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# Conception et évaluation de techniques d'interaction pour l'exploration de données complexes dans de larges espaces d'affichage.

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Dedicated to my mother.

# Abstract

Today's ever-growing data is becoming increasingly complex due to its large volume and high dimensionality: it thus becomes crucial to explore interactive visualization environments that go beyond the traditional desktop in order to provide a larger display area and offer more efficient interaction techniques to manipulate the data. The main environments fitting the aforementioned description are: large displays, i.e. an assembly of displays amounting to a single space; Multi-display Environments (MDEs), i.e. a combination of heterogeneous displays (monitors, smartphones/tablets/wearables, interactive tabletops…) spatially distributed in the environment; and immersive environments, i.e. systems where everything can be used as a display surface, without imposing any bound between displays and immersing the user within the environment. The objective of our work is to design and experiment original and efficient interaction techniques well suited for each of the previously described environments.

First, we focused on the interaction with large datasets on large displays. We specifically studied simultaneous interaction with multiple regions of interest of the displayed visualization. We implemented and evaluated an extension of the traditional overview+detail interface to tackle this problem: it consists of an overview+detail interface where the overview is displayed on a large screen and multiple detailed views are displayed on a tactile tablet. The interface allows the user to have up to four detailed views of the visualization at the same time. We studied its usefulness as well as the optimal number of detailed views that can be used efficiently.

Second, we designed a novel touch-enabled device, TDome, to facilitate interactions in Multi-display environments. The device is composed of a dome-like base and provides up to 6 degrees of freedom, a touchscreen and a camera that can sense the environment. Having a unique device for interaction in these environments limits the homing effect when switching from one device to another and leads to a coherent set of interactions with the MDE, contributing to a more fluid task flow, a key element in such environments.

Finally, we introduced a new approach to interact in immersive environments with complex data. It is based on the use of the forearm as a physical support to assist tangible interactions with a multi-degrees of freedom device. We proposed a design space for this

approach and we validated its feasibility through an experiment aimed at establishing the range, stability and comfort of gestures performed in this new paradigm.

All along this research work, resulting interaction techniques and environments have been concretely illustrated for exploring energy consumption data in the context of neOCampus, a project of the University of Toulouse 3 that aims at exploring the Campus of the Future, i.e. a smart, innovative and sustainable campus.

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# Introduction

# 1 Introduction

## 1.1 Context

Our ever-growing computing capabilities have led to a dramatic increase in data collection in the last twenty years. In 1992, Huber [88] defined a taxonomy of large data sets and used the term "huge" to describe a $10^{10}$ Bytes volume of data. At that time, multiple hard disks were necessary to hold that amount of data. Today, 26 years later, we have memory cards[1] that can hold 50 times the data sets described as "huge" in Huber's terms.

However, exploring this large collection of data, which is particularly important in scientific fields, is by no means an easy task, not only due to their volume but also to their heterogeneity. As early as 1988, Wegman [192] argued that computing resources were altering the character of some classes of data sets, making them not only much larger, but also high dimensional and less homogeneous. Today, Wegman's assumption still holds true. Making sense of such complex data, its high dimensions and large volumes, becomes even more difficult.

This thesis is part of the **neOCampus** operation, a project that relies heavily on collecting and exploiting data. This multidisciplinary project, launched in June 2013 at the University of Toulouse, involves 11 research laboratories from different fields. The goal of the project is to improve the confort of everyday life for the university users (students, professors and staff), while decreasing its ecological footprint by reducing the functioning ressources (water, electricity and so on). The project promotes research work, offering in the campus of the university, a platform for innovative experiments, done at a large scale and in vivo, with real users and real situations. The project aims to achieve its goals by taking advantage of the proliferation of inexpensive connected devices. The approach consists in creating a *"smart campus"* that would connect not only sensors and smart devices at fixed positions in the university, but also the personal mobile devices of

[1] 512 Go Memory cards

their users (smartphones, tablets, wearables…). The data produced by such an approach is complex and time-dependent, and its exploration requires adequate analysis tools. The broad objective of the work presented in this manuscript is to design and evaluate interaction solutions to facilitate exploration of such data sets.Today, there is no settled interface or interaction solution to visualize and manipulate such complex data (volume, dimensionality, heterogeneity). However, a first general solution to improve visualization and manipulation of data consists in augmenting the display and visualization surface. Several environments have been explored for this specific purpose. Some of the early ones involved the use of large displays, usually video projectors, with very low resolutions. While their size allows them to easily scale up the data displayed, their resolutions limited the volume of data that can be displayed [4]. Eventually, large displays comprised of multiple tiled screens emerged, their combination offered high resolutions and large congruous display areas [4]. Their high resolutions allow them to display large volumes of data, which in turn, facilitate data visualization by allowing the user to have an overview of data when visualizing it from afar, and a more detailed view when getting closer to it.

A second approach consists in distributing the displays in space, to compose what we will refer to in this manuscript as multi-display environments. Such environments are efficient for visualizing multidimensional data: distributing the data among displays helps organizing it and facilitates interaction with the assortment of dimensions composing it. The rapid evolution of mobile technology (smartphones, tablets and wearables in general) widened the definition of multi-display environments (MDE). They introduced the notion of personal displays in addition to new input possibilities (small touchscreens and sensors).

A third way of augmenting display surfaces involves the use of immersive technologies. The last decade saw the democratization of immersive systems, their rapid development contributes to their affordability which has a direct effect on the extent of research exploring their capabilities. Like multi-display environments, they allow the user to distribute data among the display area. However, the notion of display in immersive environment is broader, it refers to an area where data can be attached, rather than the digital technology showing the data. Immersive systems' stereoscopic and tracking capabilities allow the use of the natural spatial perception of the user in understanding the different dimensions as well as the spatial relationships in data.

# 1.2 Interaction challenges

While there is no debate over the benefits of each environment for data exploration, it comes at the cost of several interaction challenges tightly related to their inherent characteristics. In the following, we provide a broad overview of those challenges for each one of the environments described above:

## 1.2.1 Large displays

The considerable display area of large screens introduce scalability issues in that, data visualizations previously designed for traditional monitors need to be redesigned when transitioning to large high resolution displays. To fully capitalize on the high count of pixels they afford and have a full view of the displayed data sets, interaction in those environments must be performed from a distance allowing the user to have the full visualization in his field of view. It becomes then important to be able to access and interact with unreachable content.

## 1.2.2 Multi-display environments

While the heterogeneity of displays composing an MDEs makes them a compelling solution for data visualization, they introduce their fair share of challenges in terms of interaction. The different sizes, resolutions of displays and the distributed aspect of the visualized data require a suitable interaction technique for content transfer between displays. The different input modalities of each display require a unified input technique that can be redirected from one display to the other. The large displays and tabletops in MDEs introduce a privacy problem in that users should be able to see private information if needed.

In addition to their physical characteristics, the displays composing MDEs have different input capabilities. The touch input offered by smartphones or tablets is not suitable for large displays; pointing interaction techniques used to reach distant objects in large displays are not suitable for the accessible display of an interactive tabletop; the traditional mouse and keyboard used for desktop monitors are not suitable for smartphones, tablets or large displays.

### 1.2.3 Immersive environments

A large interaction vocabulary is required to tackle the diverse tasks involved in data exploration. In immersive environments, these tasks are not entirely covered by the existing solutions. Approaches based on mouse, touch and mid-air interaction fail to offer enough degrees of freedom (DoF); other solutions are often ambiguous and tiring (especially mid-air gestures); and many restrict the user's interaction to a defined place, usually a desktop, to use the input device. The challenge then is to provide interactive solutions for immersive visualizations that preserves the freedom of movement of mid-air interaction and the DoFs of tangible interactions.

## 1.3 Contributions

The objective of our work is to improve interaction in each one of the previously described environments. Our thesis was driven by the following research questions:

- How to explore and manipulate physically unreachable content in multiple zone of interest on a large display?
- How to cope with heterogeneous input and display surfaces in MDEs ?
- How on-body interaction (i.e. gestures performed with the user's body as support) can reduce fatigue while preserving the degrees of freedom required for interacting in an immersive environment ?

We address these questions through the following contributions:

- Designing and evaluating a multi-view overview + detail interface to interact with large data sets in large displays [157].
- Exploring the use of everyday objects for interaction in public multi-display environments [159].
- Designing and evaluating a touch enabled 6DOF interactive device for multi-display environments [158].
- Using the body as a support for tangible interactions to explore data in immersive environments [160].

**Contribution 1: Interaction with large datasets in large displays**

We took interest in interaction with large datasets on large displays. We specifically focused on simultaneous interaction with multiple regions of interest of the displayed visualization. We implemented and evaluated an extension of the traditional overview+detail interface to tackle this problem: an overview + detail interface where the overview is displayed on a large screen and multiple detailed views are displayed on a tactile tablet. The interface allows the user to have up to four detailed views of the visualization at the same time. While the multi-view approach in itself is not new, the optimal number of detailed views has not been investigated. Using a single detailed view offers a larger display size but only allows a sequential exploration of the overview; using several detailed views reduces the size of each view but allows a parallel exploration of the overview. We experimentally evaluated the effect of the number of detailed views in a task related to interaction with large data sets.

#### Contribution 2 & 3: Interaction with multi-display environments

Our second contribution attempts to improve interaction with multi-display environments in two different contexts: a public context and a more usual office/work context.

A) The first contribution is based on the observation that public multi-display environments are as yet mainly used to display information due to the limited interaction possibilities they offer. Using this as our departure point, we identified the unique requirements of such environments: their public aspect limits the use of expensive devices as the risk of it being stolen or damaged is significant; the casual and quick nature of interactions performed in a public context requires easy to discover, easy to perform and opportunistic interactions; the interaction proposed must respect the personal space of its users. We proposed to explore the use of everyday objects as tools to perform tangible interactions to interact with these environments. They are always available, they offer easy to perform interactions and their shapes may help suggest their potential use.

B) The second contribution is TDome, a novel touch-enabled 6DOF input and output device to facilitate interactions in MDEs. TDome offers a private display as output, and multiple degrees of freedom as input by combining touch gestures on the display with physical rotation, roll and translation manipulations of the device. TDome allows versatile interactions that address major MDE tasks, which we illustrate through various proof-of-concept implementations: detect surrounding displays, select one display, transfer data across displays, reach distant displays and perform private interactions. Having a unique device for interaction in these environments limits the homing effect when switching from one device to another and leads to a coherent set of interactions with the MDE, contributing to a more fluid task flow, a key element in such environments. We explore TDome's usability and suitability for MDEs through three user studies.

**Contribution 4: Interaction with immersive environments**

We introduced a new paradigm to interact in immersive environments with complex data requiring multiple degrees of freedom. It is based on the use of the forearm as a physical support to assist tangible interactions with a multi-degrees of freedom device. The use of the body as a support for the interaction allows the user to move in his environment and avoids the inherent fatigue of this mid-air interactions—popular in immersive environments—. We proposed a design space for this approach describing the main characteristics on the interaction support as well as the interaction performed with the tangible device. We validated the adequacy of such an approach for immersive environments through an experiment aimed at establishing the range, stability and comfort of gestures performed in this new paradigm.

## 1.4 Outline of the dissertation

This manuscript is composed of seven chapters (including the present one). Each major contribution is described in a separate chapter. The manuscript begins by an introduction, followed by a review of the existing work for each one of the three environments introduced beforehand. It ends up with perspectives for the future and a conclusion.

**Chapter 2 - Related work**

Chapter 2 details the existing work in each of the previously described environments. It is composed of three main sections: Large display, Multi-display environments and immersive environments. Each section introduces the environments by defining them and describing their major characteristics. The core of each section describes their interaction challenges and the main solutions proposed for to address them. Finally, a summary of the main solutions proposed for each environment is provided at the end of each section.

**Chapter 3 - Investigating the effect of splitting the detailed view in an Overview + detail multi-display interface**

In chapter 3, we present split-focus, the multi-display overview + detail visualization interface we designed and developed to improve work on multiple regions of the data space simultaneously. First, we lay down the benefits of using multiple-views to tackle the aforementioned problem. Then, we review Baldonado's [10] eight rules to design and use multiple views in information visualizations. Next, we state the rationale behind the design of the visualization interface and describe each view composing it. Finally, we report on the results of the study conducted to evaluate the visualization interface as well as the optimal number of views to use in such a system.

**Chapter 4 - Interacting with multi-display environments (MDE)**

In the first part of this chapter, we focus on interaction with multi-display environments in a public context. We introduce the proposed approach: using everyday objects for interaction with these environments. Next, we describe a creativity session, conducted to study the use of predefined everyday objects to perform specific tasks related to MDEs in a public context. We detail the taxonomy we used to classify the proposed interaction techniques and recap the lessons learned from the results.

In the second part of the chapter, we investigate the use of a multi-degrees of freedom mouse (TDome) to interact with multi-display environments in a work context. In a first step, we identify the requirements of interaction in such environments. Next, an overview of the device is provided, it details the degrees of freedom allowed by TDome, it describes a scenario illustrating the potential use of such a device in an MDE. Then, we detail the core elements used in its implementation and follow up by discussing its suitability for interaction with MDEs. In a first study, we explore the usability and confort of performing physical and touch gestures with the device. We experimentally validate their feasibility and identify a set of gestures that can be easily performed and efficiently detected. Finally, we collect user feedback to identify natural mappings between gestures and MDE interactions.

**Chapter 5 - Interaction in immersive environments**

Chapter 5 introduces a new paradigm for interaction with immersive environments: the use of the forearm as a support for tangible interactions to explore complex data. After introducing the concept, we identify the main interaction requirement for immersive visualizations. We then proceed by describing the multi-dof device used for interaction as well as the forearm as a support. We conclude the first part of this work by providing a design space for tangible interactions supported by the forearm. Next, we report on the results of an experiment aimed at establishing the range, stability and comfort of gestures performed with a multiple degrees of freedom mouse on the forearm. We conclude the chapter by discussing the stability of the device as well as possible mappings between gestures and the most common tasks performed in data visualizations.

**Chapter 6 - The neoCampus project**

Chapter 6 presents the neOCampus project in more details. First, we highlight the objectives of this thesis in relation to the project. Next, we introduce a description space built to identify and organize the relevant characteristics to consider when designing interactive solutions to fulfill those objectives. Finally, we discuss our contributions in relation to the description space and give a concrete example of how each solution can be applied to the neOCampus project.

**Chapter 7- Perspective and conclusion**

This chapter concludes the manuscript. It summarizes the work presented in this thesis and presents medium-term and long-term perspectives related to the work conducted in this thesis.

# Related work

# 2 Related Work

## 2.1 Introduction

Over the past decades, HCI researchers have developed a wide range of visualization interfaces and interaction techniques to tackle the unceasing challenges posed by the complexification of data. The scope of these solutions ranges from interaction techniques as simple as using a mouse to filter data on a regular 2D screen [90], to a more advanced tangible interaction in an immersive environment to explore large data sets [162].

This chapter provides an overview of the main approaches designed to support data visualization tasks on the following environments: Screens combined to form a large, high-resolution display (Section 2.2); spatially distributed displays (Section 2.3); immersive displays (Section 2.4). As we wanted to focus on interaction techniques that can be used with different types of data (text wall for instant data, graphical for historic, 3D for building application), we did not focus on specific sets of data and preferred instead to focus on interaction techniques that can be used with any set of data.

## 2.2 Interaction in large displays

Before discussing the various solutions proposed for interaction with large displays, it is important to define large displays and discuss their characteristics and the opportunities they offer (sub-section 2.2.1). Then, we introduce the underlying challenges such an environment poses for researchers and the main solutions proposed to address them (sub-section 2.2.2). A summary of the main interaction techniques as well as the challenges they address are given at the end of the section (sub-section 2.2.3).

### 2.2.1 Large displays

As per Andrews's [4] work on information visualization on large, high-resolution displays, the term "display" refers to the combined visual output that serves as a single contiguous space, whether it is composed of a single large display unit or multiple tiled units. One of the most important aspects of a display for designers is the resolution it offers. The resolution of a display (rather than its size) is the criteria that will define the quantity of data it can visually represent. However, acknowledging the importance of the resolution of a display without mentioning its size would be misleading and would offer an incomplete view of the importance of each attribute. Indeed, it is important to take into consideration the size of the display and its resolution as a combination. This is the concept behind the "dot per inch" (DPI) metric, which defines the amount of pixels available per inch. Andrews et al. [4] argue that a higher DPI means that visualizations can be shown with more details, prompting users to get closer to the display to access the details, or move away from it for an overview. While this assessment holds true for low DPI displays, accessing the overview in those displays require the user to move at a greater distance. This greatly influences the approach one would use for interaction: for instance a selection technique based on raycasting rather than tactile input would be more appropriate in this case.

Beyond the advantage of displaying more information, large displays also facilitate the physical exploration of data [29, 56, 148, 172, 173, 179, 199]. Andrews et al. [3] explain how the physical environment created by large displays supports the use of a wide range of humans' physical embodied resources. Ball et al. [11] argue that these human abilities (motor memory, peripheral vision, focal attention, spatial memory…), promoted by physical navigation (walking, head rotation and every motion that changes how we view the information space) enhance the experience of the user, his understanding, as well as his performance when interacting with data visualization.

Large displays change our approach to working with data, since interaction with data is more centered around the user than around the display itself. Andrews et al. [3] argue that the human-centric perspective on large displays introduces new design guidelines for visualizations. In the following, we discuss the main interaction challenges posed by large displays and review the existing solutions proposed to address them.

Several solutions have been designed to support visualization and interaction with large datasets on large displays. These solutions can be classified into two categories [4]: 1) visualization interfaces, which comprise the design of data visualization interfaces to answer the scalability issue inherent to the transition to large high dimensional displays; and 2) interaction with data visualization, which involves interaction techniques covering some of the main tasks in these visualizations (selection, reaching distant objects, navigation and alternative input devices) [135]. In the following subsections, we will review and discuss some of the more prominent work in each category.

### 2.2.2 Visualization interfaces

Thanks to their high resolutions, large displays can show a great amount of data, while keeping a great depth in scale [65]. This allows the user to have an overview of the displayed data by moving away from it, and a more detailed view by getting closer to the display. However, the user may need to work on the detailed view of a particular region of the visualization while simultaneously having access to the overview. Three main visualization paradigms have been proposed to satisfy this requirement: Focus+context, Overview + detail and Zooming (Figure 2.1). These paradigms have been extensively reviewed and their benefits and drawbacks discussed in several works [50, 66, 80, 85, 106, 114].

(a) Google Maps: an example overview+detail display. The overview inset in the bottom righthand corner of the display allows users to see the context of the detailed region.

(b) Two views in a zooming interface. Detailed and contextual views are temporally segregated within a single display.

(c) A fisheye view is one example of a focus+context interface. The focal region is magnified and displayed within its surrounding context.

Figure 2.1: Examples of Overview + Detail (a), Zooming (b) and Focus + context (c) interfaces [50]

An overview + detail interface allows the user to have an overview of the data and a detailed view of a region of interest. The two views are spatially separated, thereby prompting the user to interact with the views separately which require him to assimilate the relationship between the views [86].

A focus + context interface does not suffer from this problem as the focused view is integrated directly into the context. An example of such interface is the fisheye view [64, 161] which uses non-linear scaling to allow the user to see a selected region in full details.

Baudisch et al. [13], argued that fisheye views are a good alternative to overview+detail interfaces, as they allow the user to keep adjacent information together, thereby avoiding the need for explicit switching between multiple views, as is the case in overview + detail interfaces. At the same time, they introduce distortion, which makes them unsuitable for tasks where proportions and distances matter. They followed on by proposing a focus + context interface that combines the best of both approaches in their "focus + context screens" interface. It combines a projected view, serving as a contextual view and showing an overview of a scalable area of the visualization, with a high-resolution display serving as a focus, displaying a more detailed view of a particular region from the visualization (Figure 2.2).

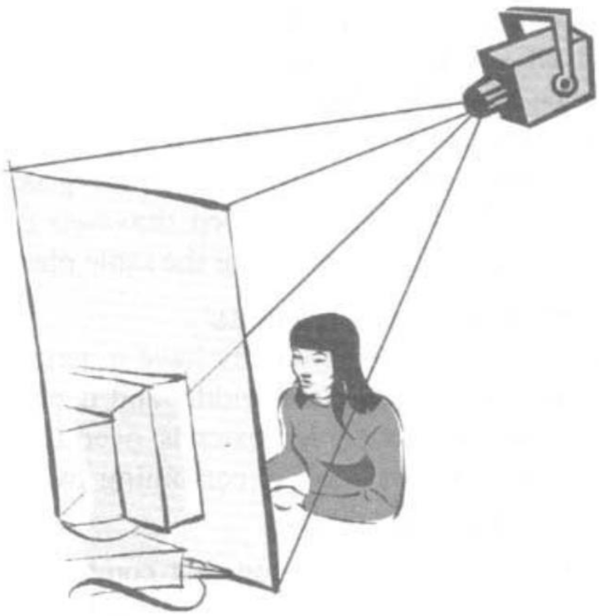

Figure 2.2: F+c prototype combining a monitor having a flat surface with a projection system. [13]

Zooming interfaces involve a temporal separation between views [50]: the user can view only one of the two views (detailed, overview) at one point in a time. The user has to zoom in the visualization to access a detailed view or zoom out if he requires an overview of the data. While zooming interfaces allow the user to exploit the entirety of the display for either an overview or a detailed view, Cockburn et al. [49] showed that the transitions between the zoomed in view (detail) and the zoomed out view (overview) disoriented the users of such systems.

While they have benefits and drawbacks, these interfaces improve the visual exploration of data. When applied to human scale displays where the display's size and resolution are closely matched to the sphere of perception and influence of the human body [4], all regions of the visualization are accessible to the user. However, in larger displays, when the region of interest is outside of the user's field of view and reach (the top left corner of the display for example), having more details of that region becomes difficult.

Enhanced versions of overview+detail interfaces have been proposed following the democratization of mobile devices. Some of these approaches are based on a combination of large displays with smartphones or tablets in what we call multi-display systems [1, 42, 47, 149]. These environments usually combine tablets, large displays and tabletops, to extend the overall interaction space. They have been proven to be useful to interact with large contexts such as geographical data [1]. Multi-display systems have been used in overview+detail configurations [13, 50]. Rashid et al. [149] found that for searching on large maps, a multi-device approach was better than a simple mobile one as it allows the user to access different regions of the maps relatively easily. Cheng et al. [47] showed that, in an overview+detail multi-display technique, moving the position of the detail in a miniaturized view was preferred over other techniques. Overview + detail configurations, combining a large display for the overview and a tablet for the detailed view, allow the user to explore the overview without influencing the detailed view. The detailed view does not clutter the large display as opposed to a traditional implementation of an O+D interface where the detailed view occupies a part of the large display (Figure 2.3).

Figure 2.3: Example of a multi-display overview + detail interface [1]

However, while the interaction solutions described above facilitates access to distant regions of the data visualization, they do not allow the user to work on different regions of the data visualization simultaneously without having to constantly switch the detailed view between the regions of interest.

The use of multiple focused views has been proposed to allow working simultaneously on multiple regions of large contexts [41, 61, 97]. Polyzoom [97] allows multi-scale and multi-focus exploration in 2D visual spaces by offering the user the possibility to create several hierarchies of zoomed views (Figure 2.4).

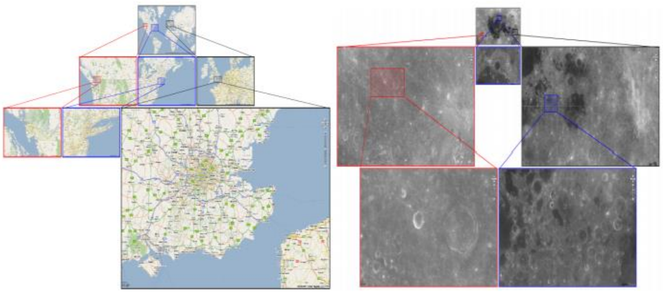

Figure 2.4: The polyzoom technique

Melange [61] uses a distortion-based technique that offers the possibility to bring together two regions of a large space by folding them (Figure 2.5). SpaceFold [41], inspired by Melange, introduces a multi-touch interaction technique to improve the manipulation of the folds.

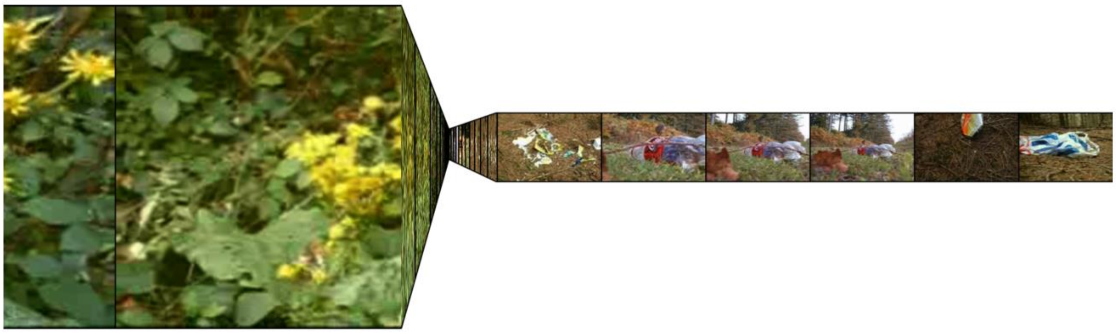

Figure 2.5: Folding a 1D video editing timeline using the mélange technique

### 2.2.3 Interaction with large displays

Interaction with visualizations in large displays have been extensively researched. The proposed solutions are diverse and cover most of the tasks frequently performed in data visualization. In this section we will focus on the main tasks: selection, reach distant objects, navigation and interaction with separate control and widgets [135].

#### Pointing and reaching distant objects

Several approaches have been proposed to reach and interact with distant objects in large displays, most notably: Raycasting, mid-air gestures and the use of smartphones and wearables.

Raycasting is a popular approach when it comes to pointing in large displays. Raycasting based pointing techniques were proposed as early as the nineties. Kirstein et al. [109] proposed a simple interaction technique, using a laser pointer detected by a video camera, as a pointing device to move and hide/show the mouse cursor. Chen et al. [45], adopting a similar approach, used multiple cameras to detect multiple pointers while Ji-Yong et al. [136] based their system on the blink patterns of the pointers to distinguish them. Bi et al. [28] proposed an approach that supports collaboration.

More recent approaches [119, 39, 103, 131, 67, 122] exploited the advances technology made, to offer more compact and efficient solutions. Nancel et al. [131] investigated pointing on large displays from a distance, they explored the limit of existing remote pointing techniques, and they investigated dual-precision techniques combining coarse and precise pointing.

More recently, Matulic et al. [122] proposed a multi-finger raycasting technique where each finger projects a ray onto the display. The technique allows its user to perform direct input using patterns of ray intersections created by his hand posture. This interaction technique can be used for tasks including object selection, object moving and zooming.

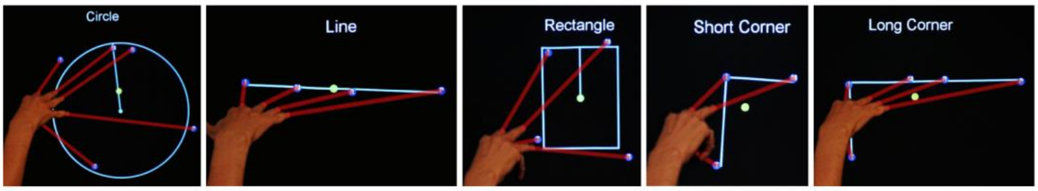


Figure 2.6: Multi-finger raycasting for large displays [122]

Mid-air gestures have been extensively used for interaction with large displays since they do not hinder the movement of the user which is critical in physical exploration and navigation. Walter et al. [189] used mid-air gestures inspired by commercial solutions and enhanced them for better usability to select items on an interactive public display. Bailly et al. [7] proposed a mid-air selection technique based on extending a certain number of fingers towards the display to activate a menu command. Vogel et al. [182] proposed two interaction techniques to perform selection tasks (AirTap, ThumbTrigger) and demonstrated that absolute pointing is more efficient when interacting from great distances. Cockburn et al. [51], Nancel et al. [134] and Haque et al. [76] proposed mid-air pointing techniques where users point at targets using their arms and fingers.

Figure 2.7: The ARC-Pad technique [123]

Smartphones and tablets based interaction are more and more popular among researchers. Mccallum et al. [123] used a handheld device as a remote controller to move a distant cursor through its touchscreen (Figure 2.7). Nancel et al. [133] worked on improving pointing accuracy in a similar approach. Boring et al. [34] used smartphones to control a pointer on a large display by scrolling, tilting or moving the smartphone to achieve the task at hand.

Raycasting technique and mid-air interactions are two popular approaches for objects selection. They offer a quick and easy way to point and select objects. However, their accuracy is limited when selecting small or distant objects. They also suffer from occlusion as the raycast and the tracking device detecting mid-air interaction should not be obstructed. Finally, an inherent problem to physical interaction is fatigue, the physical nature of both approaches render them prone to tiredness. While they are not as natural as the Raycasting and mid-air techniques, interaction techniques based on smartphones and tablets offer better accuracy through the virtual interactions they propose.

### Navigation and interaction with controls

Over the years, researchers tried to improve navigation either by implementing interactions techniques based on the traditional pan and zoom, or by designing new approaches [132, 149, 47, 24, 175, 25, 173].

Rashid et al. [149] showed that controlling large displays using smartphones is the best approach for tasks involving map, text and photo exploration. Many interaction techniques for navigation and content exploration use this modality on large displays. Cheng et al. [47] proposed four interaction techniques to explore an overview (DualTap, DirectTap, TabTilt and TapPoint). Dual tap allowed the user to use multi-touch interactions to change the position and size of a rectangle representing the detailed region. DirectTap is a version of DualTap offering absolute placement. TabTilt uses the sensors of the tablet to detect tilting and position the region of interest in the overview accordingly. TabPoint uses a WiiMote[2] to point towards the region to select. Cheng reported that DualTap is the preferred interaction technique. Nancel et al. [132] used a handheld device and free space gestures to perform pan and zoom on wall-sized displays. They identified several factors for the design of similar interaction techniques. They reported on fatigue and lack of efficiency emanating from gestures performed in free space and on the benefits of guidance for input gestures. They also found that linear gestures allowing clutching were more efficient than circular, clutch-free gestures. Sollich et al. [173] explored the use of spatially aware smartphones to make sense of data changing over time with developmental biologists.

[2] Nintendo's Wii controller

Bergé et al. [24] proposed a multi-device overview+detail interface facilitating personal 3D exploration in public displays. They designed and evaluated three types of interaction techniques to translate the detailed view: two of them were based on mid-air interactions (with the mobile device, around the mobile device) and the third used the device's touchscreen. They followed this work by evaluating around the smartphones techniques with tactile and tangible techniques for 3D manipulation [25]. Their results show that around the smartphone interaction techniques are better than tactile and at least on par with tangible techniques.

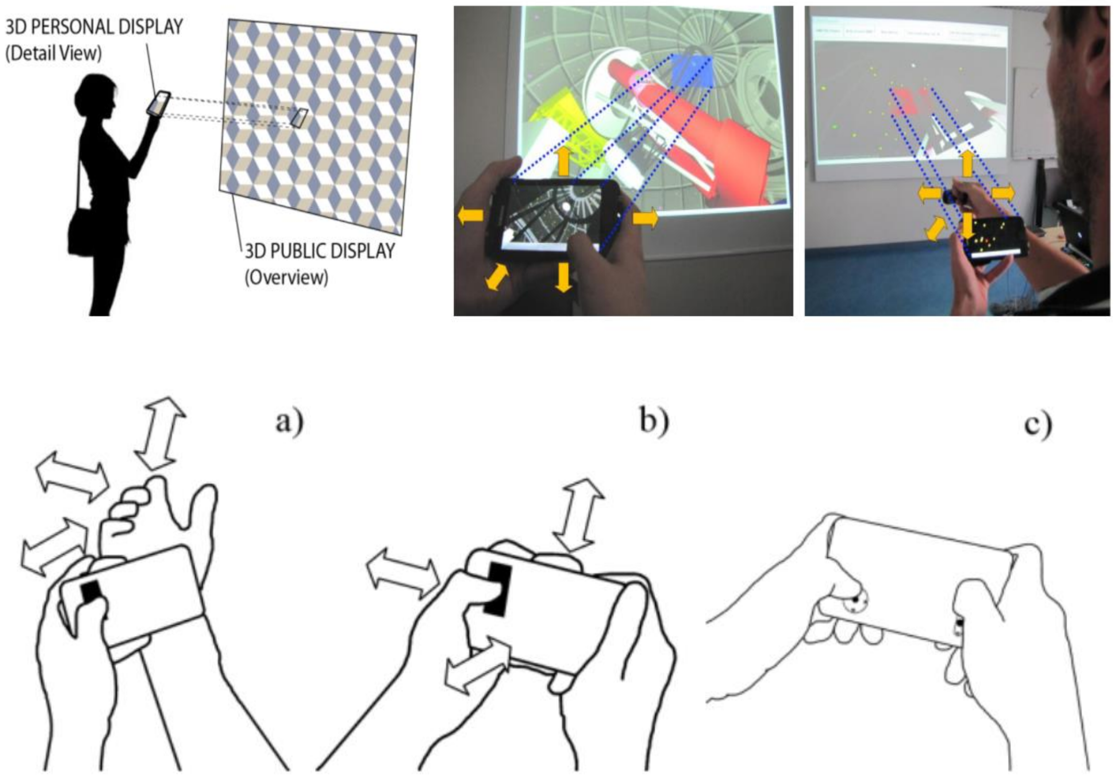


Figure 2.8: Top: General setting of smartphone-based Overview+Detail interface on a 3D Public Display. Bottom: navigation techniques: a) Mid-Air Hand, b) Mid- Air Phone and c) Touchscreen [24]

Chapuis et al. [44] proposed the customization of mobile interfaces programmatically, to support virtual widgets and gestures and to create and interact with content on a large display (Figure 2.9).

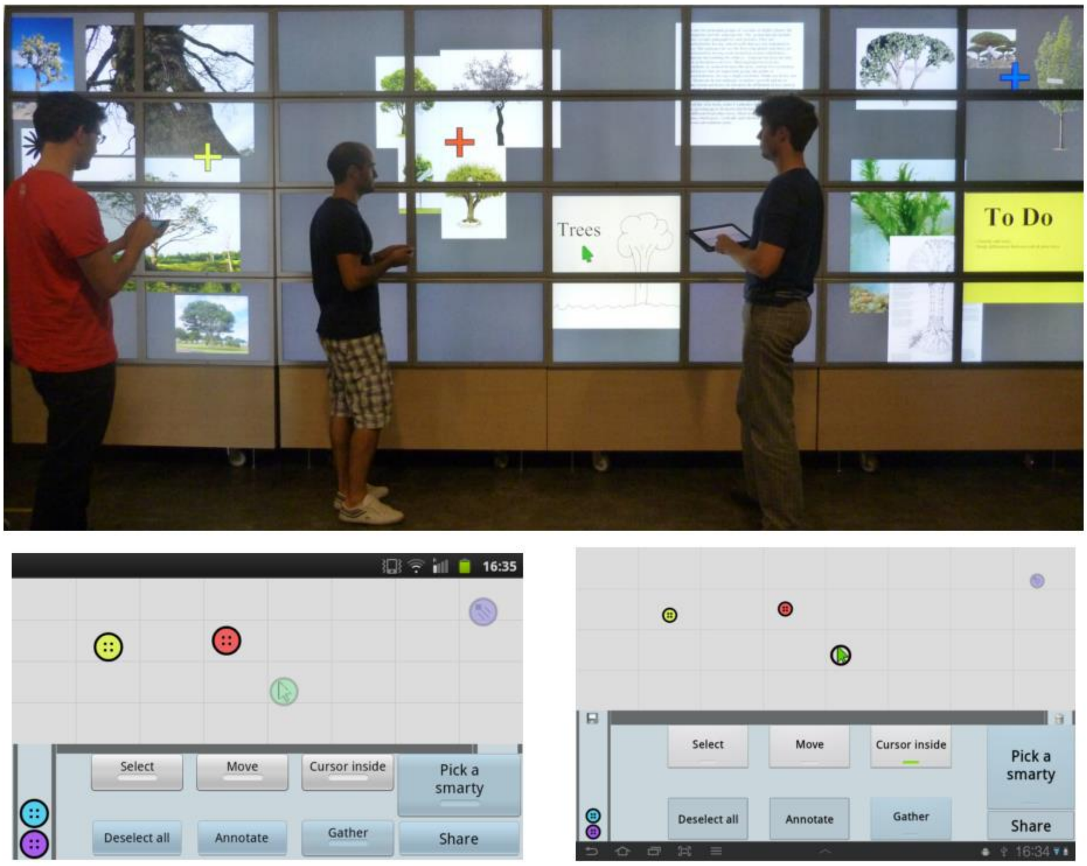


Figure 2.9: Object selection and grouping with three users. The interface running on a phone (left, middle user) and on a tablet (right, right user). Six state button widgets have been added by the application. The" Cursor Inside" action (device on the right) is attached to the active green puck, and acts as a mouse cursor confined inside a window [44].

