multi-user Surfaces." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '13. Paris, France: ACM, 2013, pp. 3335–3344. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466457.

[166] Sebastian Schmidt, Miguel Nacenta, Raimund Dachselt, and Sheelagh Carpendale. "A set of multi-touch graph interaction techniques." In: *ACM International Conference on Interactive Tabletops and Surfaces*. ITS '10. New York, New York, USA: ACM, 2010, pp. 113–116. ISBN: 9781450303996. DOI: 10.1145/1936652.1936673.

[167] Tobias Schwarz, Simon Butscher, Jens Mueller, and Harald Reiterer. "Content-aware Navigation for Large Displays in Context of Traffic Control Rooms." In: *Proceedings of the International Working Conference on Advanced Visual Interfaces*. AVI '12. Capri Island, Italy: ACM, 2012, pp. 249–252. ISBN: 978-1-4503-1287-5. DOI: 10.1145/2254556.2254601.

[168] S. D. Scott, G. Besacier, and P. J. McClelland. "Cross-device transfer in a collaborative multi-surface environment without user identification." In: *2014 International Conference on Collaboration Technologies and Systems (CTS)*. 2014, pp. 219–226. DOI: 10.1109/CTS.2014.6867568.

[169] Stacey D. Scott, M. Sheelagh T. Carpendale, and Kori M. Inkpen. "Territoriality in Collaborative Tabletop Workspaces." In: *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*. CSCW '04. Chicago, Illinois, USA: ACM, 2004, pp. 294–303. ISBN: 1-58113-810-5. DOI: 10.1145/1031607.1031655.

[170] Teddy Seyed, Mario Costa Sousa, Frank Maurer, and Anthony Tang. "SkyHunter: A Multi-surface Environment for Supporting Oil and Gas Exploration." In: *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces*. ITS '13. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 15–22. ISBN: 978-1-4503-2271-3. DOI: 10.1145/2512349.2512798.

[171] Matthew Sharifi, Terry Payne, and Esther David. "Public display advertising based on bluetooth device presence." In: *in Proceedings of the Mobile Interaction with the RealWorldWorkshop (MIRW)*. 2006.

[172] Garth Shoemaker, Anthony Tang, and Kellogg S. Booth. "Shadow Reaching: A New Perspective on Interaction for Large Displays." In: *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology*. UIST '07. Newport, Rhode Island, USA: ACM, 2007, pp. 53–56. ISBN: 978-1-59593-679-0. DOI: http://doi.acm.org/10.1145/1294211.1294221.

[173] Penn Smith, Ann Blandford, and Jonathan Back. "Questioning, Exploring, Narrating and Playing in the Control Room to Maintain System Safety." In: *Cogn. Technol. Work* 11.4 (Oct. 2009), pp. 279–291. ISSN: 1435-5558. DOI: 10.1007/s10111-008-0116-1.

[174] Neville A. Stanton, C. Baber, and D. Harris. *Modelling Command and Control: Event Analysis of Systemic Teamwork*. Farnham, UK: Ashgate Publishing Ltd., 2008.

[175] Sandra Starke, Neil Cooke, Andrew Howes, Natan Morar, and Chris Baber. "Visual Sampling in a Road Traffic Management Control Room Task." In: *International Conference on Ergonomics & Human Factors*. Taylor & Francis, 2015, pp. 503–511. ISBN: 978-1-138-02803-6.

[176] John Steenbruggen, Michel Kusters, and Gerrit Broekhuizen. "Best Practice in European Traffic Incident Management." In: *Procedia - Social and Behavioral Sciences* 48 (2012), pp. 297 –310. ISSN: 1877-0428. DOI: http://dx.doi.org/10.1016/j.sbspro.2012.06.1010.

[177] Mark Stefik, Gregg Foster, Daniel G. Bobrow, Kenneth Kahn, Stan Lanning, and Lucy Suchman. "Beyond the Chalkboard: Computer Support for Collaboration and Problem Solving in Meetings." In: *Commun. ACM* 30.1 (Jan. 1987), pp. 32–47. ISSN: 0001-0782. DOI: 10.1145/7885.7887.

[178] Jason Stewart, Benjamin B. Bederson, and Allison Druin. "Single Display Groupware: A Model for Co-present Collaboration." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '99. Pittsburgh, Pennsylvania, USA: ACM, 1999, pp. 286–293. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303064.