Jansen et al. [94] used tangible widgets attached to a tablet to manipulate remote content on a distant display. Their approach support locomotion and allow for rich interaction from a distance. They also showed that a tangible approach allows for more accurate manipulation (Figure 2.10).

Figure 2.10: Two users performing dynamic queries on a scatter plot using tangible remote controllers [94]

Sousa's DETI-Interac [175] is a system that allows interaction with public displays using gestures detected by a Microsoft kinect[3]. They argue that their approach allows for more natural interactions than existing approaches.

Baudisch's drag-and-pop [14] allows interaction with distant objects using proxy objects, a rubber band graphic is kept during the interaction to provide feedback related to the connection between the objets. Arguing that the current text entry methods are not adapted to large display, where users need to move freely, Markussen et al. (2013) explored the use of selection-based text entry methods for text input mid-air. Walter et al. [188] proposed a design space for mid-air gestures to interact with large public displays, they evaluated them and found that dwell was efficient for items selection, confirming Hespanhol et al. [81] findings. In addition to that, they provided recommendations for designers of such interaction solutions.

### 2.2.4 Summary

In this section, we highlighted the advantages large displays offer for the exploration of large volume of data, namely: their high resolutions, which allow them to display large amount of data in greater details; the physical exploration they support, which affords the use of a wide range of the users physical embodied resources, enhancing his experience, his understanding as well as his performance when interacting with data visualizations.

We identified the main challenges they generate, specifically: the scalability issue related to adapting visualizations previously designed for smaller displays; The reachability issue designers need to take into consideration when designing interaction technique to select and manipulate distant objects, navigate in the large display and interact with multiple regions of interest simultaneously.

We reviewed the existing solutions proposed to address the challenges described above, notably: the three main visualization paradigms proposed to allow the user to work on a specific region of the visualization while keeping a contextual view: Overview + Detail, Focus + context and zooming; Raycasting technique, mid-air interactions and mobile devices based interaction to perform the most common tasks in large displays; the

[3] https://developer.microsoft.com/fr-fr/windows/kinect

multi-view approach to interact with several regions of interest of large datasets simultaneously.

While several aspects of the solutions proposed above have been researched exentensively, we identified a missing piece in interaction with several regions of the same dataset simulateously. Although several techniques based their solution on multi-view to address this last challenge, the optimal number of detailed views has not been investigated. The first work of this thesis, Split-focus, aims to address this point by investigating the effects of splitting detailed views in Overview+Detail interfaces.

## 2.3 Interaction in multi-display environments

Multi-display environments (MDEs) combine several displays, usually smartphones, tablets, large displays and tabletops, to extend the overall interaction space. MDEs have been used extensively in multiple contexts: medical field [12, 71,169]; meeting rooms [147, 53, 176]; traffic management [144]; home automation [99]; exploration of large datasets [18, 120].

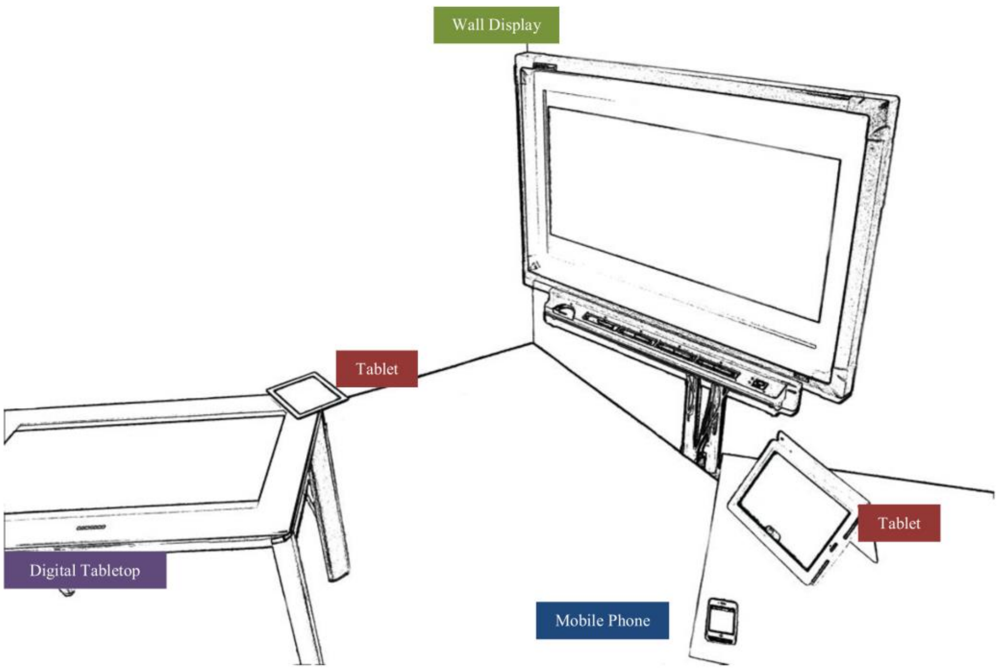


Figure 2.11: An example of a heterogeneous multi-display environment [170]

The heterogeneity of displays (mobility, orientation, position, resolution, size) composing such environments offers new opportunities for data visualization as well as new challenges when designing interaction solutions. Each one of their inherent characteristics influences the type of data visualized and changes the way users interact with such displays. In the following subsection 2.3.1, we will discuss those characteristics, their benefits and the interaction challenges they entail.

### 2.3.1 Multi-display environments

MDEs usually contain at last one large display. They offer many benefits in visualizing large quantities of data (as described in the previous section—Large displays). In addition to those benefits, their size and high resolutions make them primary candidates to serve as an overview in MDEs. Having an overview display in an MDE has been proven to improve collaboration. Brudy et al. [38] conducted an empirical study that explores the use of an overview device in a collaborative trip-planning task performed in an MDE.


Figure 2.12: Left: P8 (WO2) points toward overview device, other members shifted their attention to it. In NO groups pointing rarely led to shared attention (right): P29 (INT1) points toward her device; other members' focus stays on own devices [38].

They found that having an overview display in such environments facilitates decision-making and sense making. Wallace et al. [187] investigated the use of personal and shared displays during group work, in an MDE composed of personal workspaces (laptops) and a shared virtual work space (wall projection). They found that using a shared display appeared to support synchronization of the group activity via body language and gaze. MDEs containing large displays have also been proven to be useful to interact with large contexts such as large datasets [1].

Horizontal displays—usually interactive tabletops in MDEs—favour collaboration. Rogers et al. [155] compared tabletops to wall displays in collaborative tasks. While they did not find a difference in terms of display orientation, they found that the side-by-side arrangement of users allowed by tabletops encourages more discussion.

Mobile displays—like smartphones and tablets—trade screen real estate for mobility and privacy. Their small size allows them to be used as private displays to view personal data [60]. In addition to that, they offer a great range of input capabilities which, combined to their mobile nature, makes them an interesting controller for fixed displays.

Another characteristic that can impact interaction in MDEs is the spatial distribution of displays. As content is distributed among display in MDEs, a badly positioned display might affect the visibility of the content, an unreachable display may require an interaction solution for reaching distant objects. Su et al. [178] showed that display position impact performance and workload and proposed guidelines on how to position displays in an MDE. Fender et al. [63] developed a system that automatically suggests positions and sizes for MDEs' displays, based on user behaviour analysis.

MDEs where displays are aware of the users' position and/or other displays' positions are called spatially aware multi-display environments. Spatial awareness impact how an interaction technique is designed. As an example, Chuckling [78] is a one-handed document sharing technique that lets users physically throw content to displays, in different locations, to share information. It uses a combination of touch interaction to select the content to share and the accelerometer of the mobile device to detect the direction of the toss, and consequently, the display that would receive the shared content. In this instance, the mobile device is aware of the position of other displays.

In addition to their physical characteristics, the displays composing MDEs have different input capabilities. The touch input offered by smartphones or tablets is not suitable for large displays; pointing interaction techniques used to reach distant objects in large displays are not suitable for the accessible display of an interactive tabletop; the traditional mouse and keyboard used for desktop monitors are not suitable for smartphones, tablets or large displays.

While the heterogeneity of displays composing an MDEs make them a compelling solution for data visualization, they introduce their fair share of challenges in terms of interaction. The different sizes, resolutions of displays and the distributed nature of the visualized data require a suitable interaction technique for content transfer between displays. The different input modalities of each display require a unified input technique that can be redirected from one display to the other. The large displays and tabletops in MDEs introduce a privacy problem in that users should be able to see private information if needed. Large displays showing distant content require that the input modality used allow for interaction with unreachable content. In the following, we present a range of techniques designed to support interaction in MDEs.

### 2.3.2 Early multi-display interaction techniques

While mouse input is suited for interactions with multiple desktop monitors [20], such a device does not adapt well to multi-display environments (MDEs) where displays may be scattered within the physical space [185].

The need to design alternatives to the mouse and keyboard for such environments is consolidated by the current trend leaning towards the use of portable displays (Laptops, smartphones, tablets). One of the earliest solutions, Pick'n Drop [152], uses a stylus to transfer information from one device to another (Content redirection). The user touches an object with the stylus on a display to pick it up, and perform the same action on another display to drop it (Figure 2.13).

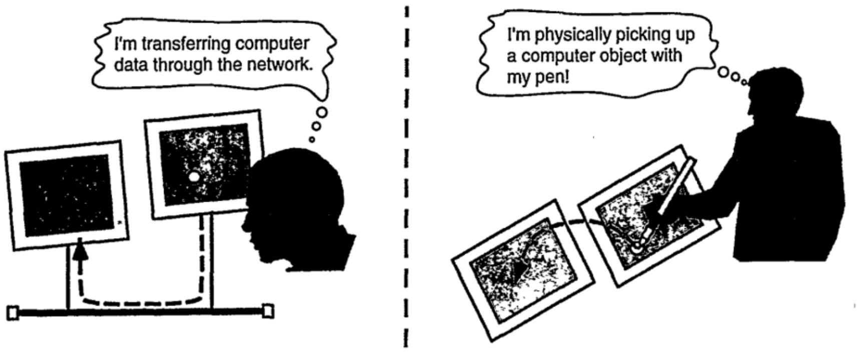


Figure 2.13: Rekimoto's [152] Pick-and-drop technique

They followed on two years later [153] by proposing an augmented multi-display environment (Figure 2.14) where the physical objects and displays are augmented digitally to create a spatially continuous shared workspace. This environment allows users to easily transfer content between displays (Content rediction). The system is augmented by video projectors and uses camera tracking to detect interactions.

Figure 2.14: Rekimoto's [153] augmented surfaces

PointRight [101] is an interaction solution designed to provide common keyboard and mouse control for heterogeneous MDEs (Input redirection). It uses a peer-to-peer[4] pointer and keyboard redirection system where each display in the MDE participates in the interaction either as a source or target of pointers events. Benko et al. [20] proposed a more basic approach in using hotkeys to redirect the cursor of a mouse from one display to another, they demonstrated that their approach was quicker than a mouse in a regular multi-monitor desktop. Nacenta et al. [129] used the stylus for pointing, a particularly difficult task when displays are large or far from the user.

In the early days of multi-display environments, input rediction and content transfer have been identified as the main challenges to address when interacting with multi-display environments. In the following, we will review and discuss the major solutions proposed to address those requirements.

[4] https://en.wikipedia.org/wiki/Peer-to-peer

### 2.3.3 Adapting mobile and wearable devices for MDEs

It is not surprising that mobile displays are an integral and almost unavoidable part of today's MDEs. The benefit of mobility has been highlighted in early multi-display environments when mobile phones and tablets were not as available as today [79, 117]. The democratization of small mobile displays provides not only output capabilities in MDEs, but also a large range of input capabilities. Performing physical gestures with mobile devices leverages significantly more DOF than those available with existing devices, such as mice. The main reason is that such devices combine a number of sensors that expand the input/output space (e.g. touch, tilt).

Content transfer is one of the tasks that benefitted the most from the arrival of mobile devices, researchers used them particularly as gesture mechanisms. Döring et al. [60] proposed a set of usable motion gestures, suitable for being used in multi-display environments with smartphones and interactive tabletops (Figure 2.15), across several application domains. Examples of proposed gestures included throwing from a mobile device to a digital tabletop to send data, as well as pulling from a digital tabletop to a mobile device to collect data.

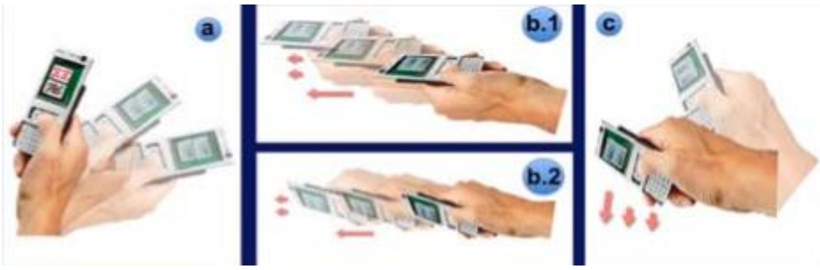


Figure 2.15: Natural gesture interactions with the mobile phone in a multi-display poker game: (a) look into cards, (b.1) fold with cards open, (b.2) fold with cards closed, and (c) check [60]

Similarly, Dachselt et al. [57] proposed throwing and tilting to transfer content to large displays. Adalberto et al. [2] proposed an interaction techniques based on Rekimoto's drag-and-drop [152] where the user can transfer data between a fixed display and a mobile device using a two-handed gesture: one hand is used to suitably align the mobile phone with the larger screen; the other hand is used to select and drag an object between the two devices and choose which application should receive the data (Figure 2.16).

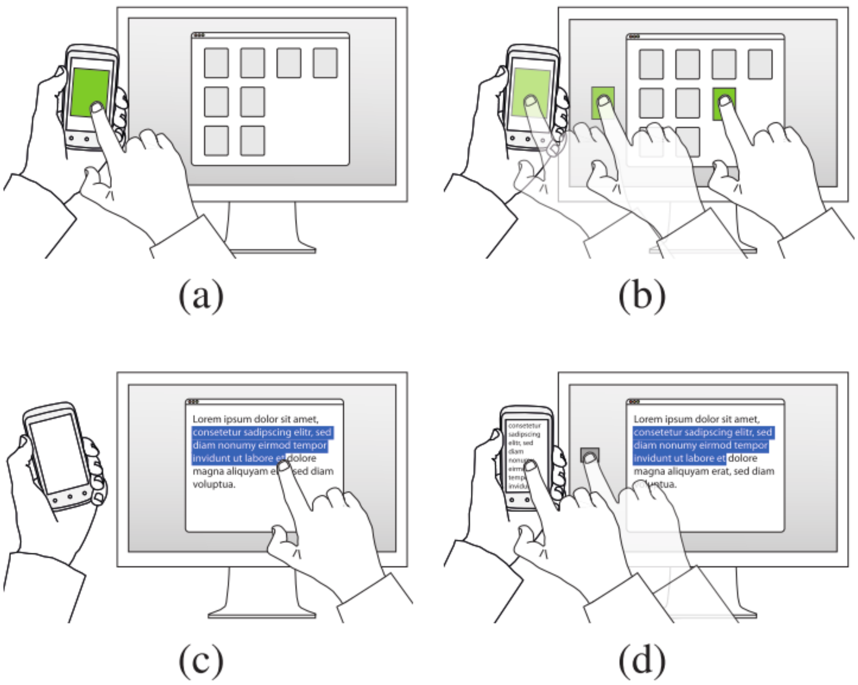


Figure 2.16: Drag-and-Drop concept: (a) a user holds the mobile phone next to the desktop screen and selects a data item. (b) The user drags it inside the screen. (c) In the other direction, a user selects data on the PC and (d) drops it on the phone [2]

Jokela et al. [102] designed three interaction techniques using the smartphone's inherent characteristics to move content (visual objects) between smartphones. The first interaction technique (Tray) enables the user to move objects through a virtual tray shared between devices; the second interaction technique requires the users to perform a simple tap to move content between them; the last technique—called Device Touch—is based on the devices physically touching (Figure 2.17).


Figure 2.17: Different cross-display object movement methods: a) Tray, b) Transfer Mode, and c) Device Touch [102]

The camera on the mobile device has also been used to transfer data between MDE displays: Boring et al. [34] developed Touch Projector, an interaction technique using the smartphone's camera to manipulate and transfer content from one display to another (Figure 2.18).

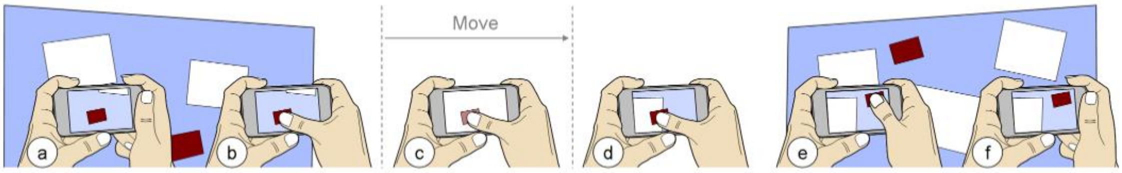


Figure 2.18: Walkthrough of the original metaphor: The user aims at a display (a) and touches the item of interest (b). When moving the device off-screen, a thumbnail of the dragged item is showing (c). After reaching the destination display (d), the item can be positioned precisely by moving the finger (e). When the finger is released, the item has been transferred successfully (f) [34]

Chang et al. [43] used the smartphone's camera to identify displays, capture the work state on the display, and transfer it to another display. Other approaches for content transfer include: using smartphones for copy-and-paste operations [163], using smartwatch-centric gestures in cross-device applications [87] and using the rotation/tilting of smartphones [27].

In addition to content transfer, mobile devices have been used to explore large datasets on large displays. Bergé et al. [25] used mobile devices for interacting with distant 3D content. Nancel et al. [133] used them for pointing on a large display. Other researchers used them for continuous map navigation [34, 132]. Another common approach is to use mobile devices for multi-display overview+detail tasks [16, 24].

Most of the interaction solutions described above require the mobile device to be held mid-air, which can be tiring [82]. It can also affect the precision of the interaction. To overcome these problems, mobile devices can be actuated. Hover Pad [166] is an MDE composed of an interactive tabletop and a self-actuated display that can move autonomously in mid-air to navigate through three-dimensional space (Figure 2.19). Kim's [108] G-Raff is an elevating tangible block equipped with a display that supports 3D interaction on tabletop displays (Figure 2.20).

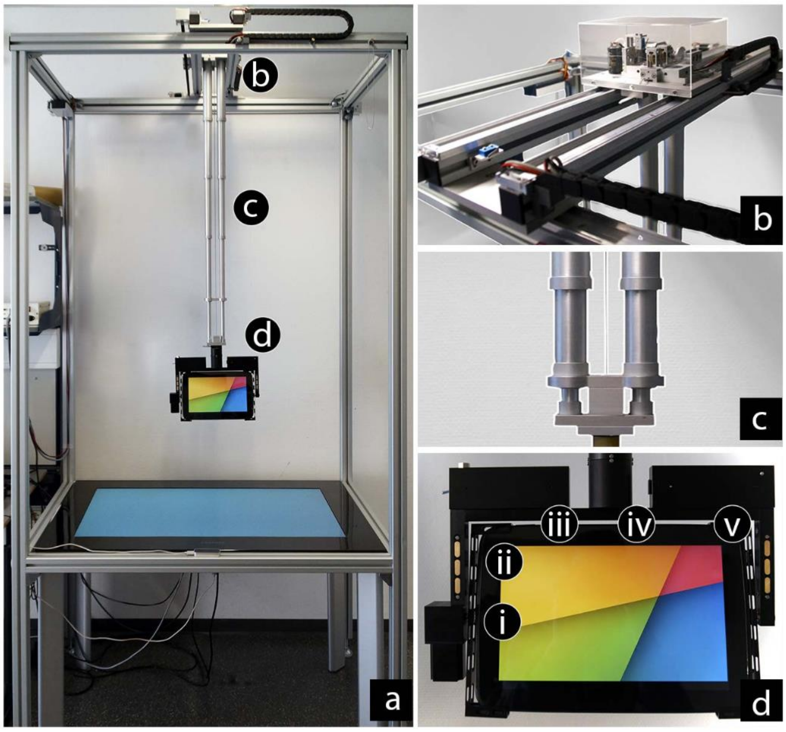


Figure 2.19: Overview and details of the Hover Pad hardware setup (a) with details regarding the sliding carriages for x, y-motion (b), the telescope bars for vertical motion (c), and the display's frame for rotation (d), comprising two motors (i, iv), a controller board (iii), a battery pack (v), and 16 capacitive buttons (ii)

Figure 2.20: G-raff: A Tangible Block Supporting Spatial Interaction in a Tabletop Computing Environment [108]

Mobile devices have also been used in complete MDE interfaces. Serrano et al. [168] developed Gluey: a user interface based on the combination of a head-worn-display with a camera, which facilitates seamless input transitions and data movement across displays. Rädle et al. [146] designed HuddleLamp: a desk lamp with an integrated camera that can track positions of multiple devices and hands on a table to allow around-the-table collaboration. The HuddleLamp can support a large set of cross-device interactions: peephole navigation, where a smartphone or a tablet is used to physically navigate a large overview; synchronous navigation, where a large overview is shared between display; spatially-aware menus and modes changing the role of devices based on their orientation or distance; cross-device flicking to transfer data between displays (Figure 2.21).

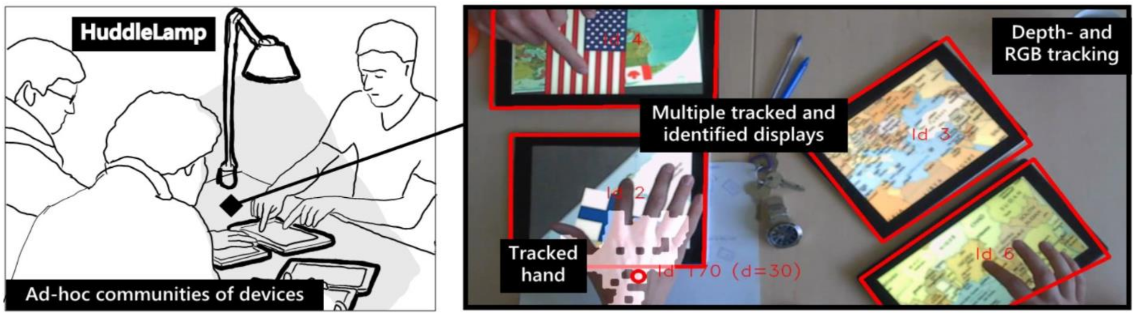


Figure 2.21: The HuddleLamp detects and tracks mobile devices and users' hands for ad hoc multi-device collaboration on desks [146]

To enable mobile users to associate personal displays with other displays in an MDE, and facilitate selection and discovery of displays, Gostner et al. [69] proposed two spatial interfaces: the first one is a list ordered by distance, describing the displays in the MDE; the second one is a miniature map of the MDE. They evaluated the two spatial interfaces in comparison to a simple alphabetical list of displays (baseline) and their results provided clear evidence of users preferring the miniature map of display over the other two options.

### 2.3.4 Augmenting regular mice for MDEs and multi-dof devices

In the early days of multi-display environments and upon identifying the inadequacy of traditional mice and keyboards for the aforementioned environments, researchers proposed several solutions based on augmenting regular mice. Booth et al. [30] proposed the Mighty Mouse, a remote control technique that allows the user to choose the display he wants to control from a list of all available displays in the MDE. The system then uses the VNC[5] protocol to redirect mouse input to the chosen display. Baudisch et al. [15] developed the mouse ether, an interaction technique that facilitates the movements of the cursor from one display to another in a multi-display environment where the displays have different resolutions and/or orientation. Benko et al. [20] augmented the mouse with hotkeys, allowing the user to redirect it between displays. The Perspective Cursor technique [130] exploit the user's perspective of the room, to map the cursor to the display space that appears the more natural and logical from the user's position. Nacenta et al. [130] evaluated their interaction technique and found that it performs significantly faster

[5] Virtual Network Computing (VNC) is a graphical desktop sharing system that remotely controls another computer (https://en.wikipedia.org/wiki/Virtual˙Network˙Computing).

for targeting tasks compared to the traditional techniques. They also showed that Perspective Cursor is effective for systems that require time-efficient interactions, and that it was strongly preferred by users. Kobayashi et al. [111] proposed the 'ninja cursors' technique that replicates the mouse cursor as much as necessary, to improve pointing performance. Other multi-DOF input devices have been proposed in the literature, although they were not specifically designed nor tested in the context of MDEs. Their capabilities and the degrees of freedom they offer make them interesting candidates to fulfill MDEs' requirements. The Rockin' Mouse [8] and the VideoMouse [84] have rounded shapes that allow tilting the device and thus, offer additional DOF in comparison to a regular mouse that can be used to perform multi-display tasks (Figure 2.22).

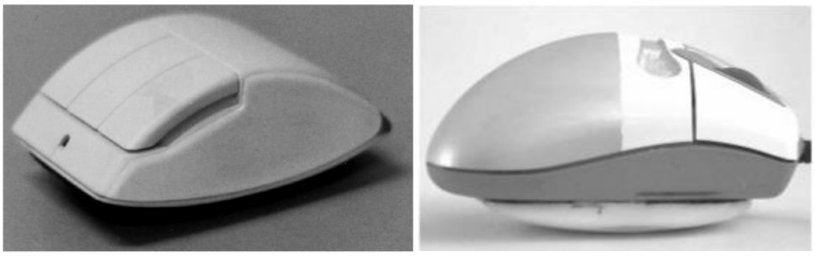

Figure 2.22: The Rockin'Mouse [8] (left) and the VideoMouse [84] (right)

The Roly-Poly Mouse (RPM) [140] uses a completely rounded bottom to augment the mouse's DOFs (Figure 2.23). It has been shown to provide larger amplitude of movement than previous tilting devices, and it also enables compound gestures (see Table 1 in 140) for a summary on the differences between RPM and previous tilting and multi-DOF mice).

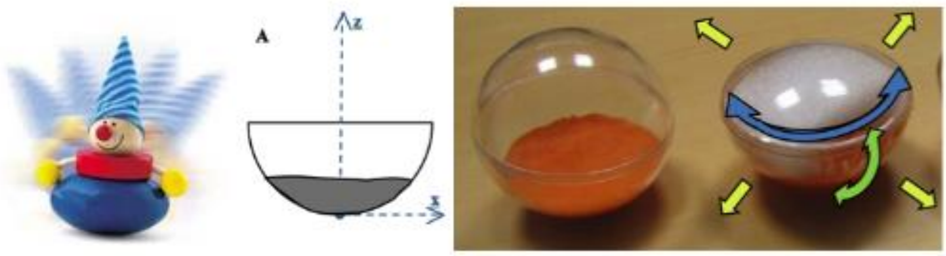


Figure 2.23: The Roly-Poly mouse [140]

While the rounded dome-like shape of RPM offers multiple degrees of freedom, it hinders the device's stability. Unintended physical manipulations (e.g. Roll during Translation) are common on devices with such a form factor (cf. study 1 in [140]). The

LensMouse [197] uses a touchscreen coupled with an input device. Other mice have also proposed the use of multi-touch [22].

### 2.3.5 Summary

In this section, we introduced multi-display environments: a combination of several displays, usually mobile devices, large displays and tabletops, to extend the overall interaction space.

We described the inherent characteristics related to the heterogeneity of the displays composing them: mobility, orientation, position, resolution, size.

We discussed the advantages resulting from those characteristics as well as the interaction requirements that stem from them: *input redirection* (i.e. redirect input channels to different displays), *output redirection* (i.e. move content between displays), *physical relationship* (i.e. possess high-level information on the spatial layout of the displays), *reachability* (i.e. interact with a distant display) and *personal data management* (i.e. personal input and output interaction).

We reviewed a range of techniques proposed to fulfill the requirements described above, notably: using tracking solutions to detect the displays of the environments and create a continuous relation between them; adapting the mouse to a multi-display setup to redirect input from display to another; using pen based interaction and adapting mobile devices to facilitate content transfer between displays or reach distant objects.

However, while several interaction techniques have been proposed to improve interaction in MDEs, they usually address one requirement at a time. To our knowledge no device has been specifically implemented to address this full set of requirements. The second contribution of this thesis lies on the design and evaluation of a novel touch-enabled device, TDome, designed to facilitate interactions and address a range of tasks in MDEs through its multiple degrees of freedom.

# 2.4 Interaction in immersive environments

Immersive technologies went from expensive, heavy VR headsets a few years ago to lightweight and as affordable as sub-50$ VR headsets that can be used with most smartphones today. Extremely performant headsets like the Hololens[6], the Oculus rift[7], MetaVision[8] or Moverio[9] can be bought commercially for a few thousands of dollars. This opened the door to new research fields like immersive analytics, reflecting the potential of such environments.

One of the main advantages of immersive environments is their spatial capacities that support human cognitive abilities and allow for a spatial comprehension of data [6,124]. In immersive environments, the information is spatially displayed around the user supporting physical exploration of data. Their performant tracking systems allow them to offer a natural way of interaction.

Beyond the challenges of interaction in direct relation to the characteristics of immersive systems, challenges of interaction with complex data in immersive environments can be task-dependent. We will focus on the challenges related to the most common data visualization tasks, which include: selection, navigation, filtering and manipulation of objects in 3D environments.

As we will see in the following section, most of the early interaction techniques proposed for these environments were inspired from desktop interfaces. The advent of affordable immersive headset combined to that of smartphones, tablets and wearables in general changed the direction of research to more creative solutions.

The rest of this section will review the interaction solutions proposed for immersive environments according to the modality of interaction involved.

## 2.4.1 Tactile interactions

In today's world, tactile is the preferred interaction technique for a myriad of tasks and environments. Immersive environments are no exception. Whether the interaction is

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[6] https://www.microsoft.com/en-us/hololens

[7] https://www.oculus.com/rift/

[8] http://www.metavision.com/

[9] https://epson.com/moverio-augmented-reality

integrated directly in the immersive device (HWD[10], Smart glasses) [156], or deported to an external supporting device (Smartphones, Tablets, Wearables, interactive tabletops) [116, 58], several research focused on the use of tactile interactions for immersive visualizations. Rudi et al. [156], explored the design space for map interaction techniques on HMDs: they proposed tactile interactions to navigate a large map (Figure 2.24). However the tasks/actions covered were limited and involved only panning and zooming.

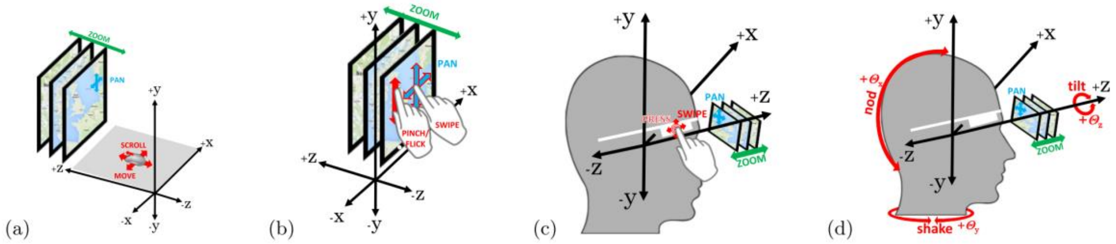


Figure 2.24: A depiction of how control inputs (e.g., moving the mouse along the x-axis to the left or right) correspond to map interactions (i.e., moving the map along the same axis/in the same direction) for: (a) mouse controls, (b) touch controls, (c) haptic controls on OHMD, (d) head controls on OHMD [156]

Giannopoulos et al. [115] went further, they mapped the input function of a Samsung VR headset [11] (Touchpad and a programmable back button) to the core functions offered by digital maps to design interaction technique to perform pan gesture, zoom gesture and selection of a point of interest in a map. Dane et al. [58] approach was based on the use of a tabletop for interaction with a large stereoscopic display. They proposed a widget based interface controlled by a set of interaction techniques to navigate 3D visualizations. The tasks covered include: data selection, controlling slicing planes and writing annotations. In a similar fashion, Claes et al. [118] use a multi-touch interactive tabletop to explore medical visualizations (Figure 2.25). Ji Sun's finger walking in place (FWIP) technique [98] allows its user to navigate a virtual world by sliding his fingers on a multi-touch sensitive surface.

[10] Head-Worn Displays

[11] www.samsung.com/global/galaxy/gear-vr/

Figure 2.25: A miniature version of the 3D data appears to float in the air above the table surface. (A digital rendering is superimposed on the photograph to demonstrate the effect.) A cutting plane through the volume data is projected (like a shadow) onto the table below, where multitouch gestures are used to navigate and interrogate the data. After navigating to a useful view of these imaging data of a heart, the user is now defining a smooth 3D curve (e.g., the shape of a catheter delivery system) relative to the anatomical data set [118].

Manipulating multidimensional data is improved with interaction techniques or devices supporting 6DOF (Translation, rotation and tilting). Researchers tried to augment the number of degrees of freedom offered by tactile interaction through multitouch interactions. Hancock et al. [75] proposed a 5DOF movement with one-touch interactions (2DOF input), up to 6 DOF using two-touch interactions (4DOF input) and a direct mapping of 6 DOF to three-touch interactions (6DOF input). Some of the take-aways from their work include that a higher number of touches allows more natural and flexible interaction and that the users are able to perform separable simultaneous control of rotation, tilting and translation. Jingbo et al. [100] limit the number of fingers needed for 6DOF manipulations to two by using a learning-based approach. However, these approaches are not natural. Martinet et al. [121] studied the integration and separation of degrees of freedom and found that, separating the control of translation and rotation significantly affects performance for 3D manipulation. Besançon et al. [26] compared tactile interaction to other modalities for 3D data manipulation and demonstrated that tactile interaction is not the most suitable to interact with multi-dimensional data.

Bergé's [24] work confirmed that tactile interactions were neither the most efficient, nor the most preferred. It requires a dedicated surface to perform interaction [24] and in an immersive environment, this can divert the attention of the user from the task to perform to the interaction tool, when the dedicated surface is a tablet or a smartphone. It can also constrain his movements in the case of fixed tactile display or an interactive tabletop [110].

### 2.4.2 Mid-air interactions

From the Microsoft Kinect[12] to the Optitrack system[13], a multitude of efficient tracking solutions are available to researchers today. They are largely available, affordable (Microsoft Kinect), and accurate (Optitrack system). The impact of these solutions on the HCI field is palpable. It is even more obvious in environments where the focus is on physical exploration of data. As we saw in (Subsection 2.2, Large displays), mid-air interactions with all the advantages they offer (unconstrained mobility, light and easy to perform) [151, 48, 174] are noticeably used to interact with immersive environments. The Hololens[14] propose a set of hand gestures to allow users to take action in augmented reality: its two core gestures are Air tap and Bloom[15]. Air Tap is "a tapping gesture with the handheld upright, similar to a mouse click or select. This is used in most HoloLens experiences for the equivalent of a 'click' on a UI element after targeting it with Gaze". The Bloom gesture is 'the "home" gesture and is reserved for that alone. It is a special system action that is used to go back to the Start Menu. It is equivalent to pressing the Windows key on a keyboard or the Xbox button on an Xbox controller. The user can use either hand. Microsoft argues that those gestures were designed with simplicity in mind, rather than precision.

The Hololens has an efficient tracking system which allows users to design their own gestures. It has been used in combination with a Microsoft Kinect in Yim's [198] proposed work, that can assist users in analyzing and understanding a topological map, as a virtual hologram (Figure 2.26). They proposed mid-air gestures to resize, rotate and reposition

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[12] https://developer.microsoft.com/fr-fr/windows/kinect

[13] http://optitrack.com/

[14] https://www.microsoft.com/fr-fr/hololens

[15] https://docs.microsoft.com/en-us/windows/mixed-reality/gestures

the map as well as several gestures specific to the task at hand (lowering water levels, viewing graphs ....).