[179] Maureen C. Stone. "Color and Brightness Appearance Issues in Tiled Displays." In: *IEEE Computer Graphics and Applications* 21.5 (Sept. 2001), pp. 58–66. ISSN: 0272-1716. DOI: 10.1109/38.946632.

[180] Norbert A. Streitz, Jörg Geissler, Torsten Holmer, Shin'ichi Konomi, Christian Müller-Tomfelde, Wolfgang Reischl, Petra Rexroth, Peter Seitz, and Ralf Steinmetz. "i-LAND: An Interactive Landscape for Creativity and Innovation." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing*

Systems. CHI '99. Pittsburgh, Pennsylvania, USA: ACM, 1999, pp. 120–127. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303010.

[181] William F. Stubler and John M. O'Hara. "Group-View Displays for Enhancing Crew Performance." In: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 39.18 (1995), pp. 1199–1203. DOI: 10.1177/154193129503901811.

[182] Hilary C. Styron. *CSX Tunnel Fire*. Tech. rep. United States Fire Administration, July 2001.

[183] Masanori Sugimoto, Kazuhiro Hosoi, and Hiromichi Hashizume. "Caretta: A System for Supporting Face-to-face Collaboration by Integrating Personal and Shared Spaces." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '04. Vienna, Austria: ACM, 2004, pp. 41–48. ISBN: 1-58113-702-8. DOI: 10.1145/985692.985698.

[184] Desney S. Tan, Darren Gergle, Regan Mandryk, Kori Inkpen, Melanie Kellar, Kirstie Hawkey, and Mary Czerwinski. "Using Job-shop Scheduling Tasks for Evaluating Collocated Collaboration." In: *Personal Ubiquitous Comput.* 12.3 (Jan. 2008), pp. 255–267. ISSN: 1617-4909. DOI: 10.1007/s00779-007-0154-3.

[185] Desney Tan, Darren Gergle, Peter Scupelli, and Randy Pausch. "With similar visual angles, larger displays improve spatial performance." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '03. Ft. Lauderdale, Florida, USA: ACM, 2003, pp. 217–224. ISBN: 1-58113-630-7. DOI: 10.1145/642611.642650.

[186] Anthony Tang, Melanie Tory, Barry Po, Petra Neumann, and Sheelagh Carpendale. "Collaborative Coupling over Tabletop Displays." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '06. Montréal, Québec, Canada: ACM, 2006, pp. 1181–1190. ISBN: 1-59593-372-7. DOI: 10.1145/1124772.1124950.

[187] John C. Tang. "Findings from Observational Studies of Collaborative Work." In: *Int. J. Man-Mach. Stud.* 34.2 (Feb. 1991), pp. 143–160. ISSN: 0020-7373. DOI: 10.1016/0020-7373(91)90039-A.

[188] M. Tobiasz, P. Isenberg, and S. Carpendale. "Lark: Coordinating Co-located Collaboration with Information Visualization." Undetermined. In: *IEEE Transactions on Visualization and Computer Graphics* 15.6 (2009), pp. 1065 –1072. DOI: 10.1109/TVCG.2009.162.

[189] C. Tominski, H. Schumann, G. Andrienko, and N. Andrienko. “Stacking-Based Visualization of Trajectory Attribute Data.” In: *IEEE Transactions on Visualization and Computer Graphics* 18.12 (2012), pp. 2565–2574. ISSN: 1077-2626. DOI: 10.1109/TVCG.2012.265.

[190] C. Tominski, S. Gladisch, U. Kister, R. Dachselt, and H. Schumann. “Interactive Lenses for Visualization: An Extended Survey.” In: *Computer Graphics Forum* 36.6 (2017), pp. 173–200. ISSN: 1467-8659. DOI: 10.1111/cgf.12871.

[191] Christian Tominski, James Abello, Frank van Ham, and Heidrun Schumann. “Fisheye Tree Views and Lenses for Graph Visualization.” In: *Proceedings of the Conference on Information Visualization*. IV ’06. Washington, DC, USA: IEEE Computer Society, 2006, pp. 17–24. ISBN: 0-7695-2602-0. DOI: 10.1109/IV.2006.54.

[192] Zachary O. Toups, Andruid Kerne, and William A. Hamilton. “The Team Coordination Game: Zero-fidelity Simulation Abstracted from Fire Emergency Response Practice.” In: *ACM Trans. Comput.-Hum. Interact.* 18.4 (Dec. 2011), 23:1–23:37. ISSN: 1073-0516. DOI: 10.1145/2063231.2063237.

[193] Edward Tse, Jonathan Histon, Stacey D. Scott, and Saul Greenberg. “Avoiding Interference: How People Use Spatial Separation and Partitioning in SDG Workspaces.” In: *Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*. CSCW ’04. Chicago, Illinois, USA: ACM, 2004, pp. 252–261. ISBN: 1-58113-810-5. DOI: 10.1145/1031607.1031647.

[194] Edward R. Tufte. *The Visual Display of Quantitative Information*. Cheshire, CT, USA: Graphics Press, 1986. ISBN: 0-9613921-0-X.

[195] Tamas Vajk, Paul Coulton, Will Bamford, and Reuben Edwards. “Using a Mobile Phone As a "Wii-like" Controller for Playing Games on a Large Public Display.” In: *Int. J. Comput. Games Technol.* 2008 (Jan. 2008), 4:1–4:6. ISSN: 1687-7047. DOI: 10.1155/2008/539078.

[196] Stéphane Valès, Stéphane Chatty, Alexandre Lemort, and Stéphane Conversy. “MAMMI Phase1- Collaborative workspaces for en-route air traffic controllers.” In: *INO 2006, 5th Eurocontrol Innovative Research Workshop & Exhibition*. Brétigny-sur-Orge, France, Dec. 2006, pp 5–10. URL: https://hal-enac.archives-ouvertes.fr/hal-01021772.

[197] Stéphane Valès, Carole Dupré, Hélène Gaspard-Boulinc, Stéphane Conversy, Claire Ollagnon, Vincent Peyruquéou, and Joel Viala. “MAMMI Phase 3 - Exploring collaborative workspaces for air traffic controllers in the scope of SESAR.” In: *INO 2008, 7th Eurocontrol Innovative Research Workshop & Exhibition*. Paris,

France, Dec. 2008, pp 15–24. URL: https://hal-enac.archives-ouvertes.fr/hal-01022265.

[198] oystein Veland and Malvin Eikaas. "A Novel Design for an Ultra-large Screen Display for Industrial Process Control." In: *Proceedings of the 2007 International Conference on Ergonomics and Health Aspects of Work with Computers*. EHAWC'07. Beijing, China: Springer-Verlag, 2007, pp. 349–358. ISBN: 978-3-540-73332-4. URL: http://dl.acm.org/citation.cfm?id=1784356.1784400.

[199] Vivek Verma and Alex Pang. "Comparative Flow Visualization." In: *IEEE Transactions on Visualization and Computer Graphics* 10.6 (Nov. 2004), pp. 609–624. ISSN: 1077-2626. DOI: 10.1109/TVCG.2004.39.

[200] Eleni I. Vlahogianni, John C. Golias, and Matthew G. Karlaftis. "Short-term traffic forecasting: Overview of objectives and methods." In: *Transport reviews* 24.5 (2004), pp. 533–557. DOI: 10.1080/0144164042000195072.

[201] F. Vogt, J. Wong, B. A. Po, R. Argue, S. S. Fels, and K. S. Booth. "Exploring collaboration with group pointer interaction." In: *Proceedings Computer Graphics International, 2004*. 2004, pp. 636–639. DOI: 10.1109/CGI.2004.1309280.

[202] Tatiana Von Landesberger, Arjan Kuiper, Tobias Schreck, Jorn Kohlhammer, Jarke Van Wijk, Jean-Daniel Fekete, and Dieter Fellner. "Visual Analysis of Large Graphs: State-of-the-Art and Future Research Challenges." In: *Computer Graphics Forum* 30.6 (Apr. 2011), pp. 1719–1749. DOI: 10.1111/j.1467-8659.2011.01898.x.

[203] Mikeal Wahlström, Hannu Karvonen, and Leena Norros. "Rehearsing for a Major Accident in a Metro Control Centre: A Naturalistic Analysis of Situation Awareness." In: *Proceedings of the 11th International Conference on Naturalistic Decision Making*. NDM 2013. Marseille, France: Arpege Science Publishing, 2013, pp. 51–58. ISBN: 979-10-92329-00-1. URL: http://arpege-recherche.org/ndm11/papers/ndm11-51.pdf.