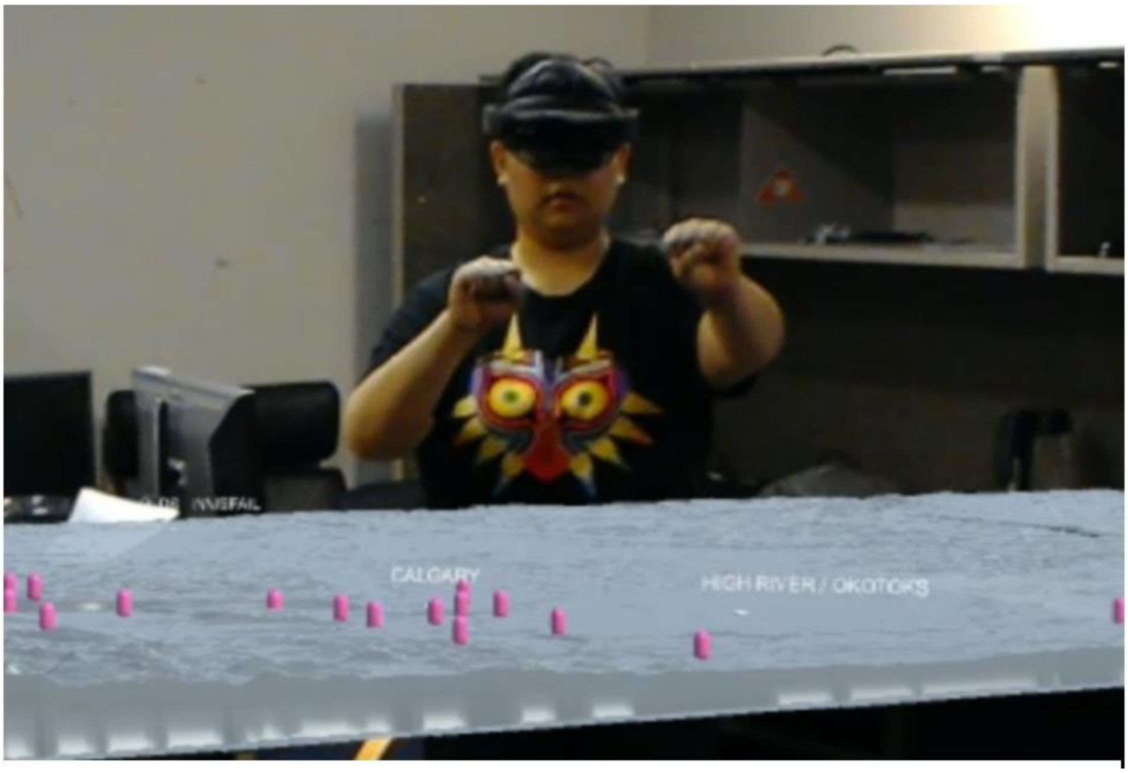



Figure 2.26: The user is wearing the HoloLens and using Kinect gestures to change the rotation of the model [198]

Radkowski et al. [145] used the Microsoft Kinect to track hand movement and recognize hand gestures. They proposed an augmented reality system to perform assembly of 3D models of technical systems and designed mid-air interaction techniques to select, manipulate, and assemble 3D models of that system. To select an item, users had to move a yellow sphere representing a 3D virtual cursor towards the object of interest by moving their hand, a collision with the object highlights it, and a fist gesture selects it. Manipulating an object (translation, rotation and scaling) is performed by selecting a function, a coordinates system or a 3D cursor appears to assist the task. The interaction techniques were evaluated and found easy to perform but at the same time, some of them were not understood as the authors intended.

Benko's [21] Pinch-the-Sky dome interface is an interactive immersive experience where users can use mid-air gestures to interact with an augmented dome (Figure 2.27). The system answers to speech commands with free hand gestures. The gestures include: hand pinch, two hand circle, one hand clasp, speech recognition and interactions with an

IR laser pointer. They performed a study in the form of public demonstrations (1000 participants) and reported the following: the proposed mid-air interaction were simple to perform, but understanding how to perform them was not self-evident. The need to give further explanation was highlighted. This is an important drawback of mid-air interactions.

Figure 2.27: Performing a pinching gesture pans the night sky imagery in World Wide Telescope [21]

Other well-known problems with mid-air interaction are fatigue [40] and without an appropriate feedback, ambiguity. Moreover, they are not easily discoverable and need to be memorized first, before being used [83, 126]. Finally, finding the right mid-air interaction for a given task/action is challenging. Even if designers use the most natural real life gestures as the interaction technique for a specific task, it may not be the same from one user to another. One of the most used approaches to design mid-air interaction is elicitation studies [196]. Piumsomboon et al. [142] compiled a set of gestures to guide designers to achieve consistent user-centered gestures in AR. They conducted a guessability study focused on hand gestures, they elicited 800 gestures for 40 selected tasks from 20 participants. They used the results of the study to create a user-defined gesture set for augmented reality interaction. Other work that used elicitation studies to design mid-air interaction for immersive environments include [73, 113].

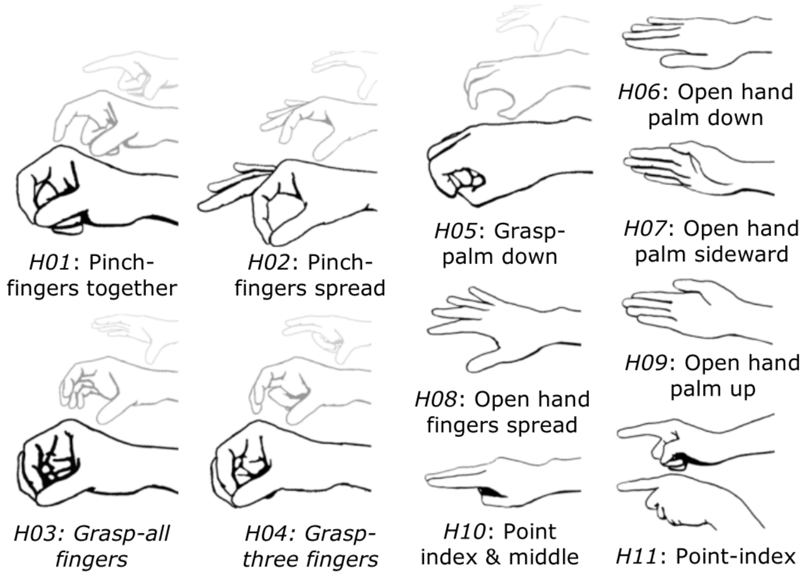



Figure 2.28: Variants of hand poses observed among gestures in [142]

### 2.4.3 Tangible interactions

Tangible interaction is a good alternative to tactile and mid-air interactions, as it covers their lack of degrees of freedom (necessary to interact with immersive visualization) [6, 25, 200]. This aspect of tangible objects allows researchers to propose natural interactions, close to what users do daily in real life. One of the grounding works in HCI using tangible interaction for immersive environments is Stoakley's [177] world-in-miniature approach (Figure 2.29). Upon observing that the then-implementations of virtual environments limit what users can use and visualize from the virtual world (the users had one single point of view), Stoakley proposed the WIM interface, a tangible handheld miniature copy of the life-size virtual environment. Their approach allowed users to have a second dynamic viewport onto the virtual words as well as manipulate objects in the virtual environment through direct manipulation using the handheld physical prop. Informal user observations indicate that users adapted quickly to the proposed metaphor and that physical props are helpful in manipulating objects in virtual environments.

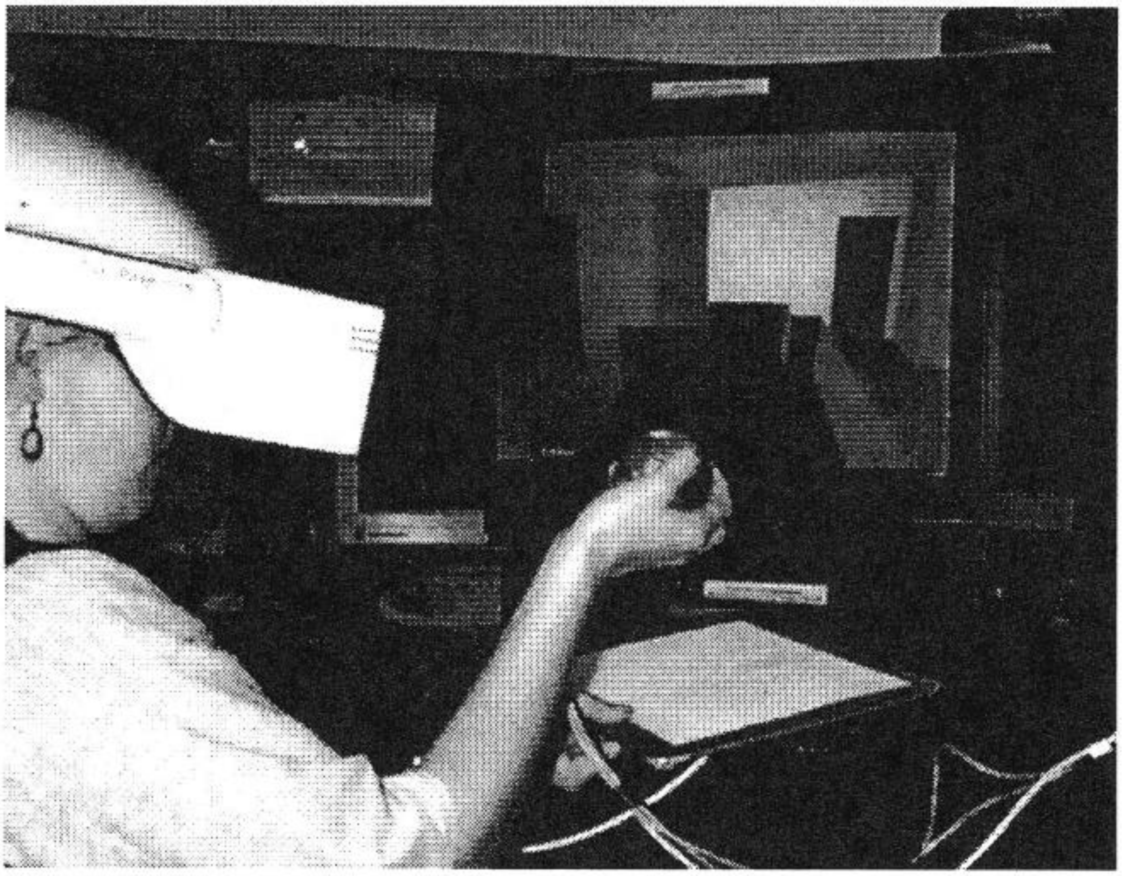


Figure 2.29: A user manipulates the WIM using the physical clipboard and button-ball props [177]

Schkolne et al. [162] proposed an immersive interface for designing DNA components for applications in nanotechnology (Figure 2.30). Their system uses tangible 3D input devices: a raygun tool: a tangible handheld object in the form of a gun, used for picking points in space; tongs: doubly sensed tongs that can detect strong and weak grabs, used to move molecules; multipurpose handle tool: a handle containing an action button, a menu button and an embedded magnetic motion sensor, used to activate functions like drawing. A user study performed with scientist shows that they find the immersive interface and the tangible approach more satisfying than a 2D interface due to the enhanced understanding gained by direct interaction within the 3D space.

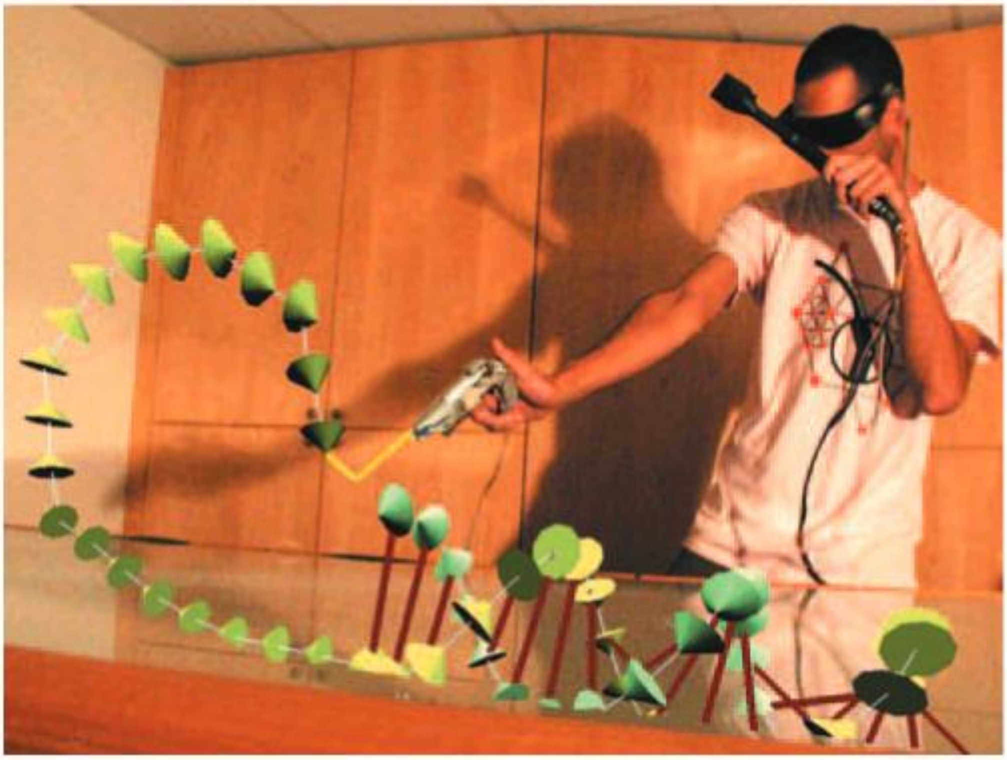
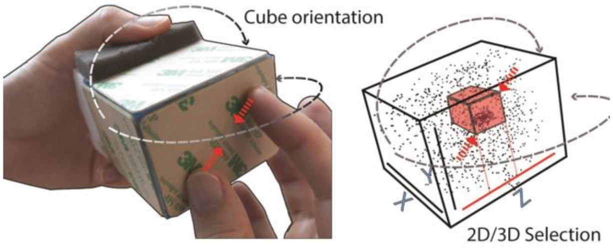
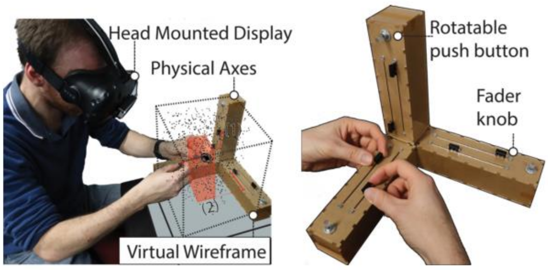


Figure 2.30: Using Schkolne's [162] system to interact with molecules

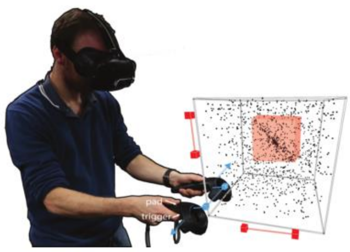
Cordeil's [55] took interest in the mapping of user actions in physical space into the space of data in a visualization. They proposed a design space to inform the design of interaction technique based on the aforementioned basis. They demonstrate their design space with three tangible prototypes (Figure 2.31): Touch-sensitive cube, Physical Axes design, Virtual mid-air design.




(a) Touch-sensitive cube




(b) Physical Axes design



(c) Virtual mid-air design

Figure 2.31: Three designs for SD coordinated interaction [55]

More recent approaches include: Jackson's [92] lightweight tangible 3D interface for interactive visualization of thin fiber structures; Issartel's [91] portable interface for tangible exploration of volumetric data;

Besançon et al. [26] compared tangible interactions to tactile and the mouse for multi-dimensional data related tasks. They found that tangible interactions perform better than its mouse and tactile counterpart, that tangible's affordance removes the need for a learning phase. However, they point out that the mouse was more precise overall. The use of tangibles in mid-air without support may have played a role in that last result. While their mid-air usage allows them—like mid-air interactions—to support physical exploration of data by not constraining the movement of the user, a prolonged usage in that condition would incur fatigue.

### 2.4.4 Mobile and Wearables devices

Kharlamov et al. [107] argue that the current techniques for 3D selection in VR environments are not adapted to the requirements of such a task. They usually use head rotation followed by a dwell time or a click of a button on the headset to validate the selection. Using the dwell time approach to validate requires the user to keep his head static for a certain amount of time, which makes selecting small target extremely difficult in addition to causing fatigue of the neck muscle. It may also result in a midas touch effect [93] where targets are selected unintentionally. The button approach may cause the Heisenberg effect [37], where the click on the headset button for validation moves the cursor and results in a miss-selection. To solve those potential problems, Kharlamov et al. [107] proposes TickTockRay (Figure 2.32), a smartwatch-based raycasting technique for smartphone-based head mounted displays. The technique implements fixed-origin raycasting using off-the-shelf smartwatch hardware to perform selection in the virtual world. They proposed several approaches to confirm the selection: tapping on the screen of the smartwatch, a grabbing gesture, a finger-snapping gesture, and a poking gesture.

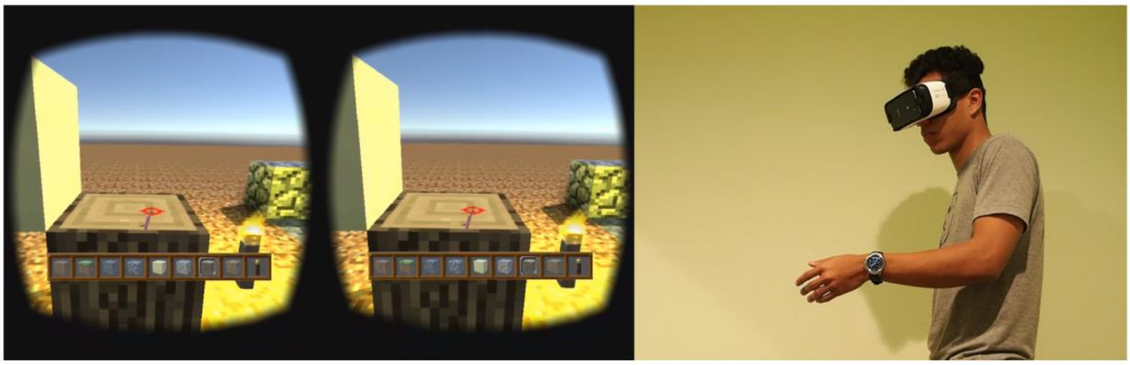


Figure 2.32: TickTockRay enables freehand pointing in mobile VR using an off-the-shelf smartwatch [107]

Benzina et al. [23] used a combination of a smartphone's touch capabilities and his sensors to develop a one-handed navigation technique in virtual environments. They use the touch capability of the smartphone for translations, and the sensors for rotation control. They developed four interaction techniques based on their approach: rotate by roll, rotate by roll with fixed horizon, rotate by heading and merged rotation. The interaction technique maps a certain number of DOFs of the phone to the VR app (+4). They investigated the number of necessary DOF to navigate in a virtual environment and found that, the rotate by roll technique, offering 4 DOF provides good performance.

They also found that the usage of the roll in smartphones to control the heading in virtual environment was preferred and seems to be the appropriate approach for such a task.

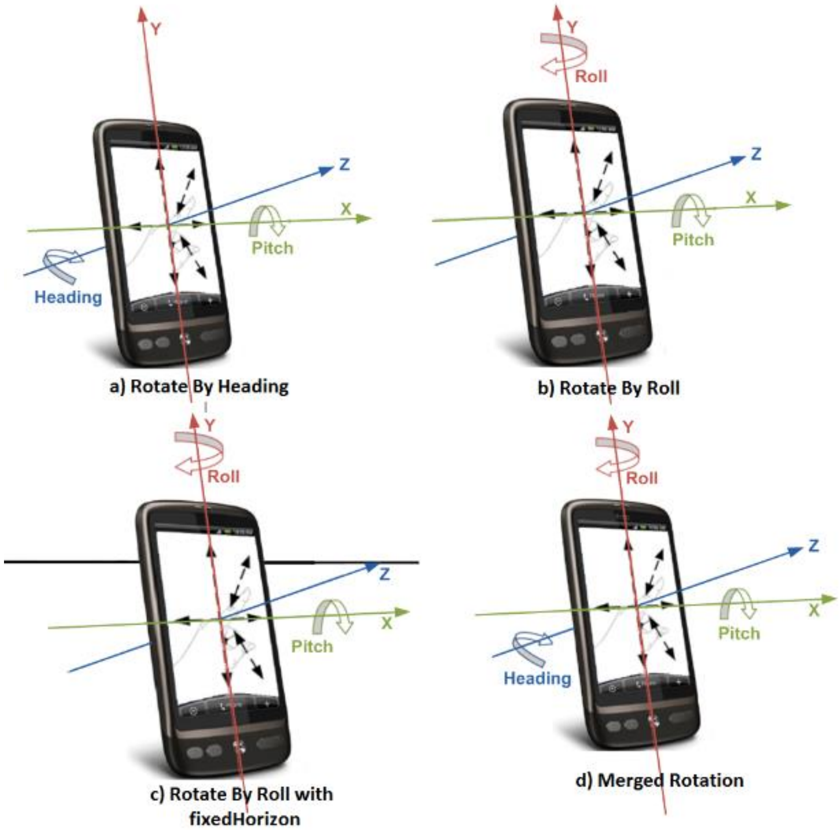



Figure 2.33: Steer Based Rotation Control Technique [23]

Wang et al. [190] presented Object Impersonation, a new HMD metaphor that allows the user to manipulate a virtual object from the outside or the inside, by becoming the object. The metaphor is based on the use of a tablet in combination with an HMD.

Smartphones and wearables are a good option when it comes to interaction with multi-dimensional data, they offer a large number of degrees of freedom as well as the necessary sensor to exploit them, touch capabilities and they can be freely moved in space, which does not hinder the movement of the user. However, this mid-air usage can induce fatigue. Their potential use in immersive environments may be limited in that, their display is not usable in a virtual reality context where the user's sight is obstructed by the HMD. In an augmented reality context, their mid-air usage also incurs fatigue. The sensors may produce noise which can impact the precision of handheld devices. Hürst et al. [89] evaluated smartphones and tablets based interaction techniques to interact with virtual reality and highlighted the unreliability of the sensors equipping them.

### 2.4.5 On-body interactions

As opposed to the previous modalities described in this section, on-body interactions have been scarcely used for interaction in immersive environments.

Serrano et al. [167] explored the use of hand to face gestures arguing that it is well suited for HDWs (Figure 2.34). They performed a guessability study that showed that participants preferred hand-to-face gestures to interact with the HWD. Their findings include: participants agreed on similar hand-to-face gestures for panning and zooming; the cheek was the most promising area of the face for zooming and panning due to its large interaction surface and lack of fatigue; hand-to-face gestures were as acceptable socially as the HWD ones.

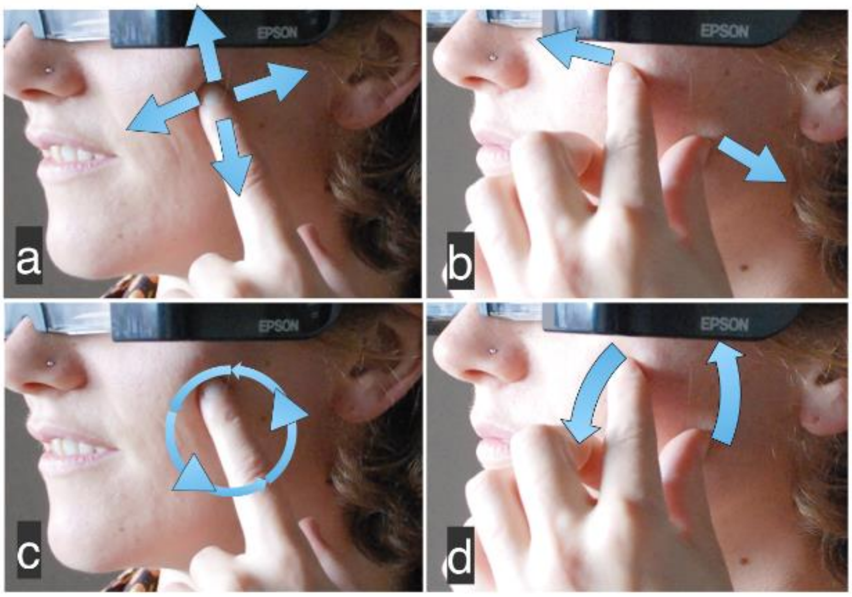



Figure 2.34: Proposed hand-To-Face input for navigation by [167] includes: a) Panning, b) Pinch zooming, c) Cyclo zooming, d) Rotation zooming

Dobbelstein et al. [59] proposed the use of the belt as a tactile surface to interact with HWD. Encircling the user's hip, the belt offers a wide input space. They mapped quickly accessible information and applications on the belt. With social implications in mind, they conducted a study to evaluate their approach. They found that users considered most of the area on the belt appropriate for short interactions, and only the front area, above the trouser pockets as acceptable for long interactions.

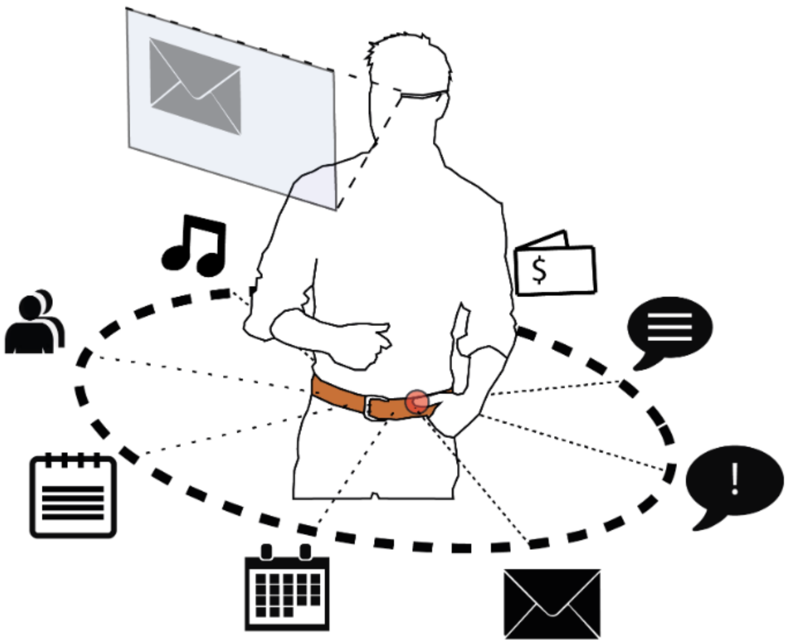



Figure 2.35: Dobbelstein et al. [59] belt technique

Wang et al. [191] focused on text input for smart-glasses: they proposed PalmType, an interaction technique that enables users to type with their fingers on the palm.

Other on-body interaction techniques that were designed for other environment and could be integrated into immersive environments include the following:

Skinput [77], which is a technology that allows the skin to be used as an input device, it provides an always available and naturally portable on-body input system. This approach could easily be adapted to immersive environments.

Belly gestures [181], which is an interaction technique using the belly as support for interactions. The authors argue that the belly's large surface which is easily reachable by two hands in any circumstances (standing, walking, running…) is an appropriate surface for interaction.

On-body interaction techniques are an interesting approach that needs to be further explored for immersive environments. They allow eyes-free interactions by exploiting the proprioception[16] capabilities of users. They do not divert the attention of users from the task at hand. However, without being augmented by a complimentary device, these

[16] https://en.wikipedia.org/wiki/Proprioception

approaches offer a limited set of possible gestures, which impacts the number of tasks that can be performed. Furthermore, on-body interaction do not offer a high degree of precision, which can make them unsuitable for tasks like data visualization in immersive environments.

### 2.4.6 Summary

In this section, we introduced immersive environments as well as the central benefits they offer for data visualization: Their spatial abilities allowing a spatial comprehension of data; their support of physical exploration which leads to a more natural interaction with data; their performant tracking systems.

We identified the challenges of interaction with such environments, often task-related, and reviewed a range of interaction solutions designed to improve interaction in these environments by modality of interaction: Tactile interactions; mid-air interactions; tangible interactions; smartphones and wearables based interactions; on-body interaction.

We highlighted the limitations of these solutions: inadequate degrees of freedom for the multidimensional tasks performed in these environments; hindering the physical exploration they allow; visual occultation; lack of accuracy; fatigue.

The last contribution of this work aims to improve interaction with immersive environments through a new paradigm: on-body tangible interaction.

Tangible interactions offer several degrees of freedom. When used mid-air, the tangible object does not hinder the movement of the user when exploring data. When used on an always—available body support, fatigue is minimized and the accuracy of interaction is improved.

## 2.5 Conclusion

In this chapter, we introduced large displays, multi-display environments and immersive environments. We identified the challenges in designing solutions to improve interaction with these environments and reviewed the state-of-the-art of existing solutions.

In the following chapters, we report on our efforts to improve interaction in each one of the environments discussed above: first, through split-focus, an overview+detail multi-display interaction interface addressing the challenge of interaction with multiple regions of interest of the same overview in large displays (Chapter 3); second, through the exploration of everyday objects to design quick and opportunistic interaction techniques for MDEs in a public context and TDome, a multi-degrees of freedom device to fluidify interaction with MDEs in a work context; finally, through the exploration of a new interaction paradigm, on-body tangible interactions, to improve interaction with immersive visualizations.

# Interaction with Large Displays

Investigating the effects of splitting detailed views in overview+detail interfaces to interact with large data spaces

# 3 Interaction with Large Displays

## 3.1 Introduction

The work presented in this chapter was originally inspired by our collaboration with biologists carrying research on cancer. They archive knowledge in graphs called molecular interaction maps (MIM) [112]. These MIM graphs contain several types of nodes (molecules, protein, etc.) and connections. There is no limit to the number of nodes that can be connected by one connection and each connection can also be connected to other connections, e.g. genes playing the role of catalysts of this connection. As research on cancer progresses, results are added to existing MIM maps, which grow extremely large—the Alzheimer MIM map contains 1347 nodes—[128] making them difficult to read and edit using the traditional panning+zooming [64] interactions (See Figure 3.1). Moreover, connected nodes can be located far apart from each other, thus, requiring even larger surfaces to visualize the data.

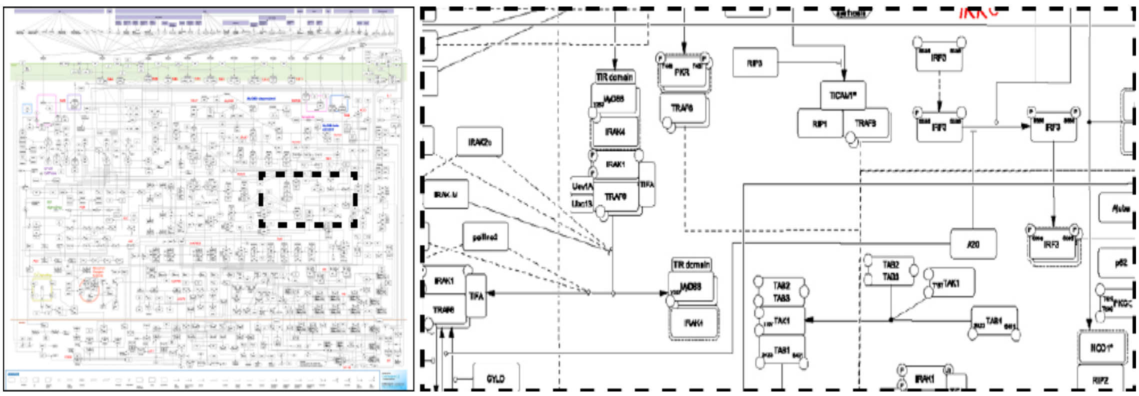


Figure 3.1: MIM map (left) and detail (right) illustrating the density and complexity of such graphs

The context described above is not specific to the biology field as data lies at the heart of many other scientific fields. A great deal of efforts have been devoted to simplify working with these ever-growing data (cf chapter 2). Overview+Detail (O+D) interfaces are one of these efforts and a well-known approach for data visualization and manipulation [61]. They allow the user to have an overview of the data, and a more detailed view that allows him to finely explore the data while keeping the overview.

In this work, we will specifically focus on these visualization interfaces. Despite the advantages the offer when working on large datasets (like graphs), these interfaces reach their limits when it comes to work on multiple regions of the overview simultaneously. An example from the context of this work would be connecting distant nodes of very large graphs for example. Moving the detailed view repeatedly from one region to another is tedious and interaction complexity increases with the number of regions to work on [64, 66].

To address this situation, several techniques have been designed in single or multi-display configurations to support the use of more than one detailed view simultaneously [61, 13, 41, 97].

Multi-display systems have been used in an overview+context configuration [9, 50]. Rashid et al. [149] found that for searching on large maps, a multi-device approach was better than a simple mobile one. Cheng et al. [47] showed that, in a focus+context multi-surface technique, moving the position of the focus in a miniaturized view was preferred over other techniques. In our work we apply this approach to multi-detail interaction.

The use of multiple detailed views has been proposed to allow working simultaneously on multiple regions of large contexts [61, 13, 97]. Polyzoom [97] allows multi-scale and multi-focus exploration in 2D visual spaces by offering the user the possibility to create several hierarchies of zoomed views. Melange [61] uses a distortion-based technique that offers the possibility to bring together two regions of a large space by folding them. SpaceFold [41], inspired by Melange, introduces a multi-touch interaction technique to improve the manipulation of the folds.

Several works have focused on the design of a set of rules for working with multiple views [10]: the "rule of diversity" recommends the use of one view per information type and the "rule of parsimony" suggests using multiple views minimally. However, none of these works has investigated the optimal number of detailed views to use. The optimal number of detailed views that will benefit complex tasks is thus still an open question.

In this chapter, we compare the use of different number of detailed views to interact with very large graphs, such as the aforementioned MIM maps.

Our work aims at answering two questions: 1) are multiple detailed views better than one to interact with large graphs? And 2) what is the optimal number of detailed views needed to perform tasks with multiple graph nodes? Answering these questions is not obvious: using a single detailed view constrains the user to translate the view sequentially to each interesting region of the graph whereas using several detailed views allows parallel access to different locations of the graphs but limit the size of each detailed view to avoid the need for a larger screen real estate to display them.

To answer these questions, we implemented an interface based on the O+D scheme. Our interface supports the simultaneous use of up to 4 detailed views independent from each other. The overview (the overall graph) is displayed on a large screen while the detailed views are displayed on a single tablet: we hereafter refer to them as the split views. Deploying O+D interfaces on multiple displays has been shown to improve data visualization and manipulation [47, 149].

We experimentally compared three values for the number of split views (1, 2 or 4) in a node connection task, where the user is asked to create a link between 2, 3 or 4 nodes. These types of multi-node links are usual in large graphs such as MIMs [112].

## 3.2 Using an overview + multi-detail interface to interact with large surfaces

To contribute to the previously identified challenges of overview + detail and better understand the potential advantages of using multiple detailed views, we first focused on the design of such a solution.

### 3.2.1 Rules for multiple views in information visualization

Baldonado et al. [10] defined several rules for multiple views interfaces. These rules are categorized in two groups:

- Rules to help designers and users assess the suitability of multiple view systems for their applications (R1: Diversity, R2: Complementarity, R3: Decomposition, R4: Parsimony)

- Rules to help designers and users make design choices related to their multiple view system as well as to help usability experts and system evaluators pinpoint trouble spots in an existing system (R5: Space/Time resource optimization, R6: Self-Evidence, R7: Consistency, R8: Attention management)

The ***Diversity rule (R1)*** indicates that a single view containing a multitude of diverse data and requiring the user to simultaneously assimilate may create significant cognitive overhead. The diversity of the data to visualize is one of the principal reasons to consider multiple view systems. The ***Complementarity rule (R2)*** states that another reason to consider multiple view systems is the need to understand the relation (correlations and/or disparities) between two components. The authors argue that multiple views leverage perceptual capabilities to improve understanding of relations among views. The ***Decomposition rule (R3)*** stipulates that partitioning complex data into multiple views create manageable pieces of information and allow a better understanding of the different dimensions composing it. The last rule of the first category, the ***Parsimony rule (R4)***, calls for designers to examine the user's learning costs and the computational and display costs of additional views by applying the 3 rules described above. Indeed, in addition to the cost of context switching, the use of multiple views introduce system complexity. Designers must take the cost of such a system in consideration when deciding if a multiple-view system is adequate for their application.

The second category of Baldonado's [10] guidelines concerns the use of multiple views. The ***Space/Time resource optimization rule (R5)*** indicates that the display space as well as the computational time to present multiple views side-by-side are two important aspects of designing such systems. Thus, they encourage designers to balance the spatial and temporal costs of presenting multiple views with the spatial and temporal benefits of using the views. The ***Self-Evidence rule (R6)*** focuses on the use of adequate feedback. It recommends the use of perceptual cues to make relationships between multiple view more visible to the user. The ***Consistency rule (R7)*** indicates that in addition to feedback, consistency in designing the interface of multiple views helps the user learn to use the system more quickly. Through the last rule, ***Attention management (R8),*** the authors point out that having multiple views requires the system to direct the user's attention to the right view at the right time, this would prevent the user from continuously monitoring the system for events that demand his attention.