[204] James R. Wallace, Nancy Iskander, and Edward Lank. "Creating Your Bubble: Personal Space On and Around Large Public Displays." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Santa Clara, California, USA: ACM, 2016, pp. 2087–2092. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858118.

[205] James R. Wallace, Stacey D. Scott, and Carolyn G. MacGregor. "Collaborative Sensemaking on a Digital Tabletop and Personal Tablets: Prioritization, Comparisons, and Tableaux." In: *Proceedings of the SIGCHI Conference on Human Factors in Com-*

puting Systems. CHI '13. Paris, France: ACM, 2013, pp. 3345–3354. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466458.

[206] James R. Wallace, Stacey D. Scott, Taryn Stutz, Tricia Enns, and Kori Inkpen. "Investigating Teamwork and Taskwork in Single- and Multi-display Groupware Systems." In: *Personal Ubiquitous Comput.* 13.8 (Nov. 2009), pp. 569–581. ISSN: 1617-4909. DOI: 10.1007/s00779-009-0241-8.

[207] Robert Walmsley, Timothy Anderson, Clay Brendish, John McDermid, Martin Rolfe, Joseph Sultana, Mark Swan, and Michael Toms. *NATS System Failure 12 December 2014 - Final Report Independent Enquiry*. Tech. rep. NATS, May 2015, p. 93.

[208] Michelle Q. Wang Baldonado, Allison Woodruff, and Allan Kuchinsky. "Guidelines for Using Multiple Views in Information Visualization." In: *Proceedings of the Working Conference on Advanced Visual Interfaces*. AVI '00. Palermo, Italy: ACM, 2000, pp. 110–119. ISBN: 1-58113-252-2. DOI: 10.1145/345513.345271.

[209] Zuchao Wang, Tangzhi Ye, Min Lu, Xiaoru Yuan, Huamin Qu, Jiaxin Yuan, and Qianliang Wu. "Visual exploration of sparse traffic trajectory data." In: *IEEE Transactions on Visualization and Computer Graphics* 20.12 (2014), pp. 1813–1822. DOI: 10.1109/TVCG.2014.2346746.

[210] Colin Ware and Robert Bobrow. "Supporting Visual Queries on Medium-sized Node-link Diagrams." In: *Information Visualization* 4.1 (Mar. 2005), pp. 49–58. ISSN: 1473-8716. DOI: 10.1057/palgrave.ivs.9500090.

[211] Colin Ware and Marlon Lewis. "The DragMag Image Magnifier." In: *Conference Companion on Human Factors in Computing Systems*. CHI '95. Denver, Colorado, USA: ACM, 1995, pp. 407–408. ISBN: 0-89791-755-3. DOI: 10.1145/223355.223749.

[212] Colin Ware and Peter Mitchell. "Visualizing Graphs in Three Dimensions." In: *ACM Transactions on Applied Perception* 5.1 (Jan. 2008), 2:1–2:15. ISSN: 1544-3558. DOI: 10.1145/1279640.1279642.

[213] Daniel Wigdor, Chia Shen, Clifton Forlines, and Ravin Balakrishnan. "Table-centric Interactive Spaces for Real-time Collaboration." In: *Proceedings of the Working Conference on Advanced Visual Interfaces*. AVI '06. Venezia, Italy: ACM, 2006, pp. 103–107. ISBN: 1-59593-353-0. DOI: 10.1145/1133265.1133286.

[214] Daniel Wigdor, Hao Jiang, Clifton Forlines, Michelle Borkin, and Chia Shen. "WeSpace: The Design Development and Deployment of a Walk-up and Share Multi-surface Visual Collaboration System." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA,

USA: ACM, 2009, pp. 1237–1246. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518886.

[215] Ka-Ping Yee, D. Fisher, R. Dhamija, and M. Hearst. "Animated exploration of dynamic graphs with radial layout." In: *InfoVis '01*. InfoVis '01. 2001, pp. 43–50. DOI: 10.1109/INFVIS.2001.963279.

[216] Beth Yost and Chris North. "The Perceptual Scalability of Visualization." In: *IEEE Transactions on Visualization and Computer Graphics* 12.5 (2005), pp. 837–844. DOI: 10.1109/TVCG.2006.184.