Table 3.1 below, presents a summary of these rules as described in [10]:

| ID | Rule Title | Rule description |
|---|---|---|
| R1 | *Diversity* | Use multiple views when there is a diversity of attributes, models, user profiles, levels of abstraction, or genres. |
| R2 | *Complementarity* | Use multiple views when different views bring out correlations and/or disparities. |
| R3 | *Decomposition* | Partition complex data into multiple views to create manageable chunks and to provide insight into the interaction among different dimensions. |
| R4 | *Parsimony* | Use multiple views minimally. |
| R5 | *Space/Time resource optimization* | Balance the spatial and temporal costs of presenting multiple views with the spatial and temporal benefits of using the views. |
| R6 | *Self-Evidence* | Use perceptual cues to make relationships among multiple views more apparent to the user. |
| R7 | *Consistency* | Make the interfaces for multiple views consistent, and make the states of multiple views consistent. |
| R8 | *Attention management* | Use perceptual techniques to focus the user's attention on the right view at the right time. |

Table 3.1: Summary of Baldonado et al.'s [10] guidelines for using multiple views in information visualization

### 3.2.2 Interface Design

Based on these recommendations, we designed and implemented an O+D visualization interface that consists of a large screen to display the contextual information and a tablet to show a magnified version of selected region(s) of the large space in addition to additional information about the selected region. We describe the three main views of our interface (overview, split views and translation view) as well as a set of interaction techniques that allow the user to move the split-views.

#### 3.2.2.1. Split views

Our technique allows the user to have up to four independent split views at the same time (Figure 3.2), offering a detailed view on a graph region. We implemented three configurations for the multiple views on the tablet: 1-view, 2-views and 4-views. Using split views allows to decompose (R3) the complex graph rendering.

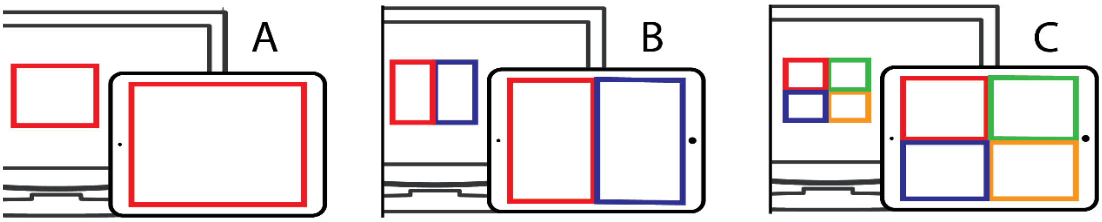



Figure 3.2: The three explored versions of split-focus

With the 1-view technique (Figure 3.2, A), the split view occupies the entire tablet display; with 2-views (Figure 3.2, B), each view occupies half; and with 4-views a quarter (Figure 3.2, C). This design conforms to the rule of consistency (R7) as the overall detailed area size is consistent over the 3 versions of our technique and when several focus are displayed their relative size is consistent as well. It also presents different conditions of space/time resource allocation (R5): sequential for 1-view, and side-by-side for 2-views and 4-views.

A swipe gesture inside one of the split views moves the underlying graph in the same direction: this behavior is consistent (R7) with regular map interactions on mobile devices. Finally, when the user selects a node in one of the split views, appropriate feedback is provided so that users' attention (R8) is focused on the appropriate view.

#### 3.2.2.2. Overview

The overview displays the entire graph on a large display. The ratio between the overview size and the split views size is 9 for the 1-view configuration (overview is 9 times bigger), 18 for 2-views and 36 for 4-views. These ratios were chosen to explore the effect of a zoom factor bigger than 30 (threshold identified in [165]). A contour color is applied to the split views on the tablet and to its representation on the overview to help the user establish the relationship between the points of view (R6) (Figure 3.3).

#### 3.2.2.3. Translation view

We call a translation technique the interaction allowing the user to explore his data by moving the detailed views to the region of interest. In our interface, positioning the split views can be achieved using two translation techniques: 1) a regular pan on the split-views; 2) A translation interface called translation view. The translation view is activated when the user presses the black button "switch" displayed on the tablet (Figure 3.3).

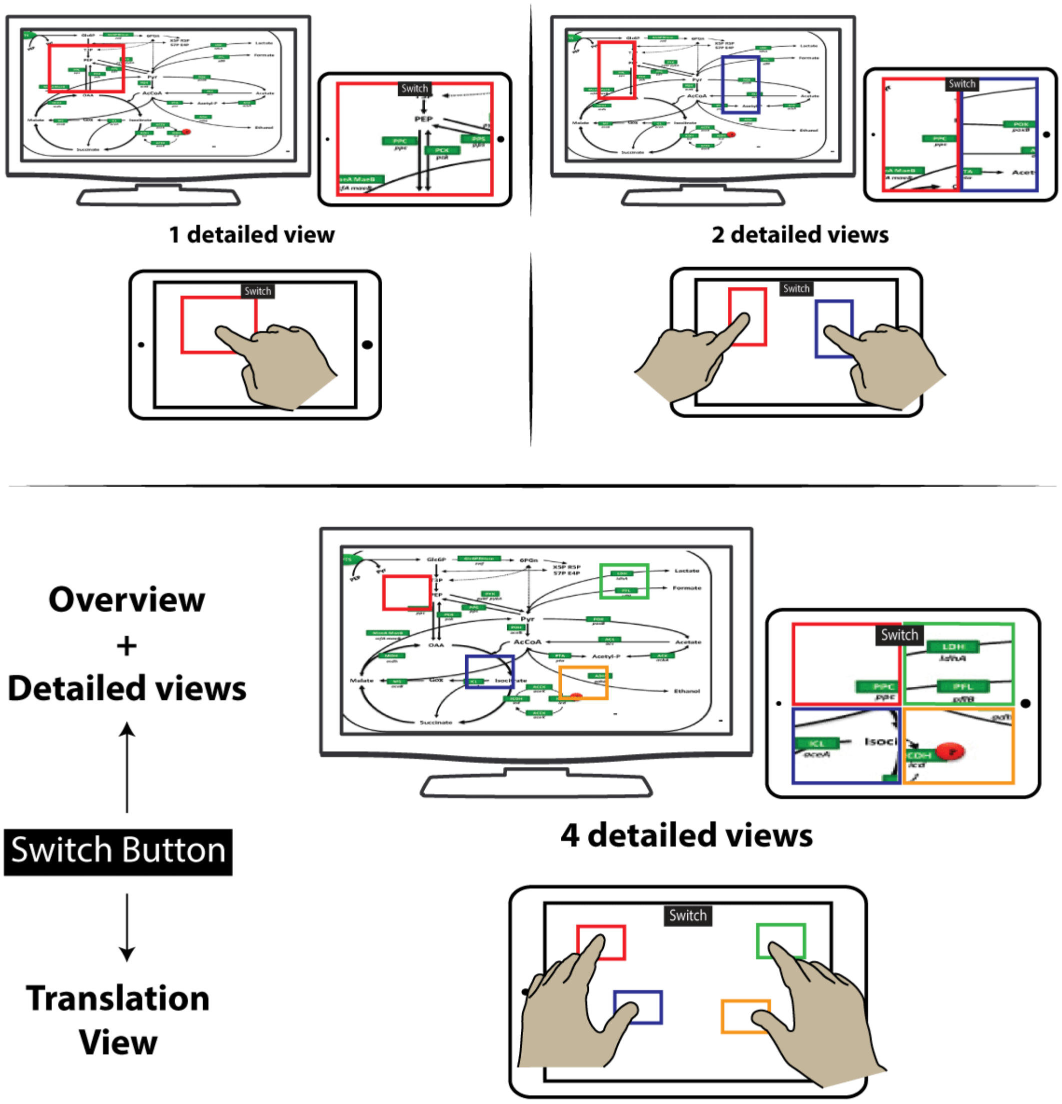


Figure 3.3: Split-Focus

The translation view provides a representation of the position of the 1, 2 or 4 split views on the overview. In the translation view, each split view position is represented using a view icon. Given the density of the graphs, displaying a miniature of it on the tablet would be useless. Therefore, the view icons are displayed on a void background. By looking at the overview, the user can use *multiple* (R1) view icons in *complementarity* (R2) for selecting multiple nodes. The user can adjust the position of one or several view icons simultaneously by direct touch manipulation as recommended in [47]. Using two hands and the multi-touch screen, the user can theoretically translate 4 view icons at the same time. Closing the translation view restores the split views. In our configuration, no zoom is allowed: this ensures a higher consistency over the split views (R7).

## 3.3 User Study

Using our multi-view interface, we conducted a controlled experiment to evaluate the effect of using multiple split views (1, 2 or 4) when connecting various number of nodes (2, 3 or 4) situated on different areas of large graphs.

### 3.3.1 Task

Participants were asked to create a connection between 2, 3 or 4 nodes. The overview displayed only the nodes to connect on a white background. To connect several nodes, participants had to select them by touching each node in the split views displayed on the tablet. Selecting one node required translating one of the split views displayed on the tablet so that the node becomes visible. On each trial, participants could translate each of the split views with swipe gestures directly in the split view or through the

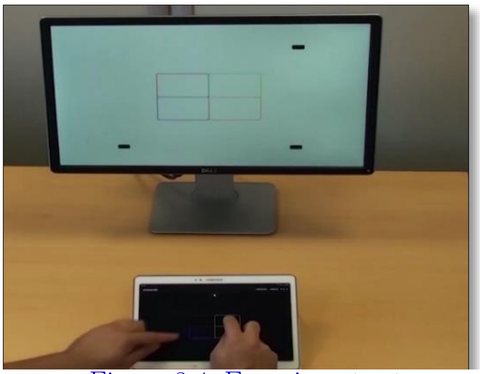


Figure 3.4: Experiment setup

manipulation of its corresponding view icon in the translation view. Selection was validated with a single tap on the node, which was then highlighted in blue. Before each task, the position of the split-views were reset to a default position.

### 3.3.2 Node positions

To define the position of the 2, 3 and 4 nodes to connect, we decided to fix their distance from the center of the overview and change their relative distance as well as their distribution. We used eight absolute positions corresponding to the intersection of an ellipse positioned at the center of the overview with horizontal, vertical and diagonal axes (Figure 3.5). The ellipse shape is used so that the positions of the nodes are spread across the width and height of the tablet. We selected 10 combinations of these positions for each number of nodes, equilibrating the number of neighbor nodes (i.e. on consecutive positions) and the cases where all nodes were far from each other with the cases where nodes were close to each other.

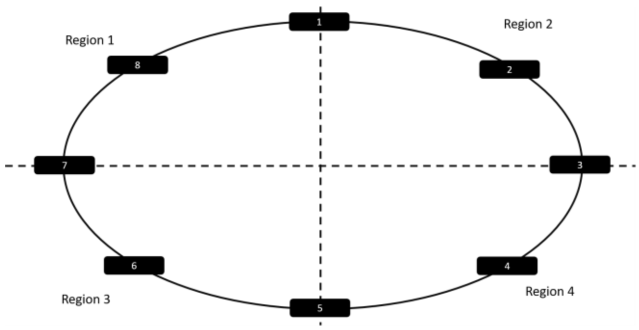



Figure 3.5: Nodes repartition

### 3.3.3 Participants

We recruited 12 participants (4 females) from our local university. They were 26 years old on average (SD 4.7) and 11 of them were right-handed. All participants had used touchscreen tablets before. No specific skill was required.

### 3.3.4 Apparatus

The experimental apparatus consisted of a multi-device setting involving one PC and one tablet. The PC had a 23 inches display, showing the overview (1920x1080px). Nodes on the overview measured 15x37px. The tablet was a 10.5 inches Samsung galaxy tab S[17] (2560x1600px). Nodes on the split views (i.e. the targets to touch) on the tablet measured 40x157px. On the translation view, each view icon measured 826x526px for 1-view configuration, 413x526px for 2-view configuration and 413x263px for 4-view configuration. A Dlink DIR-615[18] router was used to establish a wireless connection between the workstation and the tablet. We placed the tablet on a desk and allowed users to interact with both hands, a usual configuration in multi-display settings to avoid fatigue during long interactions and to benefit from multi-touch input [154]. The tablet rested on its cover at a 60° angle and in the same field of view than the large display, which has been shown to be paramount in multi-display environments [42]. Participants sat at 1m from the display and we ensured that there were no light reflections on the tablet.

### 3.3.5 Experimental Design

The experiment followed a 3x3 within-subject design with number of split views (NViews factor: 1V, 2V or 4V) and number of nodes to connect (NNodes factor: 2N, 3N or 4N) as factors. The NViews factor was counterbalanced by means of a 3x3 Latin square: three blocks were run, one for each value of the NViews factor. Trials in a block were grouped by the NNodes factor. Each subject performed 3 NViews x 3 NNodes x 10 predefined Node Positions x 3 repetitions = 270 trials. The training consisted of one block for each value of the NViews factor (36 trials in total). The experiment lasted 60 minutes on average.

### 3.3.6 Procedure and instructions

To begin a trial, the participant pressed a “start” button displayed in the center of the tablet. Between each block, the user was informed via an information screen that he was about to start another condition. Participants were asked to finish each trial as quickly as possible using any number of hands or fingers. They were told they could take

[17] https://www.samsung.com/fr/tablets/galaxy-tab-s/

[18] https://eu.dlink.com/fr/fr/products/dir-615-wireless-n-300-router

a break if required between trials. At the end of the experiment, participants were asked to fill a System Usability Scale questionnaire (SUS).

### 3.3.7 Collected Data

We logged all touch events from the screen tablet. We measured trial completion time from stimulus onset to screen release, the number of actions to complete each trial and the number of switches between overview and split views on the tablet. We also logged the number of view icons translated simultaneously, i.e. the number of fingers performing a view icon translation at the same time.

## 3.4 Results

We used a Shapiro-Wilk test to determine the normality of collected data. Our data could not be normalized, so we used a non-parametric Friedman test to compare more than 2 conditions and Wilcoxon tests otherwise. When needed we used the Bonferroni correction.

### 3.4.1 Completion time

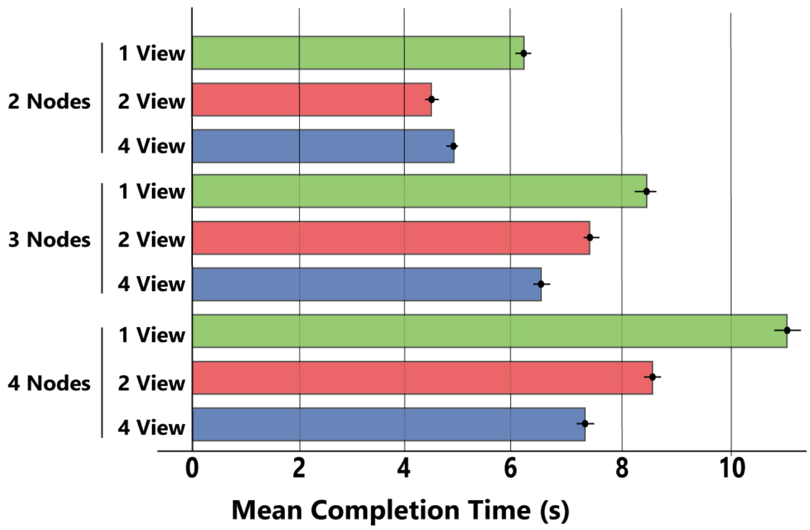



Figure 3.6: Trial completion time per number of nodes and number of views (95% IC).

Friedman tests reveal a significant effect of the NViews on completion time for each number of nodes (2N: $\chi2(2) = 34.58$, 3N: $\chi2(2) = 6.61$, 4N: $\chi2(2) = 20.30$ with $p < .01$). A Wilcoxon test confirms a significant difference between 1V and 2V ($Z = -2.98$, $p < .01$), and between 1V and 4V (Z=-3.05, p <.01). Overall, when performing the task using 2V and 4V, participants took respectively 20% and 35% less time than with 1V (Figure 3.6). There is no significant difference between using 2V and 4V when connecting 2 nodes, but using 4V, participants required 15% less time than with 2V when connecting more than two nodes (3 nodes: Z= -3.06, p <.01, 4 nodes: Z=-3.06, p <.01).

### 3.4.2 Switches between Translation and Detailed view

A Friedman test reveals a significant effect of the NViews on the number of switches between the Translation view and the Detailed view ($\chi^2(2) = 18$, p <.01). A Wilcoxon test reveals a significant difference between 1V and 2V (Z=-2.98, p <.01), between 1V and 4V (Z=-3.06, p <.01) and between 2V and 4V (Z=-3.06, p <.01). The number of switches decreases with the NViews: 2.2 on average for 1V, 1.6 for 2V and 1.0 for 4V (see Figure 3.7).

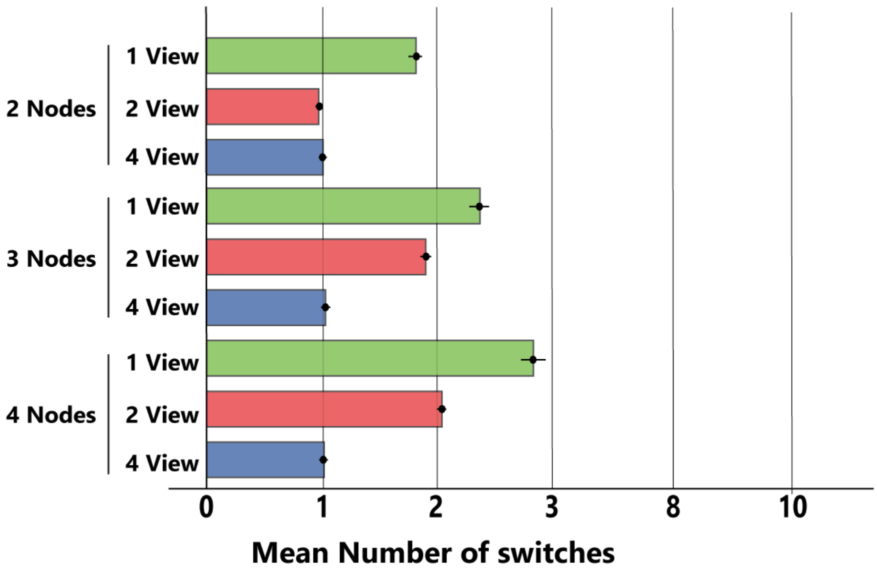



Figure 3.7: Number of switches between the translation and detailed views (95% IC)

### 3.4.3 Simultaneous icons translation

A Friedman test reveals a significant effect of the NViews on the number of view icons translated simultaneously (i.e. the number of fingers moving an icon at the same time in the translation view) ($\chi 2(2) = 22$, p <.01). A Wilcoxon test reveals a difference between

1V and 2V (Z= -2.93, p <.01), and between 1V and 4V (Z=-3.06, p <.01). For 1V, the number of icons used at the same time is slightly under 1 (0.99) because the user could pan inside the split view without switching to the Translation view. In that case no icon translation was recorded.

Interestingly, we found no difference between the number of view icons translated simultaneously in 2V and 4V, even though users could employ their two hands to translate the view icons. In these conditions, whatever the number of nodes to connect, the average number of view icons translated was very similar (2V: 1.82; 4V: 1.83), even when more than 2 nodes had to be connected (see Figure 3.8).

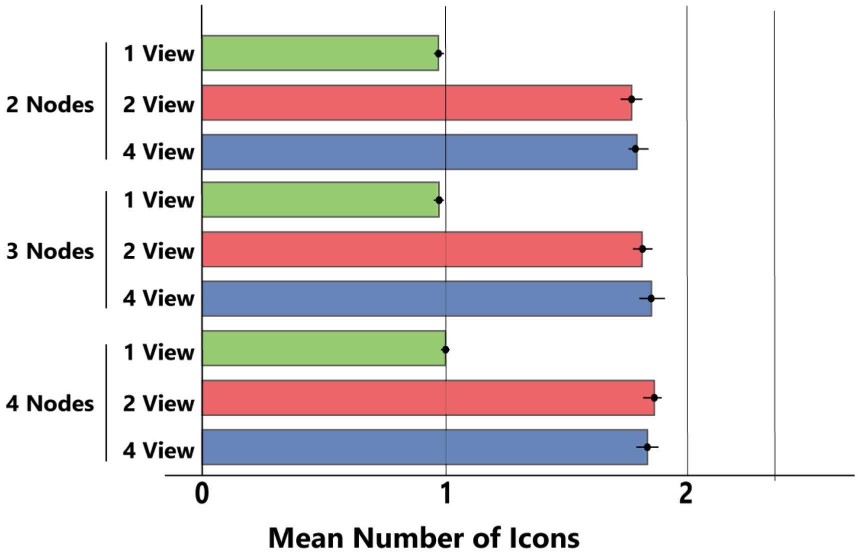



Figure 3.8: Nb. of icons moved at the same time (95% IC)

We could expect users to move 3 or even 4 icons simultaneously by using a bimanual multi-touch gesture under the 4V condition. This actually happened, but in low proportion: over the 1080 trials done with 4V, 20% were performed moving only one view icon at the same time, 77% moving two icons at the same time, 2% (22 trials) moving three and 0.5% (6 trials) moving four icons (the rest 0.5% of trials did not involve moving any icon). The same user did 15 of these 22 trials (75%) performed with 3 fingers. Five participants did the other 7 trials: they tried the gesture once or twice but did not use it any longer. The analysis of the 6 trials done with four fingers raises similar results: one subject did it 2 times, and four users tried it once. Instead, moving simultaneously two icons seemed affordable for most participants. We observed that most of these bi-touch gestures were done with one finger of each hand in a bimanual coordinated gesture.

### 3.4.4 SUS Scores and User preference

SUS scores reveal that the 1V and 4V conditions were deemed good (75 and 80 respectively) while the 2V was deemed excellent (86). Interestingly, when asked, users preferred the 4V condition for the tasks where they had to work on more than two nodes while opinions were mixed for the task with two nodes only: some participants liked having four views at hand, others disliked having smaller views than under the 2V condition.

## 3.5 Discussion and Perspectives

### 3.5.1 Possible ameliorations of the split-view interface

Below, we discuss two possible improvement of the split-view interface. The first concerns the translations techniques and the second the coherence of the split-views.

#### 3.5.1.1. Translation technique

A possible improvement for the translation technique resides in the speed of translations. When interacting with a large information space, it is important that the position of the detailed view can be adjusted quickly and precisely. The translation view is quick and it can be precise if the information space is not too large. However, with a large information space combined to the small display on tablets, moving detailed view with precision becomes difficult. One possible solution to that would be to use the regular pan, directly on the detailed view while allowing the user to control the speed of translations. We can exploit the number of fingers used to perform the translation to achieve that. The result of a one finger translation would be a regular translation, the result of a two finger translation would be a translation twice the speed of the regular one, and so on.

### 3.5.1.2. Coherence of the split views configuration

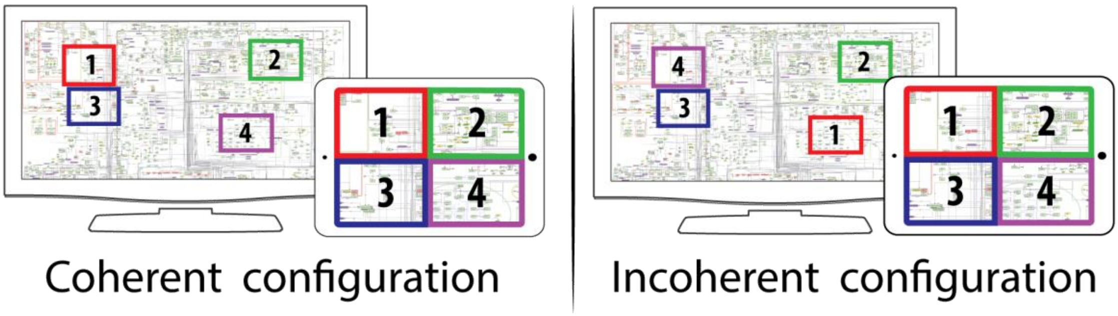



Figure 3.9: Examples of coherent (left) and incoherent (right) configurations of the split views.

One of the problems resulting from a multi-view approach is the coherence of the detailed-views positions. As the user are able to translate the views freely on the overview, a situation where the disposition of the detailed-views on the tablet may not be coherent with their icons on the overview can arise as in (Figure 3.9-right).

We developed an improved version of the split-views interface that would prevent an incoherent configuration from happening, the new version uses what we call locks. The overview is divided into 4 subregions of equal size, the principle is to lock each split view in a sub-region of the overview so that the spatial configuration of the split views on the tablet is always coherent with the icons on the overview (Figure 3.10, A). The top-left detailed view, represents, and can move only in the top-left sub-region of the overview. The same principle is applied to the three other detailed views.

The user has the possibility to release the locks between 2 subregions allowing the split views to be translated in the newly created subregion (opening the lock between the green and magenta detailed views in (Figure 3.10, B). Openning the 4 locks would make all the overview available to all the split views.

This approach is similarly applicable to the 2-views version of the split-view interface.

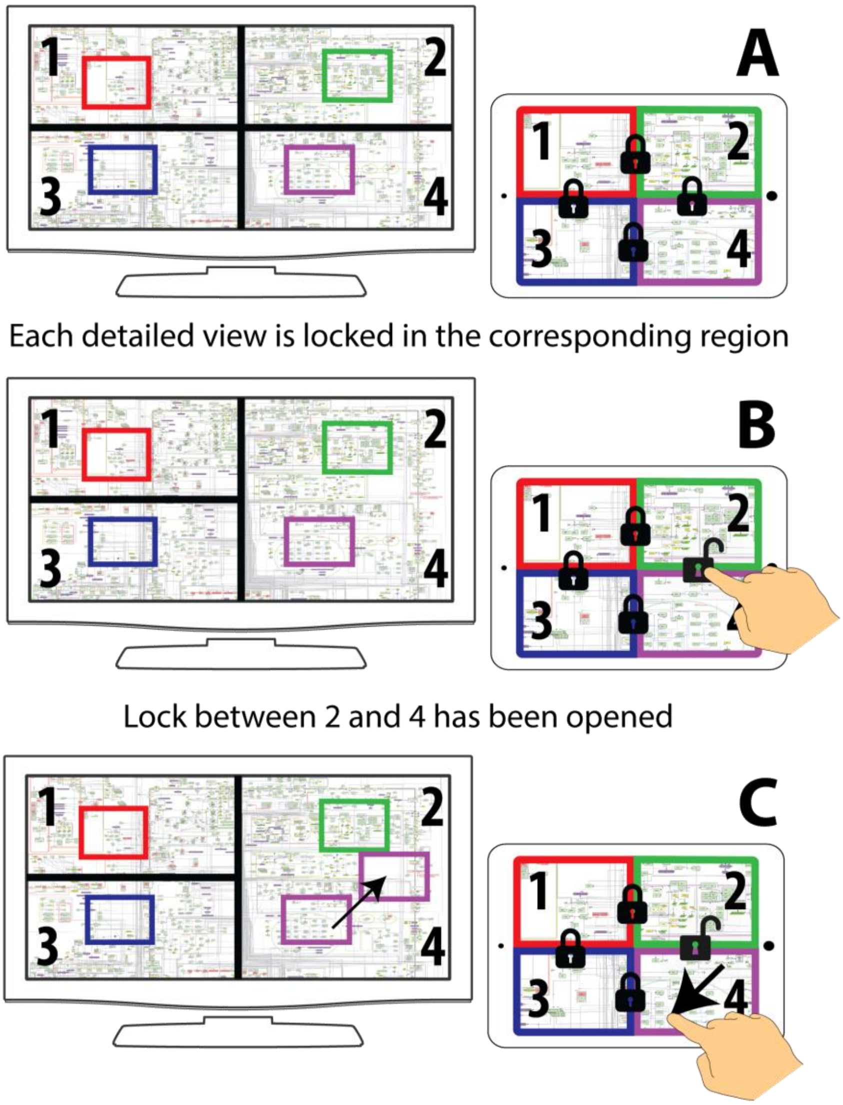



Figure 3.10: A possible solution to the coherence problem

### 3.5.2 Perspectives

While previous work on symmetric bimanual interaction (where each hand is assigned an identical role) has already highlighted its benefit in some settings [9, 127], we are only aware of one work [68] exploring symmetric bimanual *multitouch* interaction (each finger performs a pointing gesture on a different target). In this previous work, up to 47% of the trials for some tasks were performed using multiple fingers in a bimanual setting. In contrast, our results indicate that symmetric bimanual multi-touch input is hard to perform. We believe these results are highly dependent on the task. Therefore, there is a need to further explore the factors influencing symmetric bimanual multi-touch interaction.

Given our findings, a perspective to our work could concern three design questions. First, It would be interesting to explore the limits of the number of views. In this work, to respect the guidelines regarding the zoom ratio between a detailed view and an overview, we limited the number of detailed views to 4. Generalizing the results to configurations of more than 4 detailed views is not feasible without altering the design of the interface, whether it relates to the size of the screen displaying the detailed views or a mechanism to display 4 detailed views at a time and switch between them. In both cases, it is necessary to conduct a further experiment to evaluate the new design . Second, it would be interesting to explore how to improve bimanual multitouch interactions to facilitate the translation of several split views at the same time. One idea could be to study combinations of fingers that can be moved synchronously and to help the user in employing these fingers. Third, as most participants used only one finger of each hand, it would be interesting to consider other potential uses of the remaining fingers: for example additional fingers might act as modifiers to bring split views together, or to move views to specific positions such as corners, or to dynamically release locks.

# 3.6 Conclusion

In this work, we studied the effects of splitting the detailed view in an overview+detail interface to work on large graphs. We implemented an O+D multi-displays interface where the overview is displayed on a large screen while 1, 2 or 4 split views are displayed on a tactile tablet. We experimentally evaluated the effect of the number of split views according to the number of nodes to connect. We evaluated three multi-view configurations: one detailed view (1V), two split views (2V) and four split views (4V). Overall, results show that using two or more split views is significantly faster than using only one detailed view. Results reveal that using 4 split views is only better than 2 split views for working on more than 2 regions of the graph.

An interesting finding of our experiment is that, when using 4 split views, users did not take full benefit of bimanual multitouch interaction to translate several view icons at the same time. Most of them (77%) used a sequential approach, first using one finger of each hand to move two icons, and then moving the two remaining view icons.

# Interaction with Multi-Display Environments

PART A

## Interaction with MDEs in a public context

Everyday objects to interact with public multi-display environments

PART B

## Interaction with MDEs in a professional environment

Design, usage and evaluation of TDome, a touch-enabled 6DOF interactive device for multi-display environments

# 4 Interaction with Multi-Display Environments

## 4.1 Introduction

Multi-display environments (MDEs) are more and more prevalent in our daily life. Nowadays, interaction with MDEs is not limited to work environments only: they are used at home, with TVs, monitors, laptops, tablets and smartphones; in public places, where many displays have been installed in recent times, either to display commercials (outdoor advertising), give us directions (malls) or information about the delayed departure time of a train or plane (Airports, Train stations, …). Today, whether in a professional context or in our personal lives, we are overequipped with devices containing displays. The environments created by their combination is what we call multi-display environments. They combine multiple displays to offer the user another way of visualizing and interacting with information.

This type of environments have shown significant value for interacting with heterogeneous data sources and in multiple contexts such as 3D exploration [24], collaborative scenarios [36], crisis management [44] and scientific data visualization [168]. They offer numerous advantages for organizing information across displays, for enhancing individual and group work, for providing support to peripheral information and for extending the interaction space.

Interaction with each one of these individual displays has been substantially explored: tactile interactions for smartphones, mouse and keyboard for a PC, touchpads for laptops to cite the most common interaction techniques. But these interaction techniques are not as efficient when used in a multi-display context in which the various displays do not necessarily share the same characteristics (display size, form, orientation) and input capabilities: for instance, tactile interactions are not appropriate for distant displays, and the mouse is not efficient for covering large display areas. For these reasons, designing interaction techniques for MDEs is a complex task.

In addition, the context in which the MDE is deployed is also of importance for the design process. MDEs deployed in a public context require interaction techniques that respect the personal space of the user, are easy to learn and well integrated in the environment. In a work environment, the user needs an efficient interaction technique, allowing him to switch between displays and redirect content without interrupting his task flow.

In section 4.2, we present an approach based on the use of everyday objects as an interaction medium in MDEs in a public context. We detail the results of a creativity study conducted to generate ideas on how to use physical objects to interact with public MDEs and/or the content displayed on them. In section 4.3, we propose a novel device, TDome, partially based on the results of the creativity study (section 4.2), for interaction with MDEs in work contexts. We present the characteristics of the device and its suitability to MDEs. Then, we focus on the usability and comfort of the device through a set of studies. Finally, we explore the mappings between the feasible gestures with the device and the main MDEs tasks.

## 4.2 Interaction with MDEs in a public context

MDEs in public environments (such as train stations or airports) offer little or no means of interaction with the displayed information [104, 137]. One reason is the absence of adequate interaction techniques. We argue that this is in part due to the difficulty of designing such interaction techniques. A difficulty that stems from the necessity of fulfilling several interaction requirements specific to the these environments.

Substantial amount of research focused on the use of smartphones and smartwatches as interaction tools [24, 35, 133, 164]. This approach fail to respect the personal space of the user through the installation of third-party applications, necessary for the interaction with the MDE, on his personal device. Other approaches use tactile gestures [188, 139]: while this is one of the most widespread and accessible interaction techniques for public MDEs, it limits the interaction space to the accessible parts of the displays. Other researches proposed the use of gestural interaction techniques [189]. However, this approach is ambiguous and does not offer enough visibility of the possible gestures without a learning phase, one that the passing-by users of these MDEs do not necessarily have. Tangible interactions are a good alternative to the aforementioned approaches.

They rely on natural gestures. These gestures are often suggested by the physical characteristics of the objects used [171]. However, this approach is dependent on the availability of objects around the MDE. We propose to overcome this limitation through the use of everyday objects, which can be found on or around the user. This approach offer a quick, natural and opportunistic way of interacting with public MDEs. In this section, we explore the use of everyday objects to perform common tasks in a public MDEs. We present a study that was conducted in the form of a creative session and which aim was to identify the way to use objects of different shapes and materials to perform common tasks in MDEs. We amend an existing taxonomy to classify the proposed interaction techniques. Finally, we discuss the results and the main lessons learned from this creativity session.

## 4.2.1 The Creativity Session

We conducted a creativity session focusing on the use of everyday objects to interact with public MDEs. During this session, we asked participants to come up with ideas on how to use predefined objects to interact with public MDEs and/or the content displayed on them. In this section, we present the list of objects used, the proposed tasks and a detailed description of the creativity session.

### 4.2.1.1. Objects used during the session

We based our objects list on the work done previously by Pohl et al. [143], in which the authors identify the most common objects around us through a participative production service. In their work, they extracted the most common objects around the users' smartphones and classified them according to their forms in 5 categories: spherical, semi-spherical, cylindrical, rectangular and complex. We have adopted this categorization with some modifications (tFigure 4.1): we combined the spherical and semi-spherical categories due to their similar physical characteristics; we redefined the complex category as a composite category so it includes not only the object which form is not *Spherical*, *Cylindrical* or *Rectangular* but also objects made up of at least two objects belonging to the other 3 categories. As we suspected that the material of the object may play a role in how the object is used, we proposed for each category two objects made of different materials: *Soft*, *Rigid*.


tFigure 4.1: Objects used in the creativity session

#### 4.2.1.2. We did not limit our list of items to those that are more likely to be available in our daily lives in a public context. Instead, we preferred to chose objects that are representative of the different categories of objects present in our daily lives.Apparatus

The multi-display environment used for this creativity session consisted of an interactive table, two video projectors and a monitor (Figure 4.2). The interactive table was put in the center of the system with two video projectors at its sides. The monitor was placed between the two projections (Figure 4.2). The interactive table, made by the company Immersion was 42 inches wide and had a resolution of 1920x1080. The two projectors had resolutions of 1920x1080 (Sony) and 1600x1050 (Sanyo). The monitor had a diagonal of 26 inches and a resolution of 1920x1080.

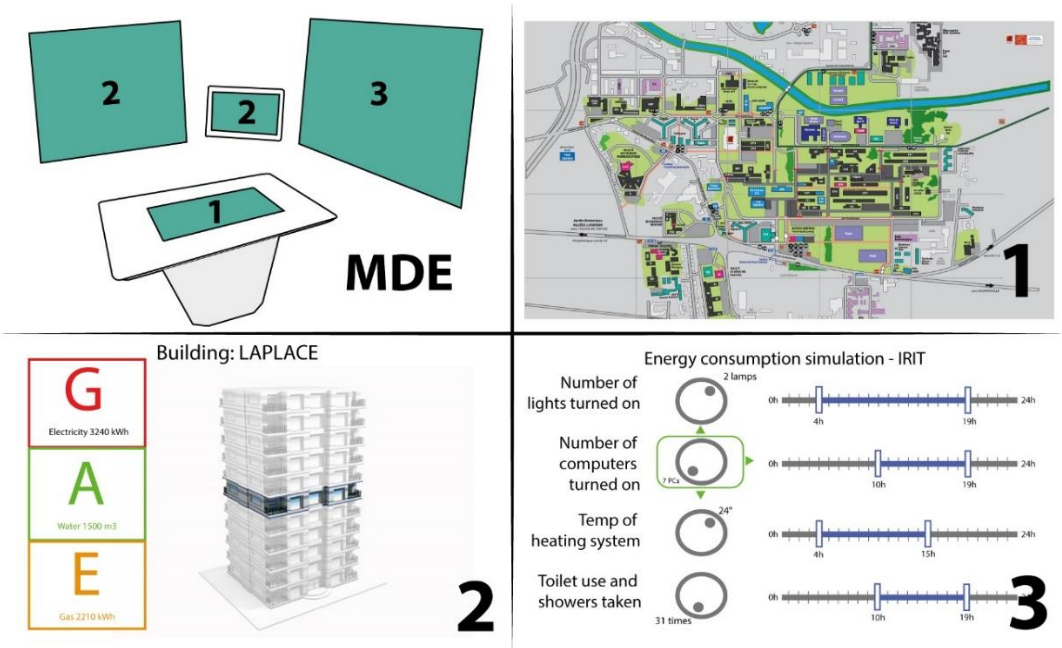



Figure 4.2: The MDE setup used in the creativity session and the content displayed on each screen

#### 4.2.1.3. Context of the creativity session

The work described in this chapter was carried out in the context of the neOCampus project (described in Chapter 6), the scenario chosen for the creativity session was in line with one of the main objectives of the project: reducing energy consumption and costs in the local university campus. The multi-display environment fits the apparatus described in 4.2.1.2.

In this setup;

- The interactive tabletop displayed a map of the campus (Figure 4.2, Thumbnail 1). The user could interact with the map using pans and zooms to choose the building (s) he wanted to simulate the energy consumption for.

- The chosen building was then displayed on one of the "floor" displays (numbered 2 in Figure 2, Thumbnail MDE). These two displays allowed the user to choose a floor of the building and visualize its energy consumption (Figure 4.2, Thumbnail 2).

- The control display (numbered 3 in Figure 4.2, Thumbnail MDE) contained a set of tools to manage the simulation (Figure 4.2, Thumbnail 3). The controls were arranged horizontally and vertically one after the other. To simulate the energy consumption of a building, the user had to select the display in which the building was shown and manipulate the controls.

#### 4.2.1.4. Participants

8 volunteers (3 female) aged 27 on average (SD = 8.58) from our laboratory participated to the creativity session. The group of participants was composed of 3 doctoral students, 4 master students and an assistant engineer. Participants had varying experience with tangible interactions, 2 of the participants had expertise in tangible interactions. 4 were involved in the neOCampus project.

#### 4.2.1.5. MDE Tasks

The set of tasks described in this paragraph represents the most common tasks done in MDEs. In the context of our study, they translate as follows:

| | Task | N° | Task in the scenario of the creativity session |
|---|---|---|---|
| Interaction with data | Pan | 1 | Pan on the map to select a building (performed on display 1,Figure 4.2) |
| | | 2 | Choosing a control to manipulate (performed on display 3,Figure 4.2) |
| | Zoom | 3 | Zooming on the map to select a building (performed on display 1,Figure 4.2) |
| Interaction with the MDE | Content transfer between displays | 4 | Sending the "building selected" information from display (display 1, Figure 4.2) to one of the floor displays (display 2,Figure 4.2). |
| | Display selection | 5 | Selecting one of the floor displays (display 2,Figure 4.2) |
| | | 6 | Selecting multiple floor displays (display 2,Figure 4.2) |

| | | | |
|---|---|---|---|
| **Interaction with the UI** | **Validation** | **7** | Validating the changes made on the controls display (Selecting one of the floor displays (display 3,Figure 4.2) |

Table 4.1: Most common tasks in MDEs adapted to our creativity session's scenarios.

#### 4.2.1.6. Procedure

The objective of the creativity session was to find interaction techniques for the 7 predefined tasks described in (4.2.1.5) and for each object of the list described in (4.2.1.1) (tFigure 4.1). To limit the session to a reasonable duration and avoid fatigue, we separated the 8 participants into 4 groups of 2. For each task, each group was responsible for a category of objects (including a soft and a rigid version) and had to propose interaction techniques for the objects belonging to it. The objects were randomly redistributed to the 4 groups at the beginning of each task. We made sure that each group, at the end of the study, had used each category of objects at least once. The creativity session was conducted as follows:

- 2 minutes of introduction: each task began with a 2 minutes introduction where the task to perform was detailed to the participants and the objects were distributed to each group. An example of interaction with each object for the current task was given during the distribution process to stimulate the participants' creativity.
- 5 minutes of thinking and discussion: each group had to think of ways to use the provided objects to perform the task at hand. The interaction techniques proposed had to be noted on post-it notes and classified from the most promising to the least promising.
- 2 minutes of presentation: each group had to present their ideas, from the most promising to the least promising. At the end of the restitution of each task, all the participants had to vote to choose their preferred idea and object for the task at hand.

#### 4.2.1.7. Collected data

During the restitution part of the session, we noted the ideas proposed by the participants. At the end of each task, participants were asked to provide the Post-it notes on which they wrote their ideas. In addition to the written notes, we also filmed and recorded the creativity session so that we could go back to the videos to annotate the exact gestures made by the participants.

### 4.2.2 Classification of the ideas -Taxonomy-

Participants produced a large variety of gestures with the objects at their disposal during the creativity session. We analyzed and classified these gestures using a taxonomy we inferred from the results of the session. The taxonomy is composed of 3 dimensions that we considered relevant to our study and that we describe below: Nature of the gesture, Gesture basis, Human effectors. We manually processed and analyzed the proposed ideas according to this taxonomy. The three dimensions are detailed below.

#### 4.2.2.1. Nature of the gesture

The *nature of the gesture* dimension contains 3 values: gestures made *With the object*, *On the object* or *Around the object*. The idea behind this dimension is to determine if the interaction technique proposed is a tangible interaction (*With the object*), a tactile interaction (*On the object*) or mid-air interaction relative to the object (*Around the object).* The user had necessarily the object in his hand for the *With the object* gestures but not systematically with *On* and *Around the object* gestures.

#### 4.2.2.2. Gesture basis

The *gesture basis* dimension is composed of 5 values: *Form, Material, Analogy, Function* and *Other*. It explicits the origin of the gesture.

- A gesture is based on the *Form* of an object if it uses the physical shape of the object. An example would be to roll a ball: the gesture "roll a ball" is based on the round shape of the ball.
- A gesture is based on the *Material* of the object if it uses the physical characteristics of the object's material. For example, the gesture "fold a sheet of

paper" is based on the foldable property of the material. If the sheet of paper was rigid, performing the gesture would be impossible.

- A gesture is performed by *Analogy* when there is a functional coherence with a common gesture performed on another device: the badge and the smartphone having approximately the same shape, making tactile gestures on a badge, for example, is an analogy to making tactile gestures on a smartphone.
- The Function criteria represents the reuse of classical gestures made with the object for other purposes. An example would be to write with the pen the number of the screen to select.
- Each gesture that can not be classified in one of the previous categories is labeled as an *Other* gesture.

#### 4.2.2.3. Human effectors

We hypothesized that gestures requiring the use of one hand would be easier to perform especially in a context where the users of the multi-display environment are going to be passers-by whose hands are not necessarily free. Therefore, it was necessary to be able to classify the interaction techniques according to two additional criterias: Uni-manual or Bi-manual. For Bi-Manuel interactions, we distinguished between two-handed interaction techniques in which the hands are used one after the other (sequentially) and where they are used at the same time (parallel).

#### 4.2.2.4. Summary

The table below summarizes the three dimensions.

| | | |
|---|---|---|
| Nature of the gesture | *With the object* | Physical manipulation performed with the object in hand |
| | *On the object* | Gesture performed on the object without systematically having it in hand |
| | *Around the object* | Gesture performed around the object without systematically having it in hand |
| Gesture basis | *Form* | Gesture based on the form of the object |
| | *Material* | Gesture based on the material of the object |
| | *Analogy* | Gesture based on an analogy to the use of another object |
| | *Function* | Gesture based on the primary function of the object |
| | *Other* | Any gesture that can not be classified in the above categories |
| Human effectors | *Uni-Manual* | Gesture performed with one hand |
| | *Bi-Manual* | Gesture requiring the use of two hands (sequentially or In parallel) |

Table 4.2: Taxonomy

### 4.2.3 Results

During a creativity session that lasted 2 hours 40 minutes, the participants produced 194 ideas for the 7 tasks with the 8 objects at their disposal. The number of ideas provided per category was balanced (Spherical-Semi-spherical: 27.32%, Rectangular: 24.74%, Cylindrical: 25.77%, Composite: 22.16%) as well as the number of ideas per object which ranged from 10.31% for the Post-it note object to 13.92% for the anti-stress ball. However, the ideas proposed per tasks varied from 10.82% for the task of selecting multiple screens to 18.04% for the validation task. Below, these results are presented with more details according to the following axis:

- The objects (4x2) described in 4.2.1.1

- The tasks (7) described in 4.2.1.5
- The dimensions of the taxonomy (3) described in 4.2.2
- The produced gestures
- Users preference

#### 4.2.3.1. The nature of the gesture

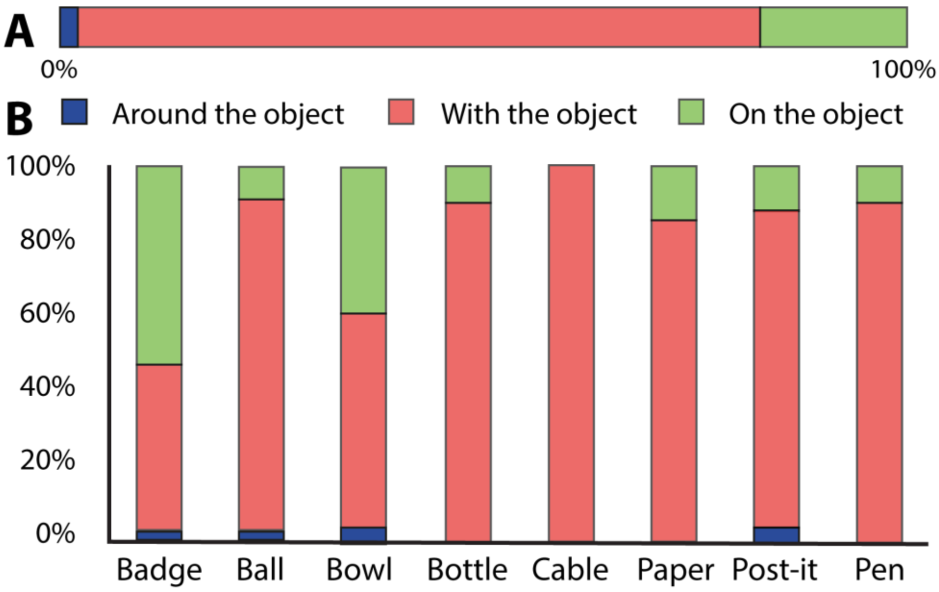



Figure 4.3: The nature of the proposed gestures (Overall A, Per object B)

The majority of the proposed interaction techniques are performed *With the object* (80.4%) followed by interaction techniques *On the object* (17.5%). Interaction techniques *Around the object* have been performed only 2.1% of the time (Figure 4.3.A). Interaction techniques *On the object* were mainly proposed for the badge object (52.0% of the gestures) and the plastic bottle (38.5% of the gestures). This distribution remains the same regardless of the task for which the ideas had to be generated (Figure 4.3.B).

#### 4.2.3.2. Gesture basis

When looking at the results regarding the gesture basis (Figure 4.4), the participants were mostly inspired by the form of the object (39.2%) and the materials (28.4%). A large part of the interaction techniques proposed for rigid objects is based on form (54.1%). This is especially true for gestures made *with the objects*: Bowl (53.9%), Bottle (70.9%)

and Pen (65.2%). Unsurprisingly, the interaction techniques proposed for soft objects use its material as a main base for the interaction (56.3%): Cable (84.6%), Post-it notes (55.0%) and Paper (52.2%). There are two exceptions to the trend described previously: 1) The majority of the ideas proposed for the stress ball—soft spherical object—are based on its shape (48.2%); 2) the majority of the ideas proposed for the badge—rigid rectangular object—are based on analogies (use of a smartphone, a remote control, ...).

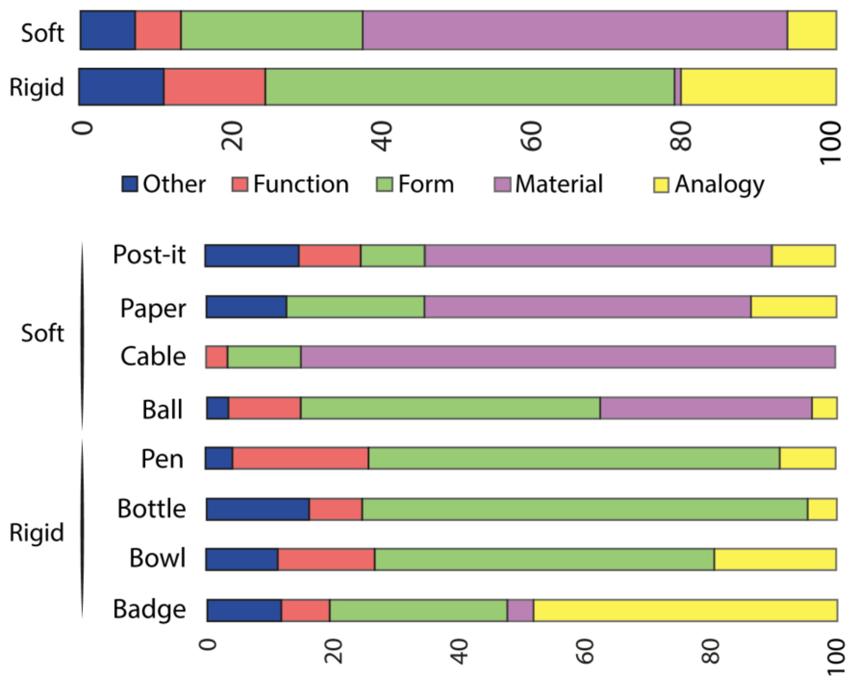



Figure 4.4: Gesture basis (Type of object, Object)

#### 4.2.3.3. Human effectors

The vast majority of the proposed interactions techniques required one hand to be performed (Uni-Manual) regardless of the task and the type of material of the object (Figure 4.5): Badge (88%), Stress Ball (85%), Bowl (96%), Bottle (92%), Paper (65%), Post-it (75%), Pen (96%). However, for the cable object, most of the gestures proposed were Bi-Manual (77%).

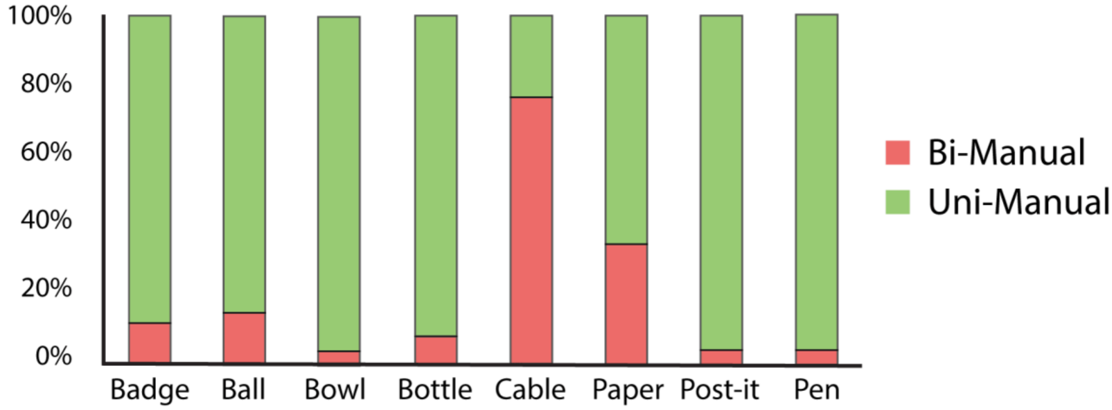



Figure 4.5: Human effectors (Objects)

#### 4.2.3.4. User preference

Each group of participants was asked to choose the most adequate interaction techniques for the current task from the set of ideas they proposed. At the end of each task, the participants voted for their preferred idea (all objects included). We report on this in the following table:

| Task | Objet | Interaction technique |
|---|---|---|
| Pan | Sheet of paper | The sheet of paper represents the map.<br>Holding the sheet of paper horizontally, tilting the sheet of paper would direct the Pan. |
| Discrete pan (8 directions) | Stress Ball | Rolling the ball towards the desired control would select it. |
| Zoom | Stress Ball | Squeezing the ball would perform a zoom on the map. |
| Content transfer between displays | Stress Ball | Squeezing the Stress ball would lock the content to transfer. Pointing towards a second display would select it as the destination of the transfer. Releasing the grip would transfer the content to the destination display. |
| Display selection | Sheet of paper | Rolling the sheet of paper and pointing with it towards the display to select it. |
| Multiple displays selection | Stress Ball | Squeezing the Stress Ball and drawing a lasso with it around the displays to select it. Releasing the grip validates the selection. |
| Validation | Badge | Making a fillip on the badge |

Table 4.3: Preferred interaction techniques and objects for each task

#### 4.2.3.5. Gestures

Although the objects were used by several participants during the creativity session, we were able to observe recurrent usages for each object (Figure 4.6):

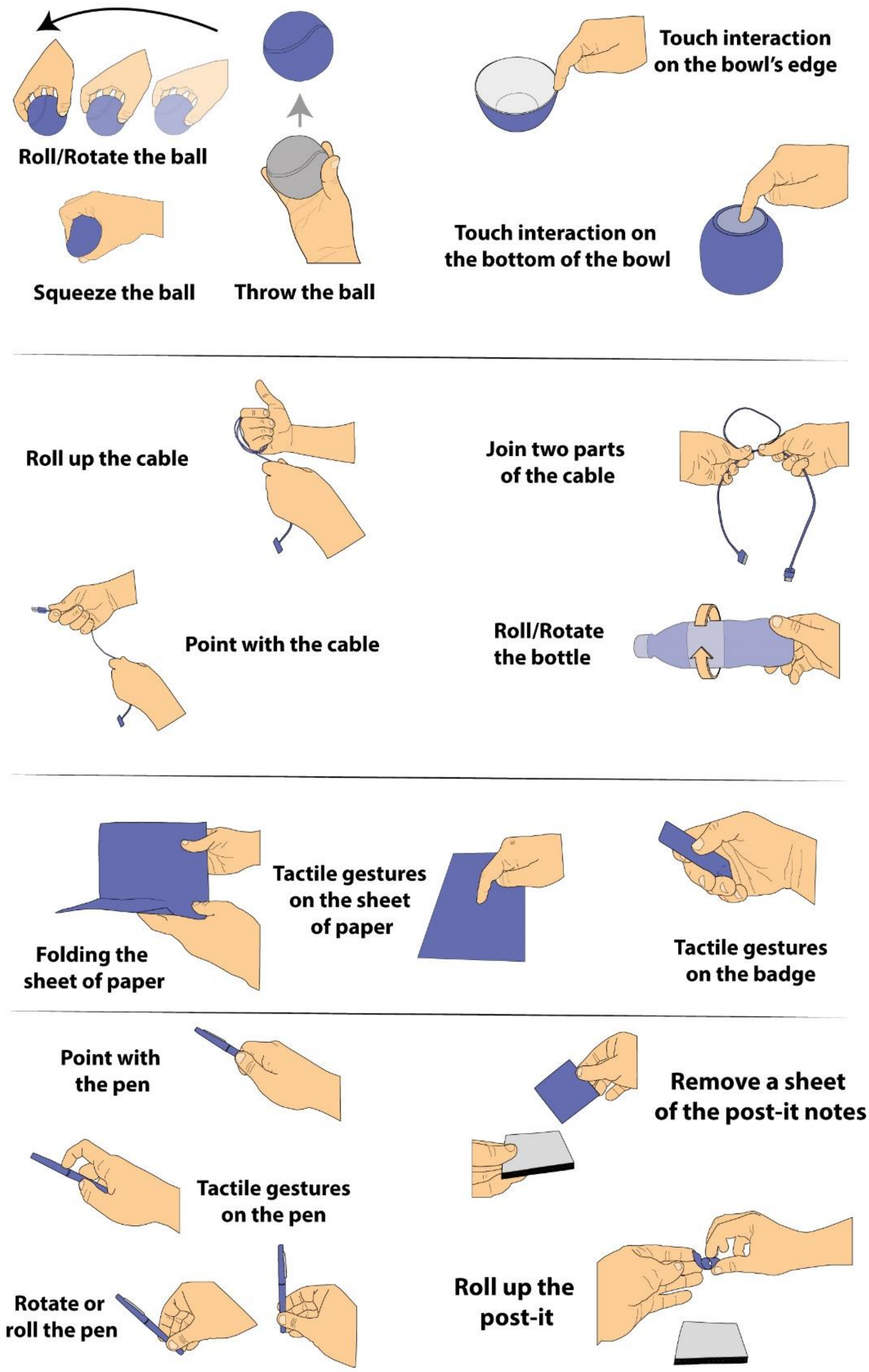



Figure 4.6: Frequently proposed gestures

### Stress ball:

The gestures proposed for the stress ball were essentially physical manipulations (throw the ball: 30%, tilt / rotate the ball: 30%, squeeze the ball: 19%). These gestures were preceded or followed by gestures of initiation or validation of the interaction. Example: to make a pan on the map, one of the participants proposed to squeeze the ball to set the speed of the pan (initiation gesture) and then to tilt the ball to activate the pan towards the direction of inclination.

### Bowl:

The most frequent interaction performed with the bowl was tactile (46%). The place of the gesture varied between the bowl's edge and its bottom (after turning the bowl upside down). Example: for the content transfer task, one of the proposed ideas was to turn the bowl over. Make a swipe gesture on the bottom of the bowl in the direction of the destination display.

### Bottle:

Inclinations and rotations (54%) were the most often suggested gestures to perform the different tasks of the study with this object. Example: to make a pan, one of the ideas proposed was to use the bottle as a joystick and performing the pan by tilting it.

### Cable:

The soft nature of the material composing the cable was extensively used in the proposed interaction techniques using this object (50%: join the two edges 38%, roll up 12%). The cable was also used to perform point gestures (23%). Example: for the display selection task, one of the participants proposed to join both ends of the cable to make a viewfinder which he used to aim at the display to select.

### Badge:

Participants favored doing tactile gestures on the badge (44%). Example: in a content transfer task, one of the participants proposed to make a swipe gesture on the surface of the badge towards the destination display.

### Sheet of paper:

As was the case with the cable object, The soft nature of the sheet of paper was the most exploited characteristic of the object. The most frequent interaction technique proposed using it was: folding the sheet of paper (26%). Example: in order to complete the validation task, one of the proposed ideas was to fold the paper in half.

**Pen:**

Pointing: 30%, Tilting / Rotating: 22%, Touch on the pen: 17% were the most frequent interaction techniques proposed for this object. Example: To select one of the controls to interact with, a participant suggested pointing towards the control with the pen.

**Post-it note:**

There was no particular gesture made with the Post-it note that stood out. The trend of exploiting the soft material of the object of interaction continued (40%—Fold: 10%, Crumple up: 10%, Scroll: 10%, Roll up: 5%, Cut: 5%). Example: to select a display, one of the proposed ideas was to remove a sheet of the Post-it notes, crumple it up and shoot it towards the display to select.

### 4.2.4 Discussion

#### 4.2.4.1. Limitations

The study was carried out in a single configuration of fixed displays (3.2.2), we think that it would be interesting to evaluate the most promising ideas proposed during the creativity study in differents display configurations. Moreover, it would be interesting to explore a more extensive list of tasks, such as 3D manipulation or text input. Indeed, while the tasks identified for the study were the most common in an MDE, they do not cover all the possible tasks.

#### 4.2.4.2. Lessons learned from the creativity session

Even though the interaction techniques proposed during the creativity session still need to be implemented and evaluated experimentally to validate them, we think that the results of our study represent a trail of natural and intuitive solutions. We suggest the following guidelines to design interaction techniques for tangible objects to interact with MDEs according to their shape and/or material:

- Interaction techniques *With the object* are preferred for spherical / semi-spherical, cylindrical, composite and rectangular categories if the object is made of a soft/deformable material.
- For rigid rectangular objects, whose shape resembles that of a common device (smartphone, remote control, music player, etc.), we suggest interaction techniques *On the object* and specifically, by analogy to those that already exist for the device resembling the object.
- When the object is made of soft / deformable material, we suggest focusing on techniques based on the material of the object. Conversely, if the object is rigid, we advise to favor its shape.
- Regarding spherical objects, we recommend the design of interaction techniques based on their shape, whether the object is deformable or rigid.

#### 4.2.4.3. Summary

Most of the gestures (80%) proposed by the participants were tangible gestures (*With the object*). We believe that this is due to the fact that gestures *Around the object* are not yet common in real life, thus, limiting the ideas proposed by the participants to *With the object* and *On the object* interactions. *On the object* were proposed mainly for the badge object (52% of the interaction for this object). The vast majority of the On the object interaction proposed for the badge were made by analogy. We concluded that the shape of the badge and its size—that resemble those of a smartphone or a remote control—encourages users to make gestures similar to those usually made on devices of the same shape and size (smartphones, music players, remote controls ….).

Participants preferred overall using the material of the object when it was a soft/flexible one instead of the shape of the object. The only exception to that is the stress ball for which, despite its soft nature, the interaction proposed were mainly inspired by its form. We believe that the rounded shape of the ball is more compelling to the users than its material in this case. The intrinsic degrees of liberty it offers allow for different ways of using it in a tangible interaction. Based on those findings, we decided to explore the rounded shape of the object in the work described in the second part of this work which consists in the design, usage and evaluation of a touch-enabled 6DOF interactive device for multi-display environments.

## 4.3 Interaction with MDEs in a professional environment

As opposed to MDEs in public contexts, which suffer from a lack of adequate interaction techniques due to their specific requirements, several interaction techniques have been proposed for MDEs in work environments.

Researchers have mainly proposed adapting existing devices to tackle individual MDE tasks, such as the mouse for multi-monitor pointing [20], or smartphones for cross-display data-transfer or distant pointing [35, 133]. However such adaptations can result in undesirable side effects: mice are not appropriate when the user is standing [133] and smartphones held in mid-air can be tiring and cumbersome for long interactions [83]. Recent research has demonstrated the use of wearable devices to perform cross-device interactions [87, 168]. However, current wearables lack proper input mechanisms and mainly serve private purposes. If MDEs are to become the office of the future, as envisioned by many [150, 153], can we design a device specifically tuned for such an environment? Adopting a unique device would indeed avoid the homing effect when switching from one device to another, enhance privacy in such environments through personal data control and visualization, lead to a coherent set of interactions with the varied MDE applications, and ultimately contribute to a more fluid task flow, a key element in MDEs [19].

To this end, we designed a novel touch-enabled device, TDome, to facilitate interactions and address a range of tasks in MDEs [33, 168]. TDome is the combination of a touchscreen, a dome-like Mouse [140] providing 6 DOF, and a camera that can sense the environment. TDome thus inherits properties of other existing mouse-like devices but includes many novel features to tackle the needs of common MDE tasks [33, 168]: TDome identifies the spatial layout of displays; facilitates distant interaction and data transfer across displays; and enables personal interactions by using the touchscreen as a private output medium. To do this, we designed and implemented different techniques employing two versions of TDome (small and large touchscreen) to address these MDE tasks.

In this section, we address two major challenges for applying TDome in MDEs: first, the device's usability, which demands the user to coordinate a physical manipulation with a touch gesture (we refer to as combined gestures—see Figure 4.7-c); second, the mapping between TDome gestures and MDE tasks. To validate TDome's usability and suitability for MDEs, we conducted three user studies. We first carried out a formative study to discard gestures deemed too uncomfortable. We followed this with a controlled system validation in which we identified the success rate and performance of combined gestures. Finally, using the resulting set of gestures, we collected user feedback on the best mappings from TDome gestures to common MDE tasks.

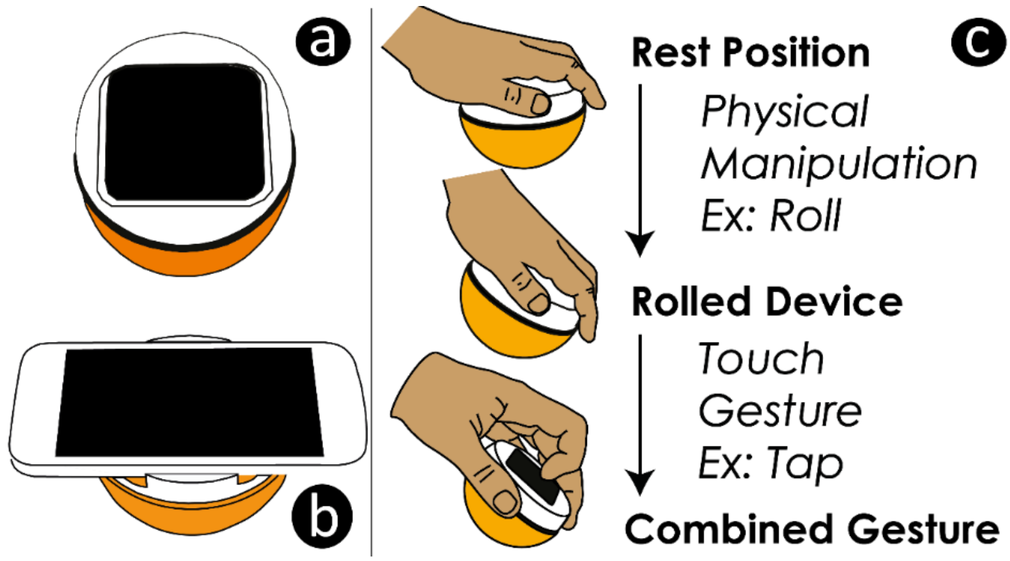



Figure 4.7: TDome combines a small (a) or large (b) touchscreen with a dome-like mouse. TDome supports performing combined gestures (c), i.e. a 6 DOF physical manipulation followed by a touch input.

### 4.3.1 TDome overview

TDome is a touch-enabled multi-DOF input device that embodies features and a form factor that facilitate MDE interactive tasks. This unique device results from the composition of a touchscreen with a dome-like mouse RPM [140], providing rotation, Roll, Translation and Lift-Up motions (6 DOF). The device also includes a camera that can sense the environment. As a result, TDome support the control of multiple commands, which is required in MDE to control the applications and their content but also managing the MDE. We present an illustrative usage scenario with TDome prior to presenting its features.

#### 4.3.1.1. Usage scenario

Harry is an engineer working on a smart campus project that monitors data collected by multiple sensors on the university. To visualize and interact with the large datasets of energy consumption, the university has set up a multi-display environment composed of several displays, a large projection wall and two TDome devices.

As Harry enters the room to start his daily supervision of the energy data, he grabs one TDome and uses it to initialize the multi-display environment by simply pointing at each active display. He then selects the wall projection by rolling the device toward the wall. Harry decides to spread the data visualization across two displays: he selects both displays with TDome and transfers the visualizations from one to the other with a TDome gesture. As he wants to look closer at information on the second display, he grabs TDome and walks towards the display, using the device in mid-air to perform a zoom on the data for a closer look.

Later that day, Mary enters the room and grabs the second TDome. They have a meeting to explore the university map to mark points of interest. Harry and Mary take their personal smartphones and bind them with each TDome to benefit from personal interactions. Each smartphone shows a personal view of the projected map, which allows them to add and access personal annotations. Before ending, Harry wants to log onto the campus website and upload his annotations: he rolls TDome towards himself to display a virtual keyboard on the device's touchscreen and enter his personal password discreetly on the login page, displayed on the tabletop.

This scenario illustrates how TDome allows users to detect surroundings displays arrangement, select one display, move content between displays, reach content at distant displays and perform personal interactions on TDome.

#### 4.3.1.2. Device Manipulation

Interacting with TDome requires the explicit combination of a physical manipulation with a tactile gesture on the touchscreen. The sequential combination of both actions acts as a delimiter whose accidental activation is unlikely, as demonstrated in our controlled evaluation (4.3.6). This approach reduces the risk of issuing a command after performing a physical manipulation inadvertently and improves the robustness of the device. As illustrated in Figure 4.8, four different physical manipulations (Translations, Roll, Rotation and Lift-Up) can be combined with four different touch gestures (Tap, Drag, Pinch, Spread) for using TDome.

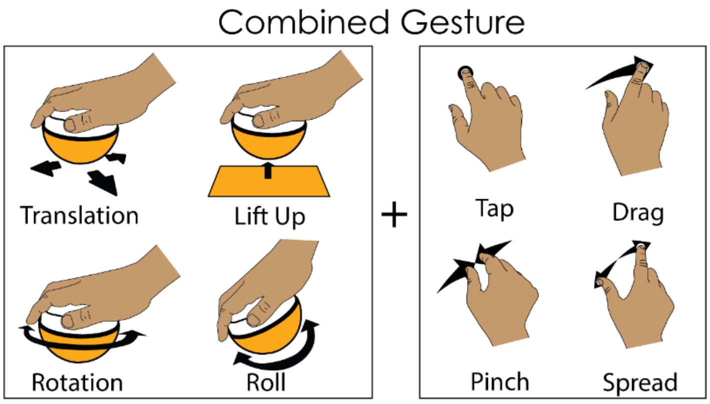



Figure 4.8: TDome allows performing combined gestures, i.e. a physical manipulation followed by a touch gesture

Initially, we favored a one-handed interaction where the dominant hand was used to perform the physical manipulation on the device and the touch gestures on the display. But our preliminary tests revealed that some gestures were easier to perform in a bimanual mode, thus extending the touch vocabulary.

#### 4.3.1.3. TDome versions: small and large touchscreen

We implemented two design variations of TDome resulting from different device composition alternatives [141]: one with a small touchscreen inserted into the spherical shell (Small version) and one with a larger touchscreen laid on top of the spherical shell (Large version). As these two versions were meant to be complimentary, we favored the possibility of rapidly switching them as opposed to having two separate devices. This opens interesting possibilities, such as switching to the large touchscreen when a larger display is needed.

### 4.3.2 Implementation

#### 4.3.2.1. TDome core elements

We used the Roly-Poly mouse (RPM) [140] design guidelines to define the dimension of our device: a diameter of 8 cm (~ 3.15 in) was the easiest to handle and manipulate.

As with the original RPM, we weighed the device with putty so that the device returns to its initial upright position when released (roly-poly toy principle).

Regarding the touchscreens, we implemented both the Small and Large versions. To restrict our device to the selected size, we had to limit the small screen size to less than 8 cm. To create the Small version, we removed the bracelet from an Android smartwatch SimValley AW-414[19] (63 g, 45x44x14mm, 28x28mm touchscreen) and enclosed the smartwatch into TDome. To implement the Large version, we used a Galaxy S4[20] smartphone (5 in, 134 g, 137x70x8mm). We used the smart-watch camera, which is situated on the edge of the watch, to provide TDome with a horizontal camera view. The camera has a 3 MP sensor and a resolution of 1728x1728 pixels. The position of the smartphones camera does not offer the possibility of having a similar view on the smartphone version.

To support device modularity, the interchange of both touchscreens had to be easy and quick. We thus 3D printed two plastic adaptors that can be adjusted on a 3D printed base: the first one holds the watch while the second one fixes the phone using a magnet (Figure 4.9). The two plastic adaptors are very rapidly interchangeable. Altogether, the Small version, involving a smartwatch, weighted 207 g in total and the Large version, involving a smartphone, weighted 297 g. We used TCP sockets over a local Wi-Fi network to connect the watch to the main computer.


Figure 4.9: Arrangement of TDome elements for the Small version (left). Both TDome versions are rapidly interchangeable (right).

[19] http://www.i-montres.net/simvalley-aw-414-go-un-smartphone-android-au-poignet/

[20] https://www.samsung.com/uk/smartphones/galaxy-s4-i9505/GT-I9505ZKABTU/

#### 4.3.2.2. Physical manipulation detection

The spherical shell holds an x-IMU of x-io Technologies[21] (48 g, 57 mm × 38 mm × 21 mm) to detect the Roll and Rotation of the device in 3D. The IMU is composed of a triple-axis gyroscope, accelerometer and magnetometer. The refresh rate of the sensors goes up to 512 Hz and we used Bluetooth to connect the IMU with the computer. The IMU offered an angular precision of 1°. We 3D printed a holder to fit the IMU in a horizontal position inside TDome (Figure 4.9).