[217] Ulrich von Zadow. "Using Personal Devices to Facilitate Multi-user Interaction with Large Display Walls." In: *Adjunct Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15 Adjunct. Daegu, Kyungpook, Republic of Korea: ACM, 2015, pp. 25–28. ISBN: 978-1-4503-3780-9. DOI: 10.1145/2815585.2815592.

[218] Ulrich von Zadow, Daniel Bösel, Duc Dung Dam, Anke Lehmann, Patrick Reipschläger, and Raimund Dachselt. "Miners: Communication and Awareness in Collaborative Gaming at an Interactive Display Wall." In: *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces*. ISS '16. Niagara Falls, Ontario, Canada: ACM, 2016, pp. 235–240. ISBN: 978-1-4503-4248-3. DOI: 10.1145/2992154.2992174.

[219] Melcher Zeilstra, Marit Wilms, Fenneke Blommers, and David de Bruijn. "Development of future scenarios by prediction of mental workload in a traffic management control room." In: *Advances in Human Aspects of Transportation: Part III* 9 (2014), p. 125.

[220] Jakob Zillner, Christoph Rhemann, Shahram Izadi, and Michael Haller. "3D-board: A Whole-body Remote Collaborative Whiteboard." In: *Proceedings of the 27th Annual ACM Symposium on User Interface Software and Technology*. UIST '14. Honolulu, Hawaii, USA: ACM, 2014, pp. 471–479. ISBN: 978-1-4503-3069-5. DOI: 10.1145/2642918.2647393.

[221] Bjorn Zimmer and Andreas Kerren. "Sensemaking and Provenance in Distributed Collaborative Node-Link Visualization." In: *IEEE VIS '14 Workshop on Provenance for Sensemaking*. Nov. 2014, pp. 1–2.

ÉCOLE DOCTORALE
Sciences et technologies de l'information et de la communication (STIC)

Title: Collaboration around wall displays in command and control contexts

Keywords: Wall Displays, Collaboration, Control Rooms

Abstract: In this thesis, I study the benefits of collaboration in front of Ultra-High Resolution Interactive Wall Displays (UHRWD). I focus on the specific collaborative context of control rooms. Visits of control rooms and interviews with operators show that different degrees of collaboration are required in function of the situation. I believe that a UHRIWD could be beneficial in situations when close collaboration is needed. I first show that wall display encourages close collaboration compared to multiple separate displays. Then I show that the interaction techniques can also influence the degree of collaboration, for instance, a technique with a large visual footprint also encourages a close collaboration. I apply this in the design of technique to visualize road traffic forecast on a wall display for road traffic control centres. Finally, I propose techniques to help the transition between the different setups of a control room: the workstations and the wall display.

Titre : Utilisation collaborative d'un mur d'écran en contexte critique

Mots clés : Mur d'écran, Collaboration, Salle de contrôle

Résumé : Dans cette thèse, j'étudie les avantages des Murs d'Écran Interactif à Haute Résolution (UHRIWD - Ultra High Resolution Interactive Wall Displays) pour la collaboration. Je me concentre sur un contexte de collaboration bien précis: la surveillance des systèmes critiques dans les salles de contrôle. Des visites de ces salles et ainsi que des interviews avec des opérateurs montrent qu'une collaboration plus ou moins étroite est nécessaire en fonction de la situation. C'est lorsqu'une collaboration étroite est nécessaire que je pense qu'un UHRIWD peut être bénéfique pour celle ci. Je montre d'abord qu'un mur d'écran encourage la collaboration étroite comparée à l'utilisation de plusieurs postes de travail individuels. Puis je montre comment une technique d'interaction peut avoir une influence sur le type de collaboration. Par exemple, une technique avec une large empreinte visuelle va encourager une collaboration plus étroite. J'applique cela dans la conception de techniques pour afficher des prédictions de trafic parallèlement au trafic en temps réel dans une salle de contrôle de trafic routier. Pour finir, je propose des techniques pour faciliter les transitions entre les différents écrans d'une salle de contrôle.

Université Paris-Saclay
Espace Technologique / Immeuble Discovery
Route de l'Orme aux Merisiers RD 128 / 91190 Saint-Aubin, France