To detect the displacement of the device, we used an infrared bezel (Zaagtech[22], 42" ) that generated TUIO[23] events. We implemented a filtering process to discard touch events that were detected when fingers touched the surface around the device. Thresholds were also empirically defined to avoid the detection of unwanted Translations, Rolls or Rotations: user's physical manipulations must reach a minimum amplitude to be detected (5 cm for Translation, 30° for Roll, 45° for Rotation). Lift-Up was detected as soon as TDome was no longer in contact with the table.

### 4.3.3 Suitability of TDOME for MDEs

In this subsection, we discuss how TDome properties suit the interaction requirements specified in Section 2.

#### 4.3.3.1. Spatial sensing

TDome physical manipulations allow performing 3D pointing in the surrounding space. Combined with the on-board camera, it allows sensing the environment. This can be used to detect and locate nearby displays, creating a spatial layout of the MDE displays represented through a radar-view (***physical relationship***).

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[21] http://x-io.co.uk/x-imu/

[22] http://www.zaagtech.com/X-Series-Features.html

[23] An open framework that defines a common protocol and API for tangible multitouch surfaces (see https://www.tuio.org/).

#### 4.3.3.2. Input interaction

TDome allows up to 3 types of 2D pointing: by moving the device, by rolling it or by interacting with the touchscreen. These ranges of positioning facilitate ***input redirection***. This also offers input that best suits a given display, such as a cursor for precise tasks, or touch input for coarser input.

#### 4.3.3.3. Output redirection

The touchscreen display can be used as a visual buffer to move data among displays in MDEs (***output redirection***). It may also be useful to display a zoomed-in version of a selected area on a distant display (***reachability***). The built-in vibratory capabilities are an alternative to discretely provide the user with private information (*personal data management*).

Through the easy interchange of the Small and Large TDome versions, the user can adopt the most appropriate display for each task; e.g., to visualize large graphs, the user can choose the Large version, but to display the compact radar-view (i.e. a view of the MDE spatial layout), a smaller display is more appropriate (***output redirection***).

#### 4.3.3.4. Mid-air interaction

Two of TDome's physical manipulations (Roll and Rotate) can be used in mid-air, thus facilitating physical displacements to interact with distant displays (***reachability***). It also offers more flexibility to the user to ensure the privacy for some of its tasks (***personal data management***).

#### 4.3.3.5. Form factor

TDome's tilting capabilities facilitate orienting the device towards oneself for private input and output interaction (***personal data management***); and attaching their personal smartphone to TDome's base allows users to access their personal applications and data (***personal data management***).

### 4.3.4 TDome MDE interaction techniques

We now introduce a set of proof-of-concept prototypes illustrating how the previous properties contribute to facilitate interaction in MDEs.

#### 4.3.4.1. Physical relationship

To fulfill the physical relationship and arrangement requirement, we implemented a semi-automatic acquisition of the displays layout in the MDE. This technique allows detecting the displays and building a radar view interface of them, which can be later exploited to interact with the displays of the environment.

During the detection phase, TDome detects a QR code ascribed to each display (better recognition algorithms may not necessitate codes for detection as demonstrated by HuddleLamp [146]. The user orients TDome toward each display successively, so that the device's on-board camera detects the QR codes (Figure 4.10—left). Once the QR code is recognized, the user taps the touchscreen to terminate the identification: the detected display is assigned a position in the environment thanks to the incorporated IMU.

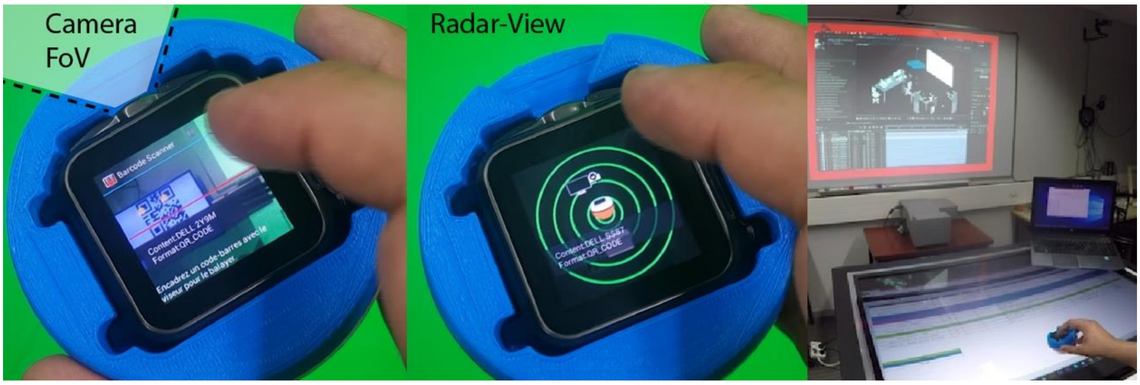


Figure 4.10: TDome's on-board camera detects displays (left) and creates a radar-view of the spatial layout (center). Then the user can select a display by Rolling + Tapping towards it (right).

The user progressively creates a radar view describing the relative position of all detected displays, with TDome in its center (Figure 4.10—center). The user can manually adjust the distance of each display to TDome on the radar view. Once created, the radar view can be used with a Roll + Tap on TDome to select a specific display, by rolling TDome in the direction of the display and tapping on the touchscreen to validate (Figure 4.10—right).

#### 4.3.4.2. Input redirection

One recurrent need in MDEs is to manage input redirection. In addition to changing focus from one display to another, TDome offers an input interaction that matches the input possibility to the display it is connected to. TDome can be used as a touch input device through its embedded touchscreen, as a mouse with its translation capability and as a 3D mouse with its rotation and tilting capabilities depending on the input capability of the display it is redirected to.

For instance, to interact with a map on a distant touchscreen, the user can perform a Roll + Drag on TDome to pan, and a Lift-Up + Pinch on TDome to zoom. Both touchscreen gestures (Drag and Pinch) are the same as what would be used on the distant touch display. While using only TDome's touchscreen gestures would be possible, using them in combination with the physical gestures (Roll or Translate) ensures a high recognition rate, prevents false positives, as demonstrated by our controlled study presented below and offers additional controls: the Roll angle may impact the panning speed.

#### 4.3.4.3. Output redirection

We developed two interaction techniques to move content from one display to another. The Translation + Pinch/Spread technique combines a physical manipulation of TDome to select a display and a gesture on the touchscreen to grab or place some content on the selected display (Figure 4.11). In our implementation, Translation + Pinch grabs the application of the screen selected by the translation's direction, and displays it on the tabletop; while Translation + Spread sends the tabletop application to the screen situated in the translation's direction.

Figure 4.11: A Translation + Spread gesture sends the tabletop content (left) to a secondary display (right).

We implemented a second technique using the radar view on TDome to create a virtual information tunnel between two displays (Figure 4.12-left). The user creates the tunnel by sequentially selecting two displays on the radar view. Once the tunnel is defined, the user can move content along the tunnel with a Roll + Tap on TDome: rolling is performed in the spatial direction of the second display (i.e. a Roll to the right if the display is on the right of the first one); a Tap gesture finalizes the transfer.


Figure 4.12: Using the virtual tunnel technique to transfer information between displays.

#### 4.3.4.4. Reachability

To support the reachability requirement, TDome provides support to interact with distant displays, i.e. beyond the user's reach. Given the size, shape and wireless design of TDome, the user can physically move to the distant display and perform mid-air interactions with TDome (Figure 4.13).

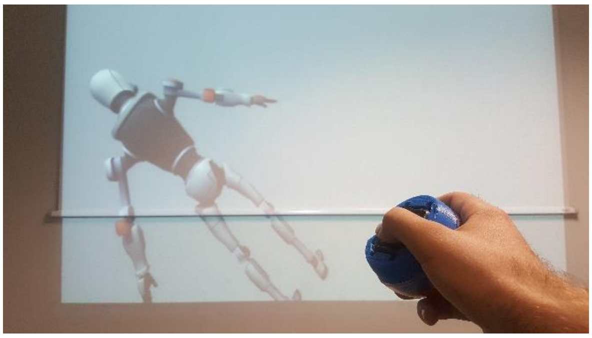

Figure 4.13: Illustrating mid-air interaction with TDome

#### 4.3.4.5. Personal data management

To preserve confidential information, the user can roll the device towards himself or lift the device to visualize and input content privately. For instance, TDome's large touchscreen can be used as a private virtual keyboard to input a password on a surrounding display (Figure 4.14). TDome can also be used to visualize a private detailed view of a public context.

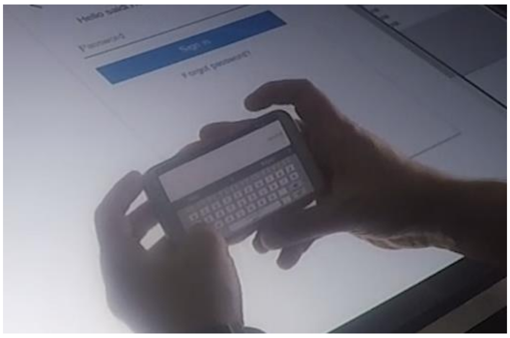

Figure 4.14: privacy conservation when typing a password

#### 4.3.4.6. Other techniques

Beyond effectively supporting essential interactions in MDE, TDome can be used for other common tasks such as controlling a pie menu on a distant display, supporting multi-clipboard copy and paste, and pointing on distant displays. We implemented all these interaction techniques using different combinations of physical manipulations and touch gestures.

#### 4.3.4.7. Resulting challenges for TDome usage

These techniques illustrate how TDome contributes to the execution of relevant interactive situations in MDEs and how it is useful and sufficient to address major MDE interactions. Using a single device contributes to a more fluid interaction in MDEs by maintaining the user in the flow of his activity [19].

Informal tests also provided some early feedback on the importance of precision and on the required number of available gestures: a precise control of the device is important to perform spatial interactions, such as rolling to select a display; and the user requires a wide set of gestures to cover the multiple set of controls and interactions across displays. Therefore, conferring the highest usability level to TDome is essential to ensure MDEs will take full advantage of the device properties.

For these reasons, we first focused on exploring the usability of the device itself. To this end we performed a user experiment dedicated to identifying the set of most precise and robust TDome gestures.

### 4.3.5 Exploratory study: TDome gestures and users comfort

The goal of this exploratory study was to inform the implementation of input gestures combining physical manipulations with touch input, by studying only their comfort and collecting initial user feedback. Ultimately we wanted to discard gestures that would be deemed too uncomfortable. While literature on physiology could be anticipatory, it would not help in identifying all the appropriate combinations of wrist gestures and multi-touch finger input. For this reason, we did not want to discard any gesture immediately and ran this exploratory study to reduce the initial gesture design space.

#### 4.3.5.1. Protocol

We carried this exploratory study with 4 participants (all right-handed) from the local university. We instructed participants to manipulate the TDome with their dominant hand. During the experiment they were confronted with the two different versions of TDome (Small and Large). In both settings, they tested three physical manipulations (Roll and Translate in 8 different directions, Rotate in two directions, Lift-Up) in combination with four touch gestures (Tap, Drag, Pinch, and Spread). Pinch and Spread gestures being more complex to perform, participants repeated these gestures twice: once with the dominant hand and once with the non-dominant hand (e.g. in a bi-manual setting).

Participants performed 2 TDome versions × 19 physical manipulations × 6 touch gestures = 228 combined gestures per participant. We asked participants to repeat each combined gesture 3 times, i.e. each participant performed 684 trials. We asked them to rate each gesture combination from 1 (comfortable) to 5 (uncomfortable) to help them verbalize their opinion and comment on their ratings. We report on their qualitative comments.

#### 4.3.5.2. Results

Participants were very positive about performing the following gestures both with the Small and Large versions of TDome:

- Tap and Drag combined with any physical manipulation (Translation, Rotation, Roll or Lift-Up).
- Pinch and Spread in a bi-manual setting (one hand manipulates the rolling device while the other touches the display) when combined with a Translation, Rotation or Lift-Up.

However some other gestures seemed too uncomfortable to be performed:

Performing Pinch and Spread with a single hand was always deemed very uncomfortable when combined with any physical gestures and for both TDome versions (Small and Large).

Performing Pinch and Spread in a bi-manual setting in combination with a Roll gesture was perceived to be very uncomfortable.

We decided to remove these uncomfortable gestures (Pinch and Spread with a single hand or in combination with Roll) from our subsequent work.

### 4.3.6 Controlled experiment: Feasibility of TDome's combined gestures

The goal of this controlled experiment was to validate the feasibility of combined gestures, i.e. physical manipulation followed by a touch input. We hypothesize that certain touch gestures could be difficult to perform on the Small version, on which certain combinations could lead to errors.

#### 4.3.6.1. Combined Gestures

From the previous exploratory study, we decided to use two touch gestures with one hand: Tap and Drag. Gestures using two fingers, i.e. Spread and Pinch, were performed with two hands: one hand held the device while the other performed the touch gesture. These touch gestures were used in combination with a Translation, a Roll, a Rotation and a Lift-Up of TDome.

#### 4.3.6.2. Task

Participants were requested to perform each gesture, according to visual indication displayed on a tabletop display (Figure 4.15). TDome was placed in an initial position at the center of the tabletop display, indicated by a visual feedback. We let users hold the device as they pleased. We asked participants to perform the gestures as fast as possible with high accuracy. We provided continuous visual feedback indicating the state of the device (position, Roll and Rotation) as well as touch gestures on the display. We provided them with knowledge of result and in case of error we indicated which gesture (physical manipulation and/or touch gesture) had been erroneously performed. Each trial started when the user pressed a button on the tabletop, which displayed the instructions, and ended when a combined gesture had been recognized.

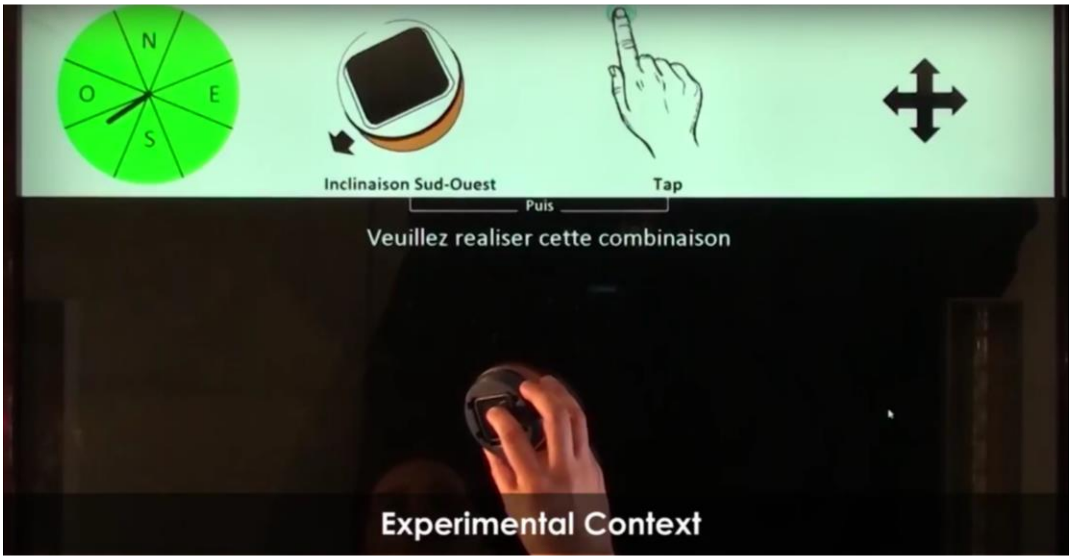


Figure 4.15: experimental context

#### 4.3.6.3. Participants

We recruited 12 participants (3 female), aged 27.5 years on average (SD=4.89) from the local university. 11 of them were right-handed and 3 of them took part in the exploratory study.

#### 4.3.6.4. Apparatus

We used the TDome implementation described earlier (Section 4.3.2). The device was used on a tabletop display (96 cm × 72 cm) of 102 cm high thus requiring the user to stand during the experiment. We used the display in an area limited to the size of the infrared bezel (42 inches, 1920×1080px).

#### 4.3.6.5. Design and protocol

The experiment followed a 2x4x4 within-subjects design, with Display (Small, Large), Physical manipulation (Translate, Roll, Rotate and Lift-Up) and Touch gesture (Tap, Drag, Pinch and Spread) as factors. We did not test the condition combining Roll with Pinch/Spread, as this combination appeared to be highly uncomfortable in our pre-study. We also decided to study one random translation direction to limit the experiment length: previous studies on RPM [36] showed that all translation directions were as easy to perform. For the other physical manipulations, participants performed eight Roll directions and two Rotations (left/right).

Our pre-study also showed that Pinch and Spread gestures seemed more difficult than Tap and Drag. Therefore, we paired Tap with Pinch, and Drag with Spread to balance the different blocks length and difficulty. Trials were grouped in four blocks: one block corresponded to one Display and two touch gestures (Tap/Pinch or Drag/Spread).

The four blocks were counterbalanced across participants using a 4x4 Latin Square. For each block, we ordered touch by difficulty: first Tap or Drag, then Pinch or Spread. For each set of trials corresponding to one touch gesture, the physical manipulations were ordered in a predefined way (Lift-Up, Translation, Roll and Rotation) because a random sorting would have made the instructions difficult to follow. Each combined gesture was repeated three times. Completing the four blocks took approximately 25 minutes.

The study started with a training set made of the same four blocks as in the experiment. The training consisted of 94 trials and took approximately 20 minutes. After the training, each participant performed 192 trials: 144 trials for the Tap and Drag: 2 Displays x 12 Physical Manipulations (1 Translation + 8 Rolls + 2 Rotations + 1 Lift-Up) × 2 Touch gestures × 3 repetitions.

48 trials for the Pinch and Spread: 2 Displays x 4 Physical Manipulations (1 Translation + 2 Rotations + 1 Lift-Up) × 2 Touch gestures × 3 repetitions.

We collected 192 × 12 participants = 2304 trials in total, which took approximately 45 minutes for each participant.

#### 4.3.6.6. Collected Data

We logged all gestures from start to finish. We calculated success rates, completion time from instruction onset to validation, unintended touch gestures on the Display and amplitude of the physical manipulations. We classified errors in three categories according to the gesture that had been erroneously performed: physical, touch or both. Finally, we asked participants to rate each condition on a 1–5 Likert scale on perceived difficulty.

#### 4.3.6.7. Results

A Shapiro-Wilk test established that the data was not normal and we could not normalize it. Therefore we used a Friedman test (we report $\chi 2$ and p) to compare more than 2 conditions, and Wilcoxon tests otherwise (we report p value). Where appropriate, we used a Bonferroni correction.

We first discuss the success rate for the Small and Large versions separately as a Wilcoxon test showed a significant effect of Display on the success rate ($p < .001$).

**Success rate: Large version**

When using the Large version, we found no significant effect of Touch gestures (Friedman: $\chi 2$=3.87, p=0.2) or Physical manipulations (Friedman: $\chi 2$=4.1, p=0.2) on the success rate. Overall, success rate with the Large version was 94.44%. Errors were distributed among Physical Manipulations (2.52%) and Touch gestures (2.86%).

A Friedman test reveals a significant effect of Touch gesture on the success rate when performing a Rotation ($\chi 2$=13.32, p=.003): a Wilcoxon test reveals a significant difference between Tap and Drag (81.94% vs. 98.61%; p=.022) and between Tap and Pinch (81.94% vs. 97.22%; p=.045).

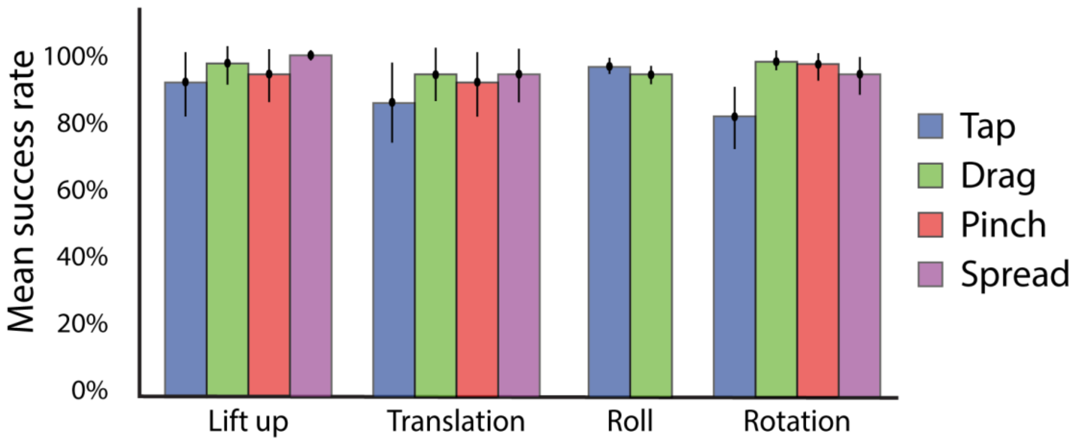


Figure 4.16: Mean success rate for each combination of Physical manipulation and Touch gesture when using the Large version.

We observed that when instructing participants to perform a Rotation + Tap combined gesture, 91% of the erroneously detected touch gestures are Drag gestures. Performing a Rotation induces a wrist distortion that may affect the user's ability to precisely tap the display without swiping the finger: this may explain why a Drag is easier to perform than a Tap. Spread and Pinch are not affected by the wrist rotation since they are performed in a bi-manual setting (Figure 4.16).

### Success rate: Small version

When using the Small version, a Friedman test revealed a significant effect of Physical Manipulation ($\chi 2$=17.46, p <.001) and Touch gestures ($\chi 2$=33.56, p <.001) on the success rate. We analyze the success rates for each combined gesture, i.e. the combined Physical manipulation and Touch gesture.

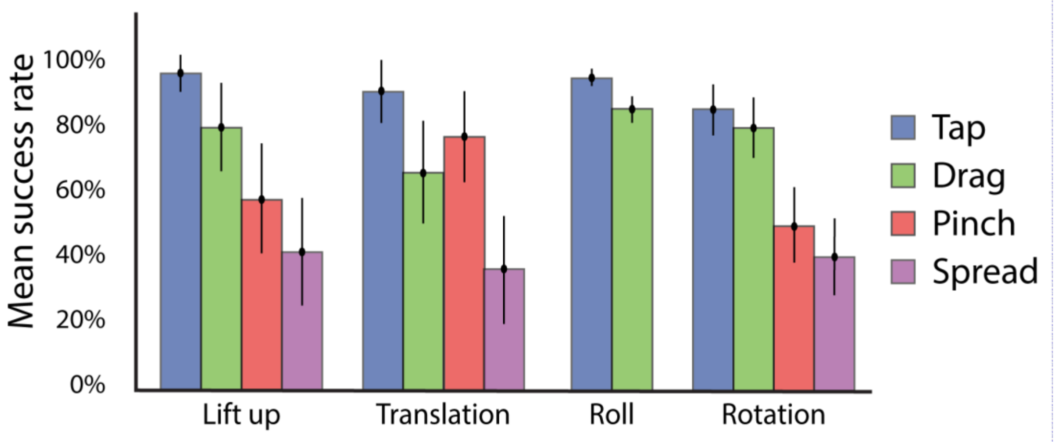


Figure 4.17: Mean success rate for each combination of Physical manipulation and Touch gesture when using the Small version.

A Friedman test reveals a significant effect of Touch gestures on the success rate when performing a Lift-Up ($\chi 2$=16, p=.001), a Translation ($\chi 2$=15.75, p=.001), a Roll ($\chi 2$=6.4, p=.010) or a Rotation ($\chi 2$=21.6, p <.001):

Lift-Up: a Wilcoxon test reveals a significant difference between Tap and Spread (92.22% vs. 41.67%; p=.001) and Tap and Pinch (92.22% vs. 58.33; p=.040). The success rate with Drag is 80.56%.

Translation: a Wilcoxon test reveals a significant difference between Tap and Spread (91.67% vs. 36.11%; p=.001) and between Pinch and Spread (77.78% vs. 36.11%; p=.020). The success rate with Drag is 66.67%.

Roll: a Wilcoxon test reveals a significant difference between Tap and Drag (95.83% vs. 86.11%; p=.040).

Rotation: a Wilcoxon test reveals a significant difference between Tap (86.11%) / Drag (80.56%) and Spread (40.28%) / Pinch (50.0%; $p < .020$).

### Completion time

A Wilcoxon test did not show any difference between the Small and the Large versions ($p = .08$). Overall, it took participants 2.5 seconds to perform a combined gesture. While we found some differences across gesture combinations, all of them are compatible with the micro-interactions concept [5], i.e. fast interactions that take less than 4s completion: all times ranged between 2.1s and 2.7s.

### Unintentional touches

We recorded unintended touches on the Small and Large versions. Overall, results were similar for both versions: we detected unintentional touches in 2% of the trials. These touches did not necessarily raise errors. The sequential use of a touch interaction after a physical gesture prevents from launching a command unintentionally.

### Subjective feedback

When considering the physical manipulations, results show that with the Small version, more than 50% of the participants found easy or very easy (4 or 5 on Likert scale) to perform a combined gesture involving a Roll, Translation or Lift-Up. In the case of the Large version, more than 75% of participants rated these gestures as easy or very easy.

When considering the touch gestures, we observed that with the Small version more than 50% of participants found difficult or very difficult (1 or 2 on Likert scale) to perform a combined gesture involving a Spread or Pinch. With the Large version, 60% or more of the participants found easy or very easy to perform combined gestures involving any kind of touch gesture.

### Summary

Results reveal differences between the Small and Large versions (Figure 4.18). With the Small version, the experiment reveals that 17 combined gestures can be comfortably and efficiently performed: those based on the combination of a Roll (8 directions), a translation (8 directions) or a Lift-Up with a Tap gesture (with a success rate of 95.83%, 91.67% and 92.22% respectively).

With the Large version, the experiment reveals that 54 combined gestures can be comfortably and efficiently performed: 16 results from the combination of a Roll (95.49% success rate) with Tap or Drag gesture, 36 results from the combination of a Translation (91.67% success rate), or Lift-Up (95.83% success rate) with one of the four touch gestures (Tap, Drag, Pinch, Spread) and 2 results from the combination of a Rotation with a Drag (98.61% success rate).

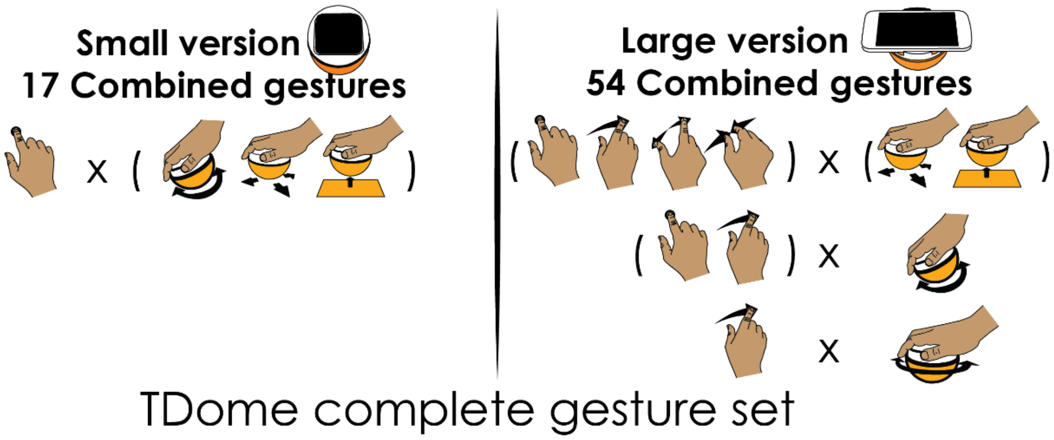


Figure 4.18: Summary of the 17 (Small) + 54 (Large) combined gestures which offer a good usability and performance.

The findings of this controlled experiment established the usability of TDome. Now, how should these possible inputs be mapped to MDEs' most common tasks?

### 4.3.7 Mapping tdome gestures to mde tasks

We elicited user input through a user study to explore how the selected set of gestures from our previous experiment can be mapped to MDE interactive tasks.

#### 4.3.7.1. Overview and rationale

We asked users to choose, for each TDome task, one gesture from the set of gestures selected in the controlled experiment.

#### 4.3.7.2. MDE tasks considered

From our scenarios, we considered the 7 tasks, each task represents one of the requirements described in section 2: pointing on a distant display (reachability); zooming on a distant display (navigation); displacing a window from one display to another (horizontal tunnel, vertical tunnel) (Output redirection); sending a window from Tabletop/TDome (user position) to a distant display and vice-versa (output redirection); selecting an icon on the radar view (interaction with UI controls); panning and zooming a focused view of a distant context (navigation); and typing on a private keyboard (personal data management).

#### 4.3.7.3. Participants

12 (1 female) students and researchers from the local university volunteered for this study. They were aged 31.9 years on average (SD=9). Five of them took part in the previous studies.

#### 4.3.7.4. Procedure

Participants were given the two TDome versions (Small and Large) and were situated in an MDE environment comprised of a tabletop, 4 displays and 1 video-projection. We familiarized our participants with TDome capabilities by showing them a video illustrating the combined gestures (without showing any interactive task). For each combined gesture, we asked participants to perform it themselves with both versions of TDome. Then, we asked participants to select and justify, for each task and each TDome version, which gesture they preferred. The session took about 15 minutes.

#### 4.3.7.5. Collected data

Every user generated one sheet with a summary of the gestures chosen for each task and TDome version. We recorded users' verbal comments.

#### 4.3.7.6. Results

Amongst all available combined gestures, only one was never used in our study (Lift-Up + Drag). Overall, participants took advantage of the gestures diversity to match the different tasks. The agreement scores [195,197] of the combined gestures (Physical manipulation + touch gestures) range between 0.3 and 0.6. These scores are in line with previous studies [197]. To find more consensus between participants and to complete the agreement score analysis, we will detail the choice of physical manipulations and touch input separately.

### Physical manipulations

Our results were similar for the Small and Large versions concerning which physical gesture to use. Thus we report both results together (i.e. 24 gestures per task).

Two physical gestures were used more often: Translate and Roll (Figure 4.19). For some tasks, one was preferred over the other: *Translation* for panning (17/24), or for moving a focus (15/24); *Roll* for private pincode input (19/24). For other tasks, such as redirecting data using the tunnel, output redirection or display selection, there was no clear preference for one of these two gestures.

The Lift-Up gesture was used for zooming 13 times (i.e. lifting up the device activates zoom mode). Rotation was used only once for each of our zooming tasks.

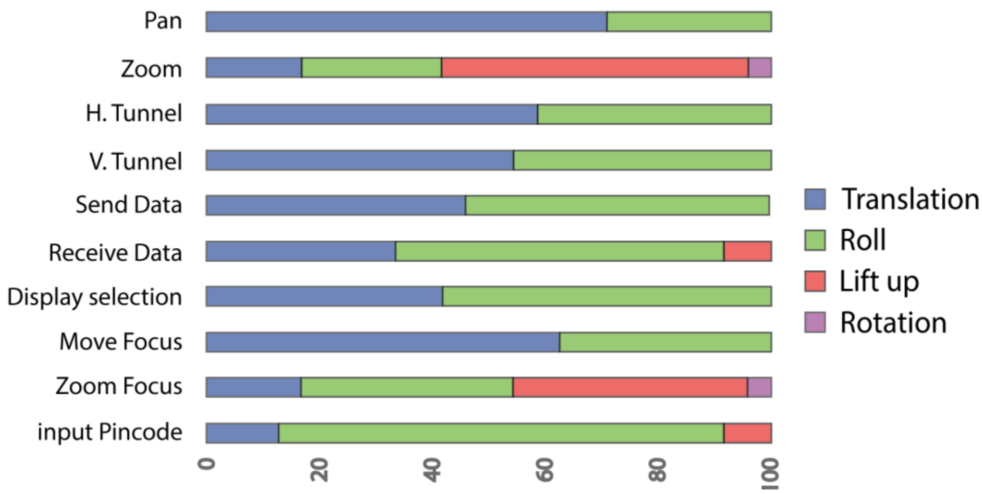


Figure 4.19: Percentage of users that chose each physical gesture on both versions of TDome for MDE tasks.

### Touch gestures

While only the Tap gesture is feasible on the Small version, users selected different gestures on the Large version according to the task (Figure 4.20). For instance, Pinch and Spread were preferred for zooming (10/12), and Drag was preferred for sending content from the tabletop to other displays (8/12) s. Taping was the preferred gesture for map panning (12/12), display selection (12/12) or pincode input (11/12).

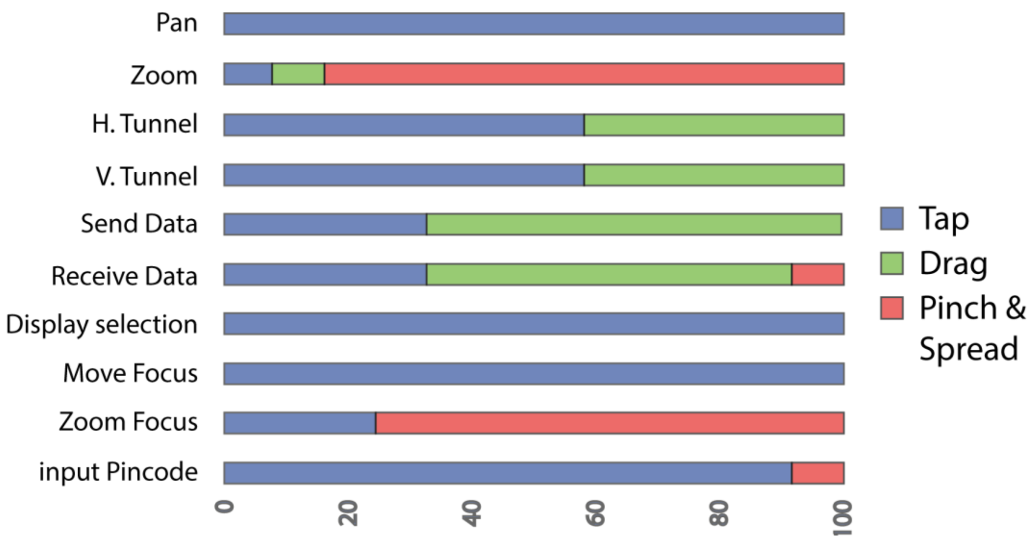


Figure 4.20: Percentage of users that chose each touch gesture on the Large version for MDE tasks

## 4.3.8 Discussion and perspectives

### 4.3.8.1. TDome benefits

We presented two versions of TDome: a Small version with an integrated touchscreen and a Large version based on attaching a smartphone. TDome's unique features offer several advantages to interact with MDEs:

TDome supports performing multiple combined gestures involving a physical manipulation of the device (Translation, Roll, Rotation or Lift-Up) followed by a touch gesture on the touchscreen (Tap, Drag, Pinch or Spread). Such a combination prevents from unintended activations due to parasite touches on the touchscreen;

The combined gestures from our final set represent good candidates to support rapid access to interactive commands;

The two TDome versions are easily interchangeable and offer complementary functionalities: the Small version is useful to rapidly launch shortcuts, while the Large version offers a larger display area and supports multi-touch gestures (Pinch and Spread);

Rolling TDome can be used to interact with multi-dimensional data through continuous physical gestures, as demonstrated earlier [140];

The embedded display can be used as a personal display area to augment output visualization, such as in overview + detail techniques;

The embedded display can also be used to show feedback of the TDome interactions, such as displaying a copied object for the copy/paste technique.

#### 4.3.8.2. Lessons learned for mapping TDome gestures to MDE tasks

We propose a set of guidelines to map TDome gestures to MDE tasks based on our mapping study as well as on our experience developing TDome interaction techniques:

- TDome offers a diversity and large number of possible gestures of which users can take advantage as illustrated in our mapping study. Some of these gestures have natural mappings with MDE tasks, such as Rolling towards oneself to display private information, Pinch and Spread for zooming or dragging for sending data to another display. Appropriately combined with a physical manipulation or a touch gesture, these should become the “default” combined gestures with TDome on MDEs.
- While some mappings are obvious and have a large consensus, others are sometimes split between two types of gestures (usually Roll or Translation): this suggests that using TDome in an MDE could benefit from a device personalization step wherein the user defines his preferred mapping, especially for output redirection.
- Interacting in an MDE involves system tasks (i.e. tasks related to the environment, such as display selection) and application tasks. Since these tasks could be assigned to the same TDome gestures, there is a need for a mode switching gesture. The Lift-Up manipulation combined with touch input, is a good candidate as it was considered for switching between pan and zoom tasks in our mapping study.

#### 4.3.8.3. Memorability of a large number of gestures

TDome offers a large set of usable combined gestures. This diversity of available controls is particularly relevant to tackle tasks in MDEs. However, increasing the number of controls might make them hard to memorize. The physical nature of these combined gestures can help cluster them according to the physical manipulation, as shown in our mapping study. Further experiments are required to identify how such clustering can improve gestures or command memorization.

#### 4.3.8.4. Collaboration

MDEs are naturally designed to support collaboration. We can envision multiple TDome like devices, each controlled by the MDE's users. However, in such cases input and output redirection mechanisms would need to be effectively controlled. Control mechanisms have been proposed by others [44] to handle synchronization, locking and input conflicts, and future iterations of TDome will adapt or build on such proposals.

#### 4.3.8.5. Discussion

In this work, we focused on the suitability of TDome capabilities for MDE tasks and the feasibility of its combined gestures. TDome interaction techniques still need to be fine-tuned and future work should compare their performance with a baseline for each MDE task. Theoretically, since TDome integrates the same capabilities as existing MDE devices, we hypothesize that it can perform similarly for each individual MDE task. For instance, TDome can perform translations like a mouse, and has the same touch and mid-air capabilities as a smartphone. Moreover, since TDome is a unique device that supports a range of core MDE tasks, it should improve the overall performance by reducing homing transition times and promoting the interaction flow. Therefore, beyond individual controlled comparisons, it would be interesting to carry a longitudinal study. We leave these studies for future work.

Beyond these aspects, we plan to focus on user expertise of TDome techniques: most menus or command techniques consider novice and expert modes as well as the transition from novice to expert [52]. In our work we focused on how the combined gestures are performed. It will be interesting to design techniques that efficiently support both novice and expert users and the transition from one group to the other, as done with the Marking Menus [201].

We also plan to investigate the extension of our physical manipulation gestures by adding thresholds. For instance, each Roll gesture could launch two different commands according to the Roll amplitude (under or over 42° according to our study results).

Technical alternatives also need to be investigated to replace the infrared bezel used to detect the TDome translations. We are currently exploring the application of conductive paint on the external surface of TDome, which will allow using the device on any capacitive surface.

Finally, TDome has been proposed for MDEs in a professional setup as using it in a public environment or an unsafe one where it might be damaged or stolen is its current limit. Exporting a similar device to public spaces remains a possibility for future work.

# 4.4 Conclusion

This chapter describes the work carried to improve interaction with multi-display environments in two contexts: public and professional environments.

In the first part of this chapter, we studied the use of everyday objects to interact with public MDEs. To this end, we carried out a study, through a creativity session, whose purpose was to identify the possible usages of objects of different shapes and materials to achieve a set of tasks representative of the most common tasks in MDEs. We defined a taxonomy to classify the ideas collected from the study. Our results showed that users prefer to rely on the materials of the objects at their disposal to perform their gestures when they are soft (flexible). Conversely, users rely on the shapes of objects when they are rigid. However, we noted some exceptions: gestures based on analogies were preferred for the badge and gestures based on the shape were preferred for the stress ball, despite its soft material. Indeed, the round shape of the stress ball was its most influencing criteria. Based on those findings, we decided to further explore the rounded shape of tangible objects to interact with professional MDEs. We focused on a rigid material as it is most probable in a work context. We also reconsidered the interaction metaphor as it is not suitable for work MDE.

In the second part osf this chapter, we presented TDome, a dome-shaped device designed for interactions in MDEs. We designed two TDome prototypes: a Small version with an integrated touchscreen and a Large version based on attaching a smartphone. We discussed how TDome properties suit the interaction requirements of MDEs and introduced a set of proof-of-concept prototypes illustrating how its properties contribute to facilitate interaction in those environments. We explored combined gestures involving a physical manipulation (Translation, Roll, Rotation or Lift-Up) followed by a touch gesture (Tap, Drag, Pinch or Spread) through a 3-step process. First, an exploratory study focusing on comfort established that 60 combined gestures could be comfortably performed. Second, a controlled experiment evaluated the user's performance as well as the subjective perceived difficulty. Results revealed that the number of gestures that can be precisely and easily performed is 17 with the Small version, and 54 with the Large version. Finally, a user survey explored the mappings between these gestures and MDE tasks. Results show that some combined gestures are more prone to be used in specific tasks than others. In general, we find participants are able to match TDome features to MDE tasks.

# Interaction with Immersive Environments

On-body tangible interactions for immersive data visualizations

# 5 Interaction with Immersive Environments

## 5.1 Introduction

Immersive systems such as the Hololens[24], MetaVision[25] ou Moverio[26] allow the user to display numerical data and visualizations directly on the physical word by attaching them to a fixed physical anchor; we hereafter refer to these as immersive visualizations These technologies offer new interaction opportunities that are to this day insufficiently explored. As such, we do not have implicit design rules to guide the developer when designing solutions for these environments. This results in a compilation of partially satisfactory solutions for interaction.

Indeed, while the numerous advantages of immersive systems make them a compelling alternative to visualizing multidimensional data on 2D displays, existing interaction techniques for exploring and manipulating this type of data is unsuitable for immersive systems. These existing solutions do not have enough degrees of freedom [59, 126, 156] and are often ambiguous and tiring (especially mid-air gestures [24, 126, 138]). Moreover, some of them constrain the mobility of the user to a defined place where the device (3D mouse or other) can be used [110], usually a desktop.

The challenge is to maintain the freedom of movement of mid-air interactions, the degrees of freedom of tangible interactions and the accuracy of the mouse to provide a flexible and precise solution for interaction with immersive visualizations.

In this work, we propose to study *on-body tangible interactions*, i.e. using the body as a physical support for interaction with an input device. We thus present a new approach that combines 1) the use of a multi-DOF mouse-like wireless device, combining

[24] https://www.microsoft.com/en-us/hololens

[25] http://www.metavision.com/

[26] https://epson.com/moverio-augmented-reality

the precision of a mouse, tangibles' multiple degrees of freedom, and 2) the use of the body to guide the physical manipulations of the device and exploit users' proprioception[27] (i.e. sensing its own body parts) while limiting muscle fatigue inherent to mid-air interactions.

To explore this new interaction approach, we define a new design space that encompasses the physical properties of the body (support) and the interactions that can be performed on the body. To evaluate the feasibility of such an approach, we conducted an experiment investigating the amplitude and comfort of on-body tangible gestures.

Our contribution is both conceptual and experimental. First, we detail our design space for tangible interactions on the body. Then we evaluate them through an experiment. Finally, we discuss the advantages and disadvantages of these tangible interactions before illustrating them through two concrete scenarios.

## 5.2 On-Body tangible interactions

In this section, we present a new interaction approach for immersive visualizations based on the use of the body as a support for tangible interactions. We detail the main requirements to interact with immersive visualizations, our choices of body parts and tangible objects to use, before presenting the design space.

### 5.2.1 Interaction requirements for immersive visualizations

There are different types of immersive visualizations. They range from a simple interactive visualization of a 3D object to complex multidimensional data. These immersive visualizations all share a set of basic requirements:

Unconstrained mobility (R1): the main advantage of immersive systems for data visualization is that they offer physical exploration capabilities. It has been demonstrated that the physical exploration of data, as opposed to the virtual one, allows for a better spatial understanding of the visualization. The user can have an overview of the visualization from afar, or a more detailed view by getting closer. He can also analyze the

[27] The sense of the relative position of one's own parts of the body and strength of effort being employed in movement (see https://en.wikipedia.org/wiki/Proprioception).

data from different angles [94]. It is thus important that the interaction techniques do not constrain the mobility of the user.

Multiple degrees of freedom (R2): the multidimensional nature of the data visualized in this type of systems requires enough degrees of freedom to tackle the tasks related to their manipulation [17].

Limited visual clutter (R3): the interaction techniques should not occult the data visualization. They should also allow the user to interact with data without having to divert his attention from the visualization [94].

- Precision (R4): the interaction techniques should offer enough precision to tackle the type of tasks performed in immersive systems, such as filtering.

The on-body tangible interaction approach can satisfy the requirements mentioned above. Indeed, the body is an always available physical support that favours physical exploration of data. It does not constrain the movement of the user (R1). Thanks to the body's natural capacity to sense its own body parts (proprioception), the user can perform tangible interactions on the body without having to switch his attention from the data visualization to the interaction tool (R3).

### 5.2.2 Tangible device

Regarding the tangible device, we decided to explore the use of the Roly-Poly Mouse (RPM) [140], an input device with a semi-spherical shape that offers up to six degrees of freedom. This device is particularly suitable for manipulating multidimensional data (R2, R4) [140]. Moreover, the device can be manipulated mid-air and therefore does not constrain the user's movement (R1).

RPM allows 3 types of physical manipulations (Figure 5.1): translations, rotations and rolls. These manipulations can be performed in several directions [140]: 2 directions for the rotations (Left, Right), and at least 8 distinct directions for the rolls and the translations (North, North-East, East, South-East, South, South-West, West and North West).

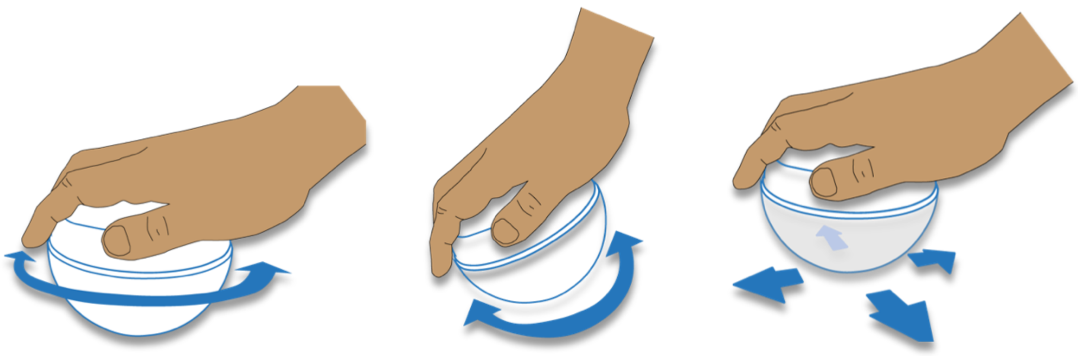

Figure 5.1: RPM's degrees of freedom

### 5.2.3 Physical support

Many research works have focused on interaction on or with the body [77, 105,183 184]. The arm and hands were the preferred body part in most works. These body parts offer numerous advantages: they are easily accessible for interaction, they are in the user's field of vision and generate less social discomfort than other body parts [105, 181]. In their work on interacting with interactive clothing [105], Karrer et al. did an experiment in which they tried to identify the most appropriate region of the body to perform interaction with clothes. Among the observations they made, the non-dominant arm as well as the hip are the preferred body-parts for interaction. Other parts of the body, such as the stomach and legs, have been rejected for social or personal reasons (Figure 5.2).

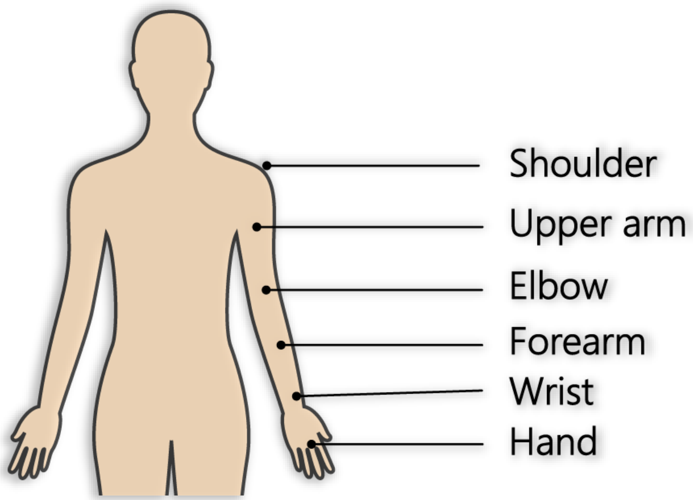


Figure 5.2: Body parts

We decided to focus on the forearm of the non-dominant arm as a support for the interaction for several reasons: it offers a large surface on which the tangible interaction can be performed, and it is effortlessly accessible by the dominant hand as opposed to the arm which needs a consequent effort to be touched by the dominant hand. Moreover, several poses can be adopted with the forearm (Figure 5.3) increasing the possible interaction vocabulary.

### 5.2.4 Referential

As interaction with data is performed in a spatial context in immersive systems, it is important to choose the right frame of reference for the interaction. The frame of reference can be allocentric (external: it can be world-centered, data centered…) or egocentric (relative to the body). In an egocentric frame of reference, the output of a given manipulation is determined by how it is performed with regards to the body. A translation parallel to the body for example will have the same effect regardless of the body's position and orientation in the world. In our approach, we adopt an egocentric frame of reference to allow the user to interact from anywhere with geographically-anchored data in the physical world [124].

### 5.2.5 Design space for tangible interaction supported by the forearm

As a result of the previously identified characteristics, we propose a design space that describes the properties of the physical interaction support. It is composed of 3 dimensions: the *Pose*, the *Place of motion* and the *Range of motion*.

#### 5.2.5.1. Pose (POS)

We identified three main poses for the forearm: Vertical, Parallel (to the body) and Forward (Figure 5.3). The three poses embody the 3 axes of a three-dimensional cartesian coordinate system.

In the *Vertical* pose, the forearm is vertical, the hand points upwards. In the *Forward* pose, the forearm is perpendicular to the shoulders. In the *Parallel* pose, the forearm is parallel to the shoulders.

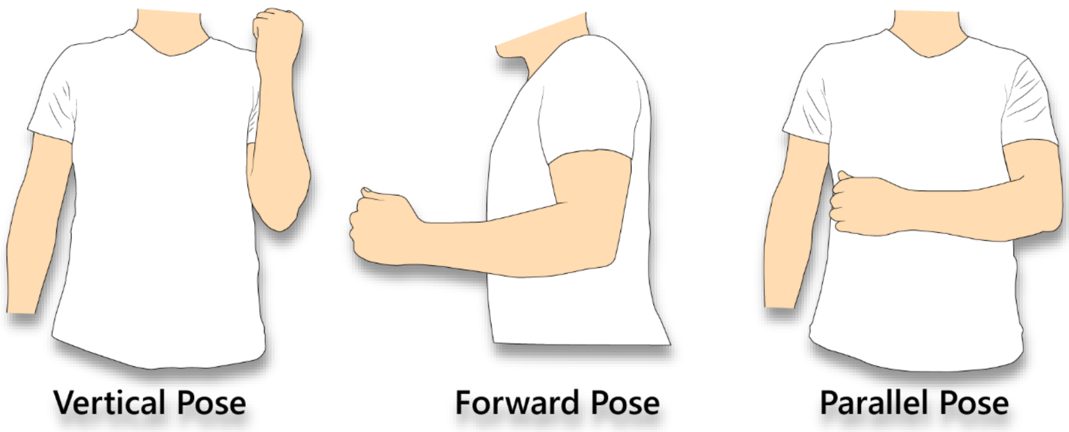


Figure 5.3: Poses

#### 5.2.5.2. Place of motion (POM)

The *Place of motion* represents the surface of the forearm on which the interaction will be performed. We identified two types of places: the first one extends over the length of the forearm, from the elbow to the wrist (*length POM*); the second one extends over its width (*width POM*). There are three types of *width POM:* close to the Elbow (*Elbow POM*), in the middle of the forearm (*Middle POM*) or close to the wrist (*Wrist POM*). This results into 12 different interaction supports (Figure 5.4) which increases the possibilities of interactions exploiting the proprioception of the user and avoiding the fatigue of a mid-air usage.

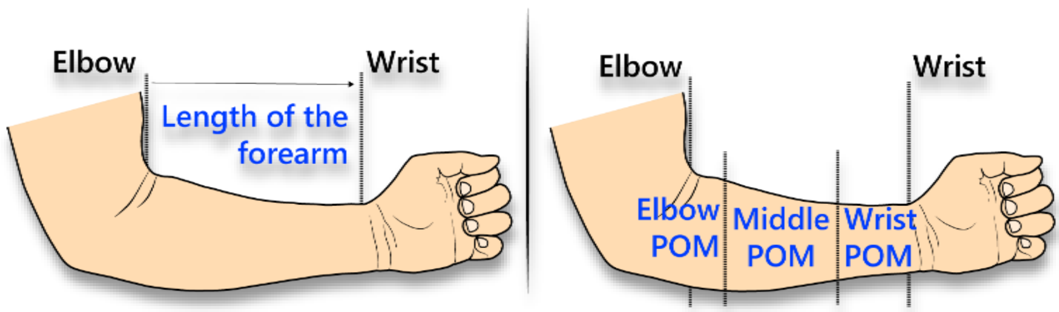


Figure 5.4: Place of motion

#### 5.2.5.3. Range of motion

The *Range of motion* represents the exploitable surface for each pair of *Pose and Place of motion* (Figure 5.5). It describes the maximum range of translation that can be performed with RPM. The greater the range of motion, the greater the range of values that can be manipulated on the concerned place.

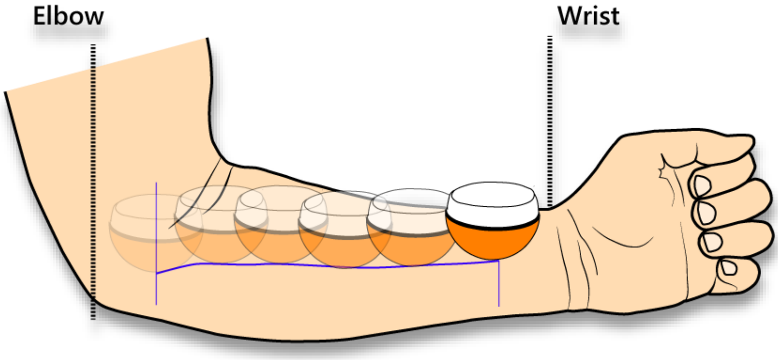


Figure 5.5: Range of motion

We explore these three dimensions in a controlled experiment, detailed in the next section.

## 5.3 Experiment: Tangible Interactions On The Forearm

The aim of the experiment described in this section is to study the characteristics of the implementation of an on-body tangible interaction solution, using RPM as a tangible object for interaction, and the non-dominant forearm as the support.

### 5.3.1 Goals

The main objective of the experiment is to study the movement of the device on the forearm and specifically, its translations. Indeed, we hypothesized that performing translations on the forearm could lead to systematic rolls. We decided in this first study to limit our evaluation to the translations. The experiment includes measuring the possible range of motion as well as identifying the areas of the forearm (width) on which translations can be performed distinctly. The second objective is to study the stability of the forearm as a support for the interaction in addition to the stability of the device (RPM) during its use. It has been observed before [140, 158] that the device suffers from involuntary rolls (up to 12°) when used on a flat surface. This aspect of the device can potentially have an impact on its usability.

### 5.3.2 Task

During the study, we asked participants to perform translations on different places of motion: the length of the forearm (*length POM*) and the width of the forearm (*Elbow POM, Middle POM, Wrist POM*). A trial is defined as a back-and-forth translation on the forearm (Figure 5.6). The starting points of the translations were chosen by the participants at the beginning of each group of 10 trials: the possible starting points of the *length POM* are the elbow or wrist. The possible starting points for all the *width POM* are the inside or the outside of the forearm. It was not necessary to control the starting points for gestures as the participants did the same gesture 10 consecutive times in each group. The device had to be manipulated with the dominant hand while the forearm of the non-dominant hand acted as physical support. The participants had to perform translations on each of the four *Places of motion* (*Length POM, Elbow POM, Middle POM, Wrist POM*), and for each *Pose* (Vertical, Parallel, Forward). The poses and places of motion were explained and illustrated to the participants at the beginning of the experiment. Participants were free to grasp the device as they wished. Since the purpose of the experiment was to study the use of the device on the forearm, no feedback was provided to the participants.

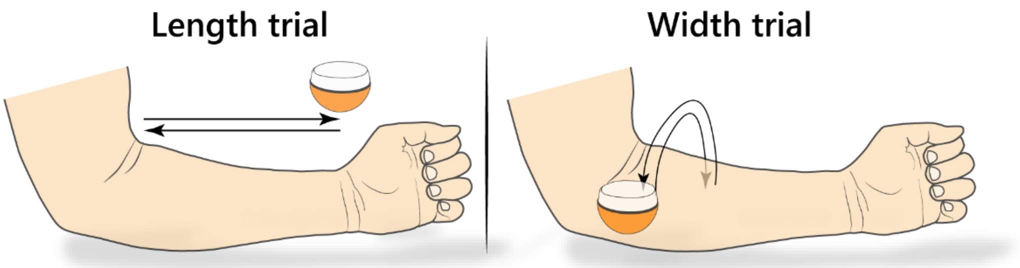


Figure 5.6: Length and Width trial

### 5.3.3 Apparatus

The diameter of the RPM version used for the experiment was 8 cm. In order to detect involuntary rotations and rolls of the device, an IMU of X-io Technologies was used (x-IMU: 48 g, 57 mm × 38 mm × 21 mm). The IMU is composed of a triple-axis gyroscope, accelerometer and magnetometer, offering an angular precision of 1°. The refresh rate of the sensors goes up to 512 Hz and we used Bluetooth to connect the IMU with the computer.

To locate the position of the device and the body parts, an OptiTrack system composed of 12 cameras was used. The cameras track infrared reflective markers to detect objects with a precision of 1 mm. The markers were carefully placed on the device so that they do not influence the participant's grasp (Figure 5.7).

In order to detect the position of the forearm and identify the different poses described previously, additional infrared reflective markers were placed on the main joints of the arm / forearm (Figure 5.7). The wrist and the elbow of the non-dominant arm were tracked as well as the shoulders of the user.

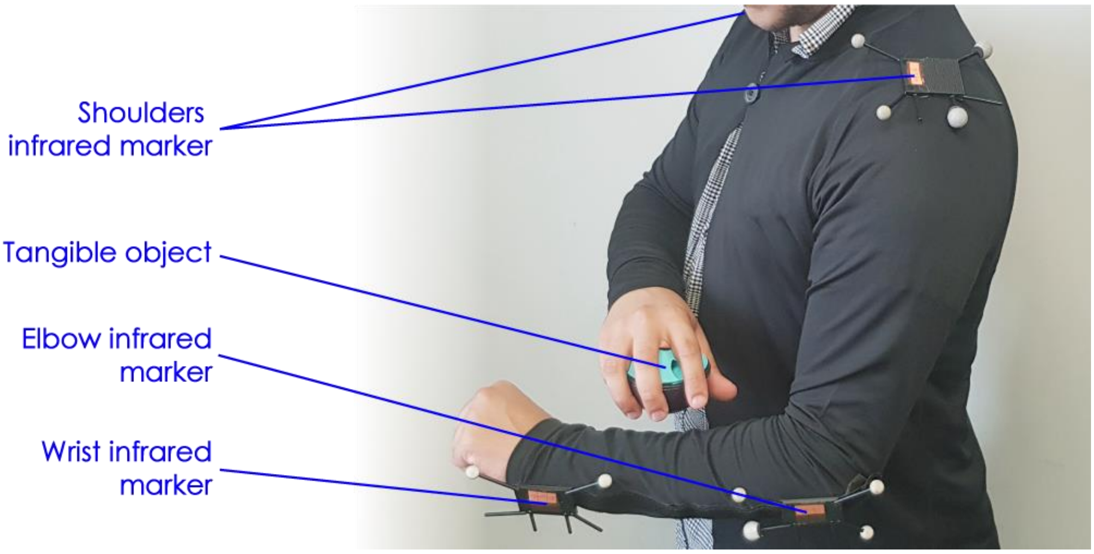


Figure 5.7: Placement of the infrared tracking markers

### 5.3.4 Procedure

The experiment follows a 3x4 within-subject design with the *Pose* (*Forward, Parallel, Vertical*) and the *Place of motion* (*length POM*, *Elbow POM, Middle POM, Wrist POM*) as factors. The *Pose* factor was counterbalanced using a 3x3 Latin square. The study is composed of 3 blocks, each block consists of 4 places of motion in a random order. For each pair of *Pose and Place of motion*, participants had to do 3 groups of 10 trials. The participants could take a break between each group of 10 trials. The study lasted approximately 40 minutes. We collected 360 trials per participant, 4320 trials in total.

### 5.3.5 Participants

We recruited 12 participants (5 females), 10 from the local university, aged 26 years on average (SD=5,4). 4 of the participants were PHD students, 5 were MSc students, 1 was a research engineer and 2 were external to the university. All the participants were right-handed.

### 5.3.6 Collected Data

We measured the circumference of the forearm near the elbow and the wrist for each participant as well as the inner and outer length of the forearm (Figure 5.8). We collected the position of the device, the wrist, the elbow, the shoulders using the infrared reflective markers and the optitrack system. We also collected the rotations and rolls of the RPM device using the IMU. To evaluate the physical fatigue associated with the use of the RPM device on the forearm, we asked participants to fill out a Borg scale [32] for each (*Pose, Place of motion*) couple.

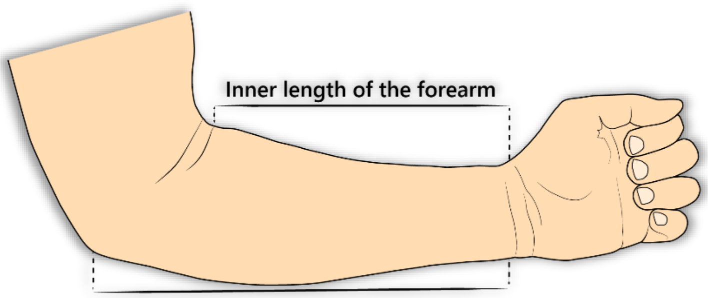


Figure 5.8: Forearm measurement

## 5.4 Results

In this section, we report on the results of the study. First, we focus on the physical support (forearm): we present the results concerning its stability as well as the exploited surfaces for each *Place of motion*, in each *Pose*. Then, we detail the results related to the usability of the device. Finally, we present the results on users fatigue. All error bars in the following results represent 95% confidence intervals.

### 5.4.1 Forearm stability: elbow and wrist movements

Ideally, for the forearm to be a support for interaction, it is important that it remains stable. We therefore logged the movements of the forearm during interactions: we measured the positions of the elbow and the wrist every 10 milliseconds. The movements of each of the two joints were computed with regards to their starting position, collected at the beginning of each group of 10 trials. We report the average movement of the elbow and the wrist during these 10 trials using the axes described in Figure 5.9.

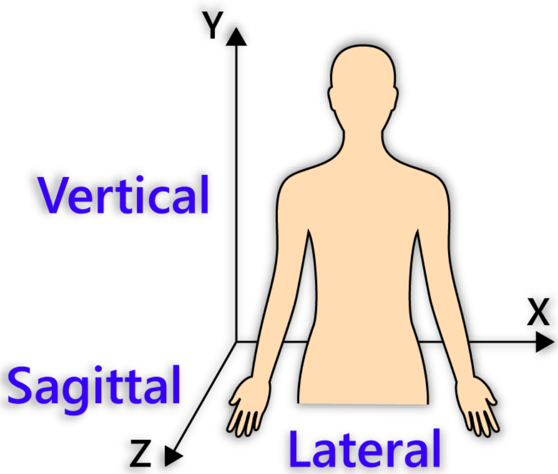


Figure 5.9: Mouvement – Axes

The elbow was relatively stable (Figure 5.10): the maximum movement (all directions included) did not exceed 1,7 cm on average. The biggest movement of the elbow was lateral (on the X axis) and it ranged from -0,86 cm to 0,84 cm for a total of 1,7 cm. The smallest movement was vertical, ranging from -0,65 cm to 0,5 cm for a total of 1,15 cm.

The results observed for the wrist are similar to the elbow, i.e. generally stable, with a maximum movement of 1.57 cm on average. The biggest movement of the wrist was sagittal (on the Z axis) and it ranged from -1 cm to 0,57 cm for a total of 1,57 cm. The smallest movement was lateral, ranging from -0,59 cm to 0,42 cm for a total of 1,01 cm.

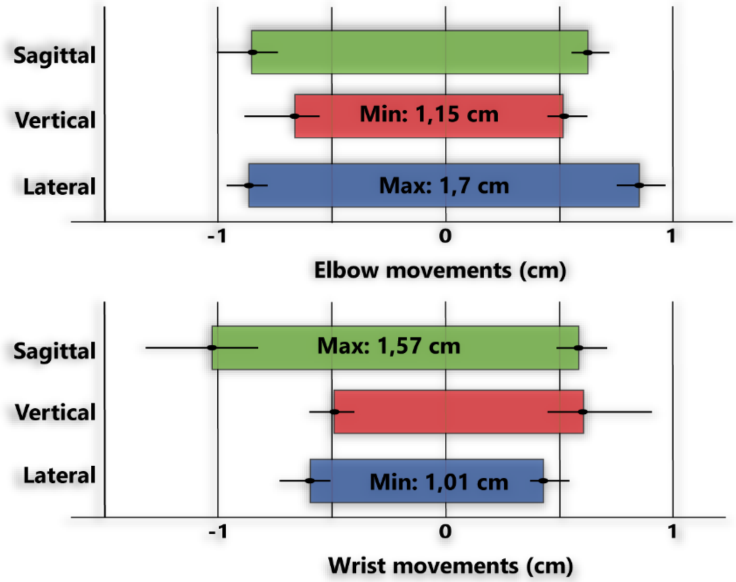


Figure 5.10: Elbow and Wrist movements

These results remain valid when we consider each *Pose* independently. Taking into consideration these findings, we can say that the forearm is sufficiently stable to be used as a support for tangible interactions in immersive systems.

### 5.4.2 Range of motion

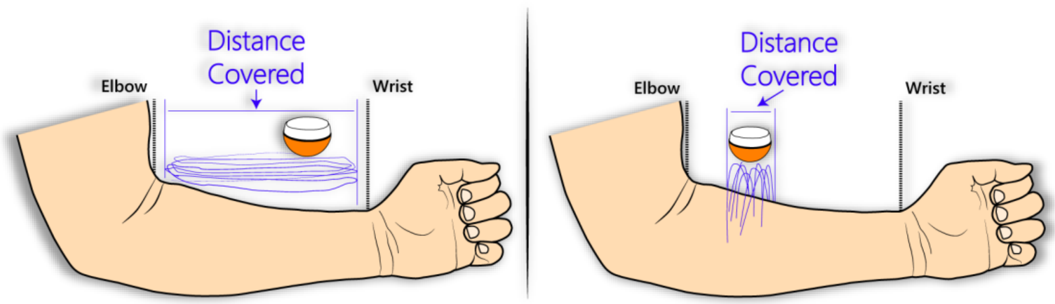


Figure 5.11: An example of distance covered for a group of gestures

The *Range of Motion* was measured by calculating the average distance covered by RPM for each group of 10 successive trials (Figure 5.11). It was computed for each pair of *Pose and Place of motion*. As the size of the forearm differs from one participant to another, we standardized the collected data.

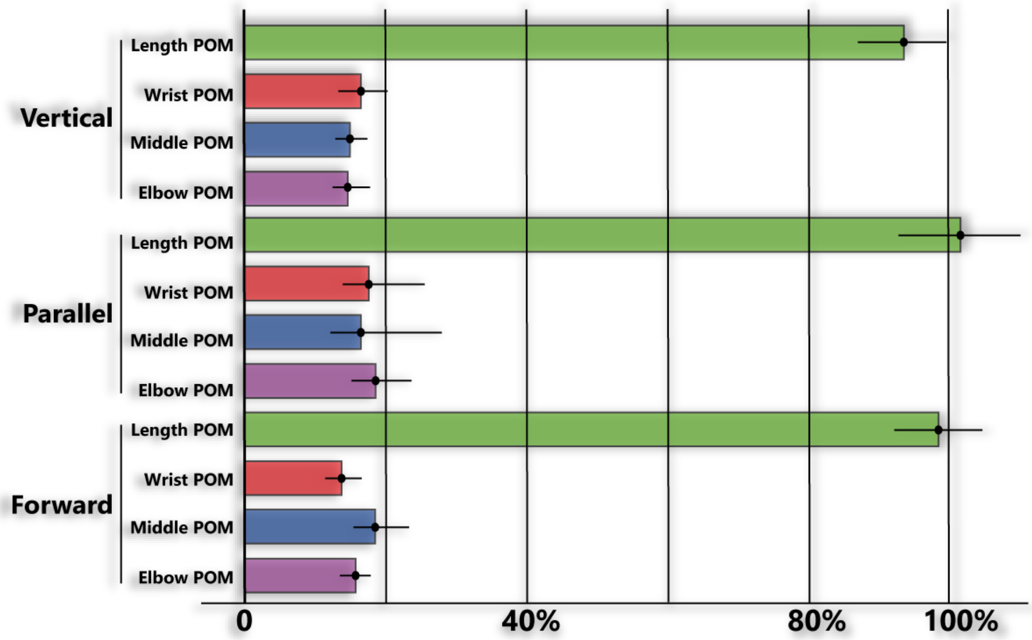


Figure 5.12: Mean distance covered by the RPM for each condition

### 5.4.3 *Range of motion* along the forearm

Participants exploited at least 93,6% of the forearm when performing translation on the Length POM. Overall, the translation distance ranged from 93,6% to 101,7% of the forearm (green bar Figure 5.12). However there were no significant differences between the poses. We observed that the translations performed in the Parallel pose extended to the hand, thus surpassing the wrist (explaining the values going above the 100%—wrist— mark on Figure 5.12).

### 5.4.4 *Range of motion* around the forearm

We also calculated the range of motion for translations performed around the forearm (width POM). We observed that for each width POM, the exploited surface of the forearm equaled 15,6% of the total length of the forearm on average. This value ranged from 13,8% for the *wrist POM* in the *Forward* pose to 21% for the *elbow POM* in the same pose. The largest exploited surface in the width POM is smaller than a third of the forearm. Theoretically, it is possible to consider using the three *width POM*. It should be noted, however, that these three regions of the forearm should be distinct, in other words, they should not overlap each other. Therefore we study the dispersion of these exploited surfaces in the next section.

### 5.4.5 Dispersion of the translations performed on the *width POM* on the forearm

This measure describes the distribution of the points of contact of RPM on the forearm (between the elbow and the wrist) for the complete experiment (i.e. 360 trials).

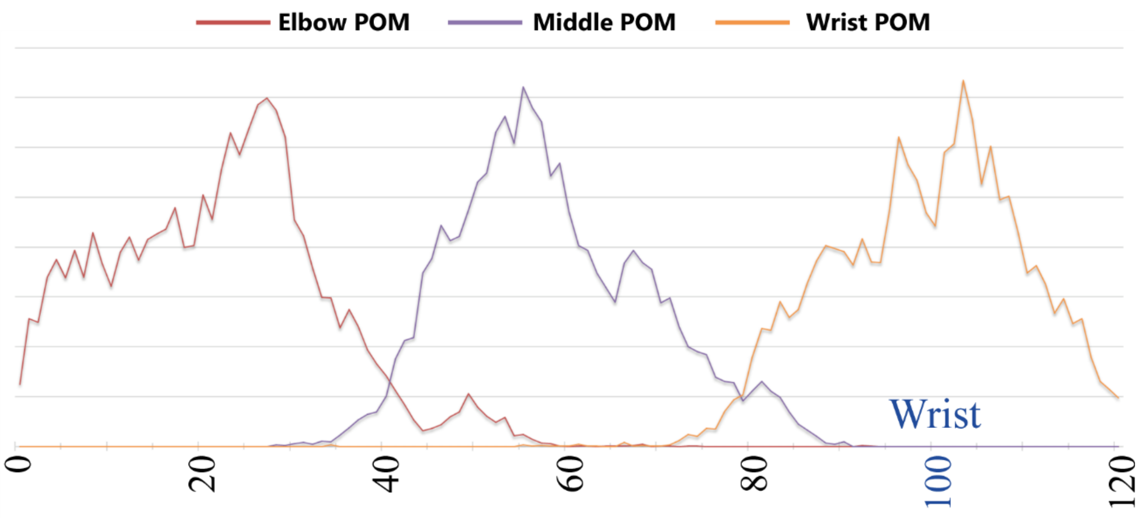


Figure 5.13: Dispersion of the translations performed on the width POM (0: Elbow position, 100: Wrist position)

The results show that there's a fairly large dispersion of the exploited surfaces (Figure 5.13). The surfaces exploited in the *elbow POM* and *Middle POM* overlap on the forearm subpart ranging from 30% to 60% (Figure 5.13); similarly, the surfaces exploited in the *Middle POM* and *Wrist POM* overlap on the forearm subpart ranging from 70% to 90%. However, it appears clearly that the translations performed on the *elbow POM* and *Wrist POM* were always done in distinct regions of the forearm throughout the experiment.

Finally, despite the clear instruction that required participants to perform translation from the elbow to the wrist, we can observe that a fair number of translations were performed beyond the wrist position (i.e. on the hand, above the 100% mark).

### 5.4.6 Width POM: Device Rolls

As the RPM device offers multiple degrees of freedom, namely: Translations, Rotations and Rolls, it was important to study the separability of these physical manipulations when used on the forearm. In the following, we will report on the involuntary Rolls of the device for each *POM* in each *Pose* when performing translations of RPM. The results are presented as averages accompanied by 95% confidence intervals.

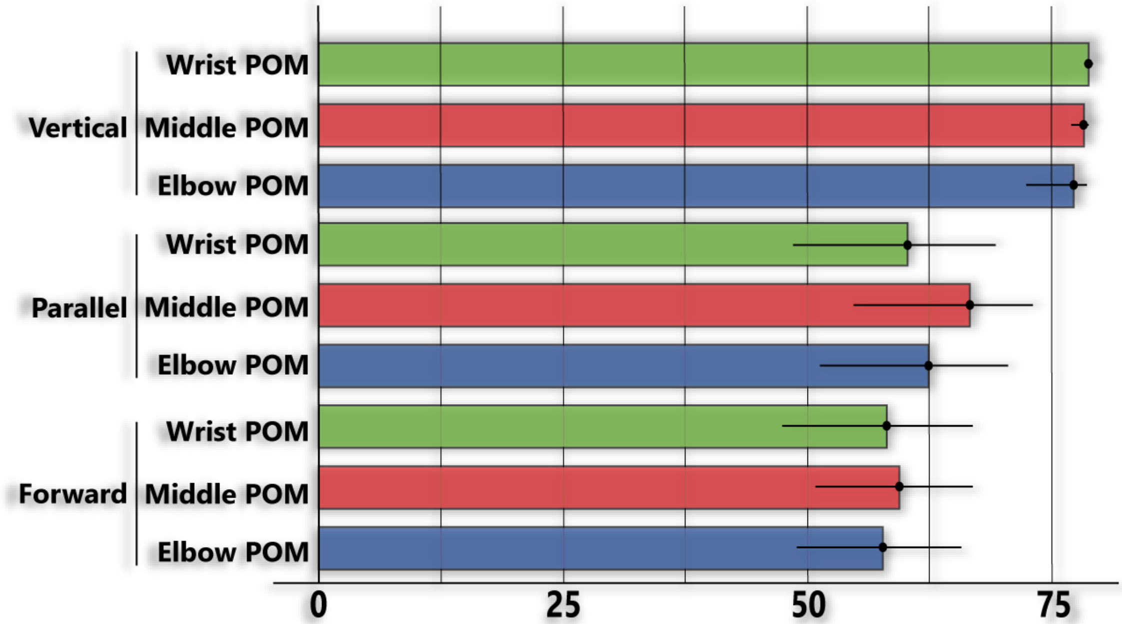


Figure 5.14: Device rolls when performing translation on the width POM (degrees)

Figure 5.14 shows that the translations performed in each one of the *Width POM* (performed around the forearm on its width) and in each *Pose* are systematically accompanied by a pronounced roll. The device is not maintained horizontally during translations.

The results show that the rolls were more conspicuous in the *Vertical* pose where the average roll was approximately ˜ 78°. This number decreases to about ˜ 62° on average fo the *Parallel* pose and ˜ 58° for the *Forward* pose. The results were constant for all *POM* (*Elbow POM, Middle POM, Wrist POM*).

### 5.4.7 Involuntary device rolls

We studied the amplitude of involuntary rolls produced while performing translations over the length of the forearm (i.e. on the *Length POM)*. This measure is calculated as follows: first, we collect the maximum and average degrees of roll observed for each trial. Then, we subtract the average roll of the device from the maximum roll observed. This gives us the maximum involuntary roll for the trial in question. The results are presented as averages accompanied by 95% confidence intervals.

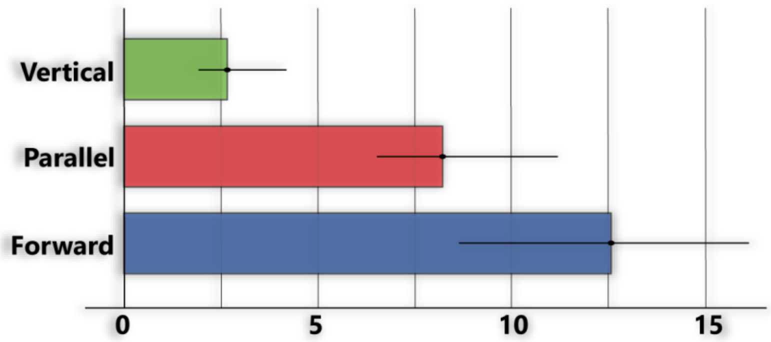


Figure 5.15: Device rolls when performing translation on the length POM (degrees)

Results show that on average, the involuntary roll did not exceed 13° for the *Forward* pose, 8,2° for the *Parallel* pose and 2,7° for the *Vertical* pose (Figure 5.15). The *Vertical* pose clearly triggers less involuntary rolls than the other poses. It also seems that the *Forward* pose is the most prone to unwanted rolls. These findings are in line with the results of the studies conducted on RPM: the involuntary rolls of RPM when performing translations were of 12° on average [140].

### 5.4.8 Fatigue

Fatigue was measured using a 6–20 Borg scale [32] (Table 5.1). The average Borg score obtained ranged from 'extremely light' for the Forward (8,63) and Parallel (8,79) pose to 'very light' for the Vertical pose (9,58) (Figure 5.16). The pose does not appear to affect the fatigue scores. Overall, participants did not consider the interaction with the device tiring, despite using the device for at least 25 minutes. It should also be noted that while participants had the opportunity to take breaks during the experiment between each group of 10 trials, only one participant asked for a break.

| Rating | Perceived Exertion |
| --- | --- |
| 6 | No exertion |
| 7 | Extremely light |
| 8 | |
| 9 | |
| 10 | |
| 11 | |
| 12 | |
| 13 | |
| 14 | |
| 15 | Hard |
| 16 | |
| 17 | Very Hard |
| 18 | |
| 19 | Extremely hard |
| 20 | Maximal exertion |

Table 5.1: Borg Scale

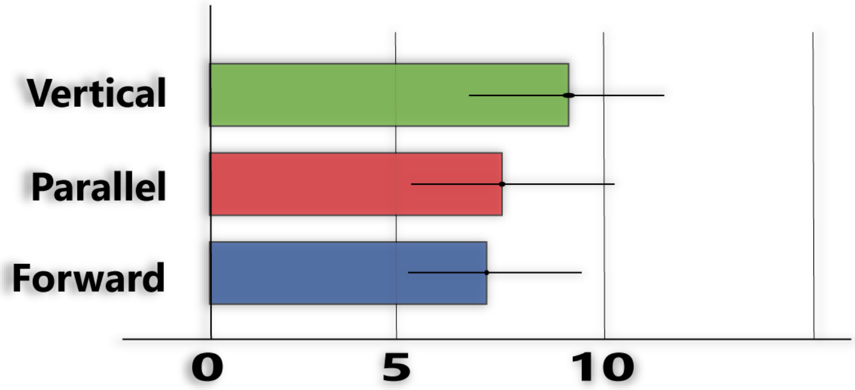


Figure 5.16: Fatigue

# 5.5 Discussion

The findings presented above consolidate our hypotheses that on-body tangible interaction is a promising approach for use in immersive visualizations.

## 5.5.1 Support stability

Elbow and wrist movements are minimal, making the forearm a steady and reliable support for interaction. For this reason, we believe that tangible interactions on the forearm could be performed without locating the position of the arm in real time: the pose could be deduced from the movement of RPM relative to the user.

### 5.5.2 Places of motion

The surfaces covered while performing translations around the forearm were small enough to consider three distinct regions of the forearm for interaction. However, the dispersion of these surfaces showed that they overlap, making it difficult to employ more than 2 distinct regions of the forearm in practice. However, we believe that with a visual feedback showing the position of each region on the forearm in the immersive environment, the three regions would be easily distinguishable. This hypothesis should be studied in a complementary study.

### 5.5.3 Other physical manipulations of RPM

The involuntary rolls observed during the translation of RPM in a *Length POM* were minimal and in line with the previous findings of Perelman et al. [140]. The rolls observed when translating RPM around the forearm seemed voluntary, since participants systematically tilted the device. These rolls go up to 78° regardless of the *Pose* or the *POM* on which the interaction was performed. It thus appears impossible to distinguish a translation around the forearm, from a roll or rotation. Consequently, these two physical manipulations cannot be performed for different tasks around the forearm.

### 5.5.4 Mapping between gestures and tasks

Overall, results show that the translations performed on the length POM were the most stable in terms of involuntary rotations and rolls in addition to offering the largest exploitable interaction surface. Therefore, these gestures can potentially be used to control a large set of values, to have a substantial precision or a greater data coverage. These gestures could be used for instance to manipulate slider type controllers that require a certain degree of precision depending on the manipulated data. The translations performed in the Width POM seem to be better adapted to controllers that do not require a large amplitude given the limited interaction surface they allow. We believe that they could be mapped to " Rate control" type controllers for example. They could also be used to control a menu with a limited number of sub-items or to activate toggle menus (two modes, discrete two-state tasks). In the following section, we describe two usage scenarios that illustrate a possible and concrete use of on-body tangible interactions.

# 5.6 Usage Scenarios

Taking into consideration our findings, we will illustrate a detailed use of the On-body tangible interaction approach presented in this chapter, through two concrete scenarios: 1) an interior design scenario where we show a possible use of the approach to manipulate simple 3D objects; 2) a more elaborated scenario detailing a possible use of on-body tangible interactions to interact with multidimensional data.

## 5.6.1 Interior design

Jeremy is an interior designer. He rethinks the interior of his clients' homes to make them more functional and pleasant by choosing the appropriate furniture. To this end, Jeremy visualizes the furniture in the final space using a mixed reality headset (Hololens). He manipulates RPM on the body to move, rotate and scale the virtual furniture.

To move the furniture, Jeremy uses RPM on the *Length POM* on the forearm. He puts his forearm on the pose representing the movement to be made and adjusts the position of the piece of furniture by performing translations of RPM over the length of his forearm. For example, if he wants to bring the furniture closer to him, he places his forearm in the pose *Forward* and performs translations of RPM over the length of his forearm, from the wrist to his elbow, whereas the *Parallel* pose allows him to move the piece of furniture to the right/left. The Vertical pose allows him to adjust the height of a photo frame or a mirror for example.

Jeremy can also rotate furniture using the same principle as for translations. He puts his forearm in the pose representing the axis in which to make the rotations and perform translations around the forearm, on the *Width POM*, according to the direction of the rotation to make.

## 5.6.2 Data exploration

Emily is an air traffic controller. Part of her work consists of improving traffic management in the control tower [90] (analyzing past conflicts, improving the ecological footprint, increasing the profit by improving the trajectories of aircraft…). To this end, Emily must analyze large quantities of aircraft data (time, position, altitude, speed…) on a regular basis [90] The manipulated data represents complete aircraft journeys, from takeoffs to landings, containing multiple dimensions. Visualizing this data in an immersive context helps Emily having an optimal understanding of it. Indeed, by anchoring the volume of data to a wall for example, she can move around it and analyze it from different angles. She can have an overview of the data by moving away from it, or a more detailed view by getting closer. For instance, when Emily, facing the wall, observes a high concentration of points, she knows it probably represents an airport. A side view of data allows her to observe the most used altitudes by the aircraft. Standing with her back to the wall and looking at the data, Emily can observe the main airways.

Emily uses a mixed reality headset (Hololens) to visualize the data and our device (RPM) to interact with it. The tasks Emily performs on the data are [54, 90] selecting data using range-sliders; applying a command on the selected data (e.g. data subsampling); changing colors; scaling, etc. Emily has configured her system so that each pose of the forearm represents a coordinate in the immersive visualization: the latitude is represented by the *Forward* pose, the longitude by the *Parallel* pose and the altitude by the *Vertical* pose.

Range sliders are controllers that allow the user to select values included in a range (an interval). The range sliders are composed of two cursors, one defines the minimum value and the second defines the maximum value. To control the range slider and select data, Emily uses translation over the length of the forearm (on the *Length POM*). The cursor to manipulate is automatically selected according to the starting position of RPM on the forearm: if RPM is placed on the *Wrist POM*, the cursor defining the maximum value is manipulated; if RPM is placed on the *Elbow POM*, the cursor defining the minimum value is manipulated; and finally, if RPM is placed in the *Middle POM* of the forearm, the two cursors are moved simultaneously while maintaining the range length initially defined.

## 5.7 Perspectives

The next step in this work will consist in conducting studies to validate the accuracy and usability of the physical manipulations for basic tasks, like controlling a slider. Due to its complexity, the study described in this chapter was limited to translations. A short-term perspective would be to study the other physical manipulations offered by the device. A first conclusion regarding rolls and rotations can be deduced from our experiment: it is impossible to distinguish translations from rolls when performing translation around the forearm (*Width POM*). This also closes the door to the exploitation of combined physical manipulation (simultaneous rolls and translations) in the *Width POM* (i.e. translations around the forearm). However, this is not the case for translations performed on the length of the forearm thanks to the minimal involuntary rolls observed in this POM. Therefore, we can explore potential usages of the approach that would exploit the combined physical manipulations of the device.

## 5.8 Conclusion

In this chapter, we proposed, described and studied a new paradigm for interaction with immersive visualization: On-Body tangible interactions. This approach is based on the use of the forearm as a physical support for tangible interactions using a device with multiple degrees of freedom. It takes advantage of the body's natural capacity to sense its own body parts (proprioception) to allow the user to perform tangible interactions on the body, without having to switch his attention from the data and minimizing the fatigue.

We proposed a design space for the support of interaction. It describes the Pose (*Forward*, *Parallel*, *Vertical*) in which the interaction is performed, the Place of Motion (*Length POM, Width POM: Elbow POM, Middle POM, Wrist POM*) of the interaction and the range of motion of the interaction. To explore the feasibility of such an approach, we conducted a study with the following objectives: studying the stability of the forearm as a support for tangible interaction; studying the stability of the RPM mouse; measuring the Range of motion of translation in each (*Pose, Place of Motion*) couple; identifying the regions of the forearm on which translations can be performed distinctly; measuring the fatigue relative to this type of manipulations.

The results showed that on-body tangible interactions are a promising approach to interact with immersive visualizations since the interaction support (forearm) is stable and can support a tangible interactions appropriately. The device we used (RPM) offers enough degrees of freedom, precision and is stable enough to be used in an immersive context. With an adequate visual feedback, the user could benefit from 3 regions for interaction around the forearm. The study also showed that users found the approach comfortable.

Finally, we illustrated the possible usages of this approach through two concrete usage scenarios: the first scenario describes interaction with fairly simple 3D objects, while the second explores a more elaborated interaction with multidimensional data.

# The neOCampus Project

A smart, innovative and durable campus

# 6 The neOCampus project

## 6.1 Introduction

This thesis is part of the neOCampus project, an initiative of the University of Toulouse, launched in June 2013 in a bid to create an innovative and smart campus. The objectives of the project are three-fold: 1) to improve the daily comfort of the university students and personnel; 2) to decrease the ecological footprint of its buildings; 3) to reduce its operating costs (fluid, water, electricity…). To attain its objectives, the neOCampus project relies on repurposing the large number of connected devices available on the university campus and completing this net of connected devices with eco-friendly connected sensors, to better gather and exploit data.Similar to a small city with its 407 000m$^2$ of built-up areas, 70 research structures, several solutions of mobility and in excess of 39000 employees and students, improving the quality of life inside the University of Toulouse's campus can be equally challenging [69]:

- The heterogenous devices and sensors composing the campus and designed to observe specific features result in large volumes of heterogenous data, that require the creation of new tools and norms to explore and manage them.
- The non-linearity of the campus where a small change in the input may result in big output changes make them difficult to control and predict.
- The openness of such systems, where sensors and devices can be easily added or removed is a key component in making the system sustainable and needs to be facilitated.
- The spatial distribution of the campus's entities may require new types of communication technologies and infrastructure and may even change the way systems are developed for this platform.
- The large-scale collection of data in such a large campus may introduce privacy issues and require the design of new development methodologies taking into consideration privacy when designing IT applications.

The challenges are numerous and require a wide range of skills to be addressed. To reach its objectives and address those challenges, the neOCampus project favoured a multidisciplinary approach which comes from the 11 laboratories participating to the project and the different fields that they cover (a detailed listing of the participating laboratories can be found here[28]). Each laboratory brings its own scientific expertise, thus, transforming the university into a platform for innovative experiments performed at large scale and in vivo (with real end users, in real situations).

### HCI axis of the neOCampus project

As one of the participating partners and an HCI oriented research team, the Elipse research group[29] focuses on the challenges related to the exploration of the complex data provided by the numerous sensors and devices distributed over the campus. It aims to design and evaluate novel interaction solutions to visualize and interact with these data. The possible usages of these solutions include, but is not limited to:

- To review or monitor energy consumption data in real time or deferred at various scales (building, room, sensor…).
- To pilot a simulator at campus scale that would include: energy consumption data, weather data, crowd behaviour, etc.
- To offer intelligent solutions to remotely control heating systems, sunblinds, lights, etc.

However, designing interactive solutions for such a diverse context is not straightforward. The campus provides different types of data that can be exploited by several profiles of users and in different ways, some may just want to visualize data while others would want to extract meaning from it. An important part of designing these interactive solutions consists in identifying the potential users of the solution, their needs as well as the manipulated data.

[28] https://www.irit.fr/neocampus/

[29] Elipse is an interdisciplinary research group (computer scientist, neuroscientist, HCI specialist) focusing on Advanced forms of Interactive Techniques as research tool and research object.

https://www.irit.fr/-Equipe-ELIPSE-

In this chapter, we will detail a description space built to illustrate the different aspects of data exploration in the neOCampus context, we demonstrate its use through a set of interactive situations and we discuss our contributions in relation to it.

## 6.2 Description space

To go beyond the simple design of ad hoc interactive solutions on the campus, we built a description space that identifies and organizes the relevant characteristics to consider when designing these solutions.

In this section, we will present the description space's dimensions and illustrate them through a set of interactive situations related to the neOCampus context.

This categorization is the result of a collaboration with the 11 laboratories participating to the project and several in-situ observations. It has been validated by the steering committee of the project and **was one of the** deliverables of an ANR[30] project[31] (project link).

### 6.2.1 Dimensions

#### 6.2.1.1. Users

The user dimension is a classic HCI criteria, when designing an HCI system, it is important to focus on the potential users of the system and the way each category of users is going to use it. We classify the users in three categories:

**Casual**

The *Casual* category includes all users that will use the system occasionally. In the context of the neOCampus project, it could translate into visiting researchers, decision makers, visiting elected officials, etc.

[30] http://www.agence-nationale-recherche.fr/

[31] http://www.agence-nationale-recherche.fr/Project-ANR-15-CE23-0001

#### Regular

The *Regular* category includes users that will use the system in a regular fashion without it being their daily work tool. In the context of the neOCampus project, it could translate to students, university staff, faculty members, etc.

#### Frequent

The *Frequent* category includes users for whom the system is a daily working tool. In the context of the neOCampus project, it could translate to the local maintenance staff like plumbers, heating specialists, electricians, etc.

### 6.2.1.2. Services provided

We identified four types of services the system can provide:

#### Visualization

A *Visualization* service offers the user the necessary tools to view data (energy consumption, affluence, temperature, etc).

#### Comprehension

A *Comprehension* service enables the users to understand and analyze data. An example would be diagnosing an electricity overconsumption using energy consumption data.

#### Production

A *Production* service supports the user in producing something to enrich the data. An example would be an electrician generating an intervention roadmap from building locations data and a list of interventions.

#### Collaboration

A *Collaboration* service allows a group of users to aggregate, inform and create knowledge from their collaboration.

### 6.2.1.3. Data exploited

We identified four types of data that can be manipulated:

### Raw data

It represents the data as collected from the sources, unmodified. An example would be energy consumption data: water, electricity, gas, etc.

### Activity data

It represents the data inherent to the activity. An example would be the post-processed energy data used to diagnose an electricity overconsumption.

### Incident data

It represents the data related to an improper execution of an activity which may generate an alert or a blockage that may use or generate specific data. An example would be the data related to a heating problem, a network issue or a power failure.

### Ambient data

It represents the data characterizing the environment in which the activity takes place. It may refer to the data related to the interior and exterior environment of the campus: temperature, weather, affluence, CO2 consumption, confort level, diversity of flora and fauna of the local ecosystem, etc.

## 6.2.1.4. Deployment context

We identified two possible deployment contexts:

### Open-access system

*Open-access* systems are usually available in public places. They are accessible to the general public. The interaction ressources in those systems are usually scalable. Their numbers and types vary depending on: the interaction devices used by the users interacting with the system (Smartphones, tablets, wearables, etc); the interaction space already available (large displays, interactive tabletops, etc).

### Dedicated-access system

*Dedicated access* systems are usually available in a fixed context like an office or a control room. In those systems, the interaction ressources are stable, predefined and always available.

### 6.2.2 Diagram representation

The dimensions described above are summarized in the following diagram (Figure 6.1):

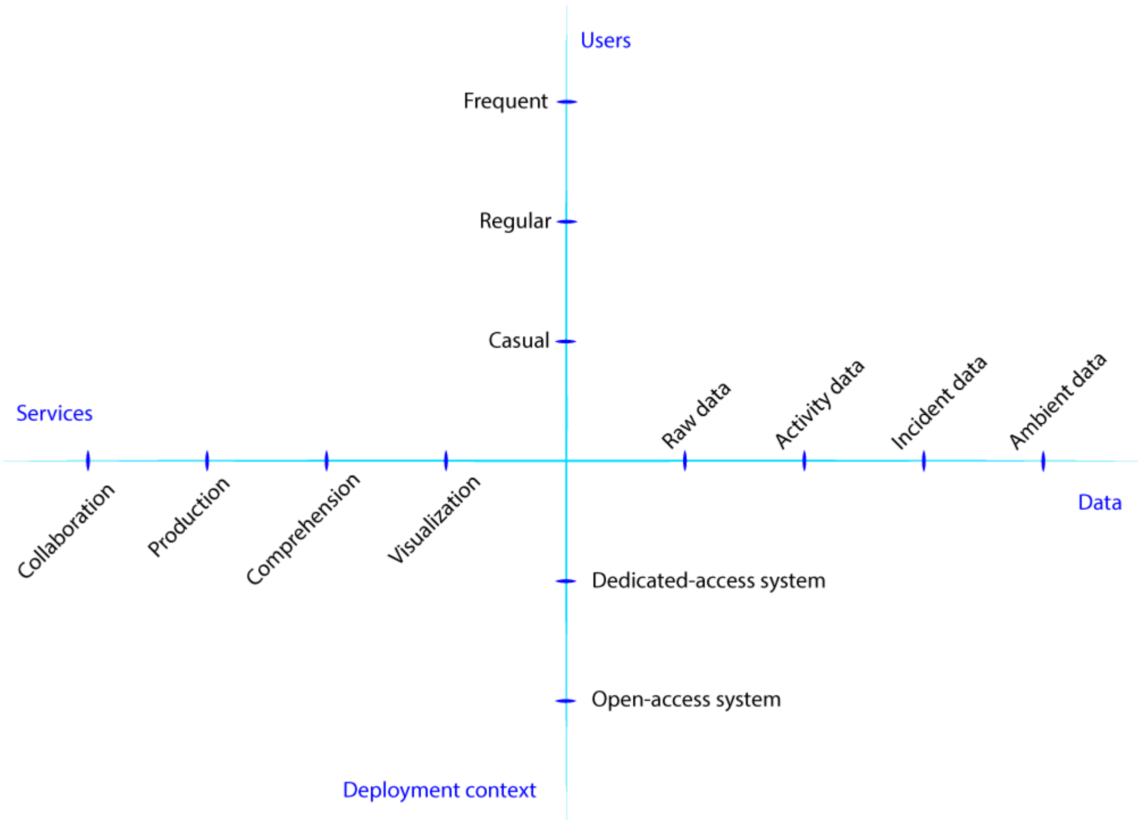


Figure 6.1: Description space

### 6.2.3 Illustration of the description space

In this subsection, we will describe three interactive situations in the context of the neOCampus project. They represent situations of interest to us and illustrate the different aspects of data exploration identified in the description space.

As the sole aim of these scenarios is to illustrate the description space defined previously, no interactive solution is going to be proposed to address them in this section.

#### 6.2.3.1. Scenario A: energy consumption visualization

##### Description

In the course of the promotion of the neOCampus project, its steering committee invites an elected official of the city to visit the campus of the University of Toulouse and to attend a demonstration of the project (Figure 6.2).

An interactive demonstration is prepared: it allows the visualization of different data provided by the numerous sensors installed on the campus (water, electricity, gas, temperature, weather, affluence, CO2 consumption…).

The setup of the demonstration contains two displays: a tabletop containing the 2D map of the university and a second display showing complementary information.

On the day of the demonstration, the elected official is received by a representative of the Department of Heritage and Logistics of the University of Toulouse.

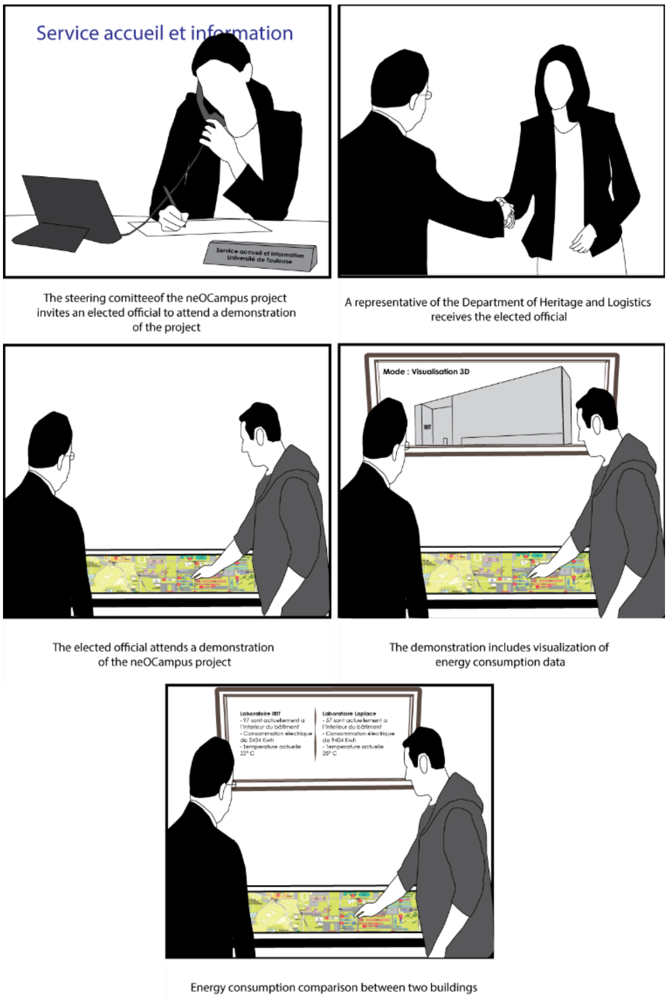


Figure 6.2: Scenario A, energy consumption visualization.

### Characterization

**User(s):** The elected official is a *Casual* type of users as he never used the system before.

**Service(s) used:** The system is used to visualize data and compare the data provided by several buildings. The service provided by the system is a *Visualization* service.

**Exploited data:** Two types of data are manipulated in this interactive situation: *Raw* in electricity, water and gas; *Ambient* in temperature, affluence, CO2 consumption.

**Deployment context:** As the demonstration and the data provided are public, the system used in this interactive situation is an *Open-access* one.

**Description diagram:** The characterization translates to the following description diagram (Figure 6.3):

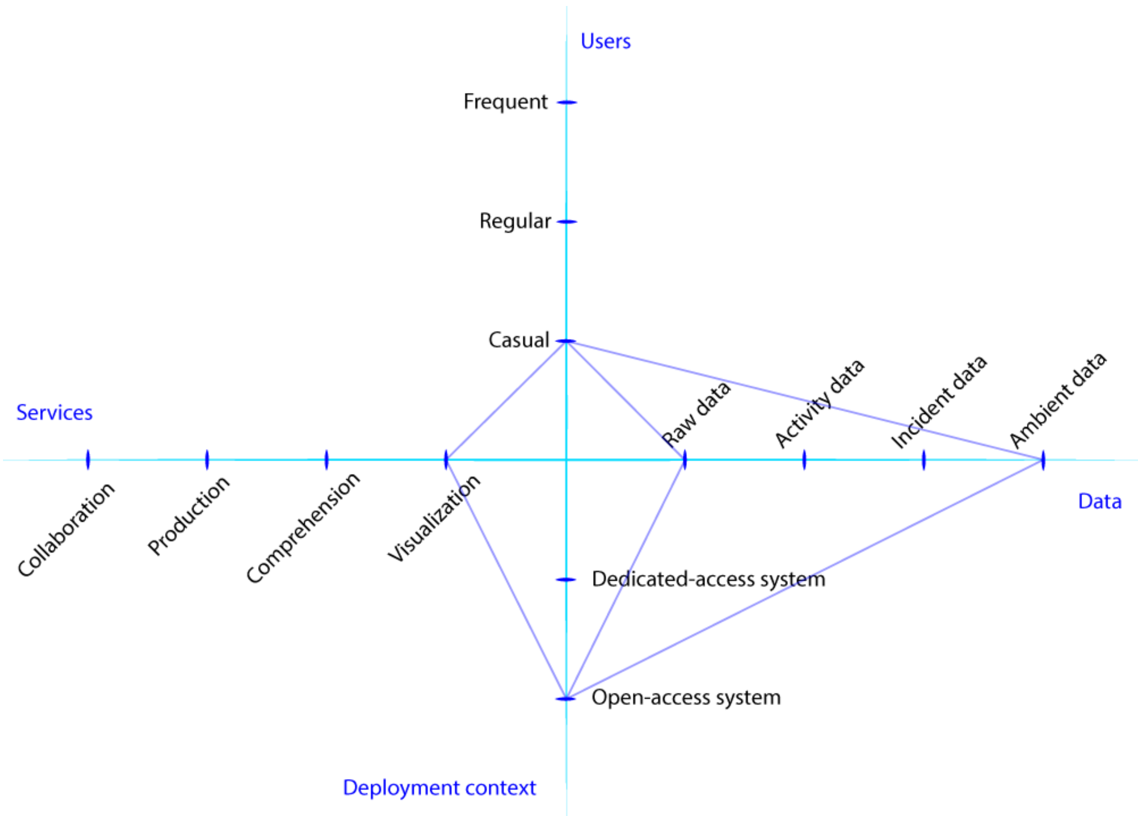


Figure 6.3: Description diagram of scenario A

#### 6.2.3.2. Scenario B: distant collaboration

##### Description

A lecturer arrives at his conference room and finds that it is already taken. He contacts the local logistics service (LS). The service deals with requests related to reservations of conference rooms (Figure 6.4).

The logistics service (LS) uses the interactive system to find a conference room that is heated and contains the required equipment for the lecture to take place. To accomplish this task, the LS checks the teaching schedule, the available conference rooms and the equipment list of each conference room. The LS can guide the lecturer to his new conference room if necessary.

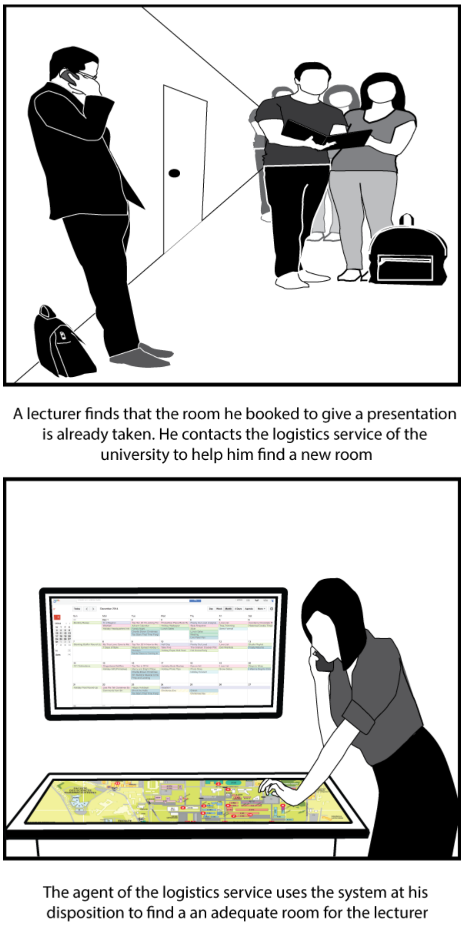


Figure 6.4: Scenario B, distant collaboration

### Characterization

**User(s):** the LS agent uses the system daily as his principal work tool. In this situation, the user is a *Frequent* user.

**Service(s) used:** To accomplish his task, the LS agent visualizes different types of data. The service provided by the system in this situation is a *Visualization* service.

**Exploited data:** the LS agent uses data relative to his activity to find a suitable conference room for the lecturer.

**Deployment context:** the system is not available to the public and is dedicated to the work of the LS agent. It is a *Dedicated-access* one.

**Description diagram:** The characterization translates to the following description diagram (Figure 6.5):

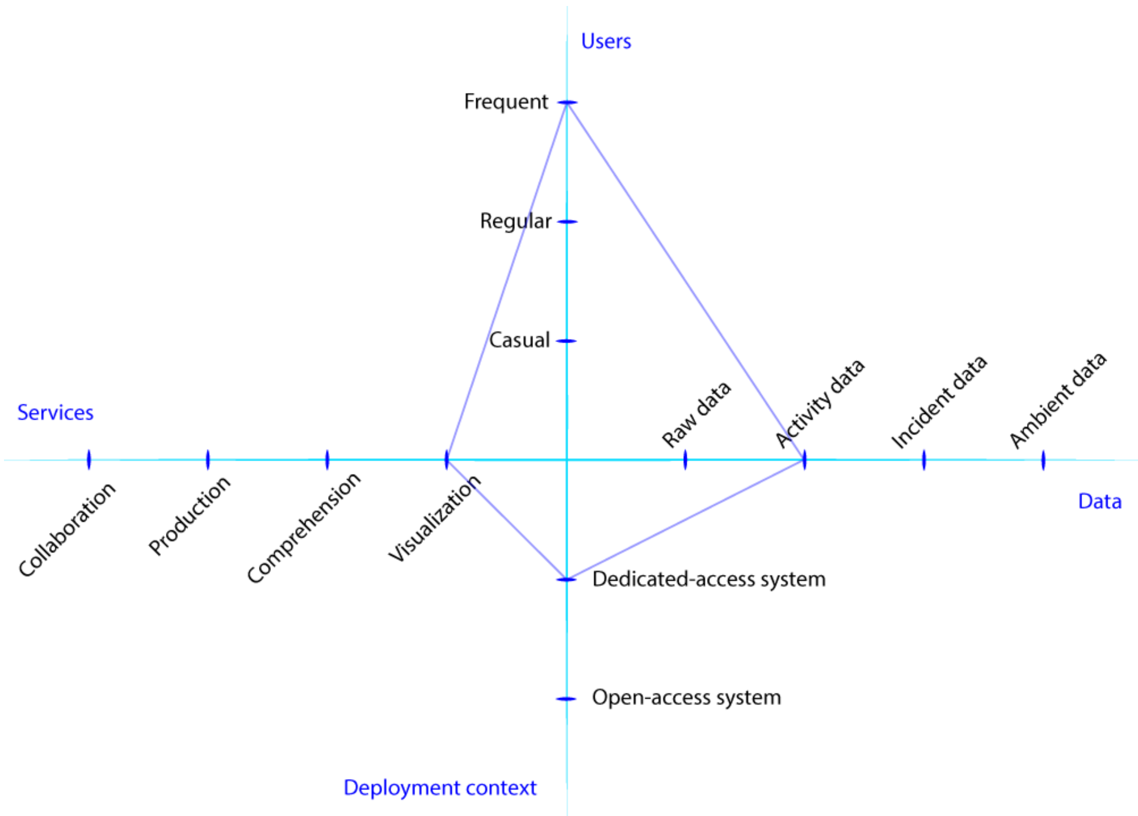


Figure 6.5: Description diagram of scenario B

#### 6.2.3.3. Scenario C: Itinerary Creation

##### Description

Failures on several locations in the electrical network of the campus are reported to the assets and logistics service (ALS) of the University of Toulouse. The service is responsible for the safeguarding of assets and logistical support which includes electrical maintenance works. To address the reported failures, the ALS has two options:

**Scenario C1:** request the intervention of the local maintenance group which sends one of its electricians to intervene on the failures on-site (Figure 6.6). Before intervening, the electrician diagnoses the issues and identify the probable nature of the faults using the energy consumption data. Then, he generates an intervention itinerary containing the location of each failure and the electrical equipment installed in each of these locations.

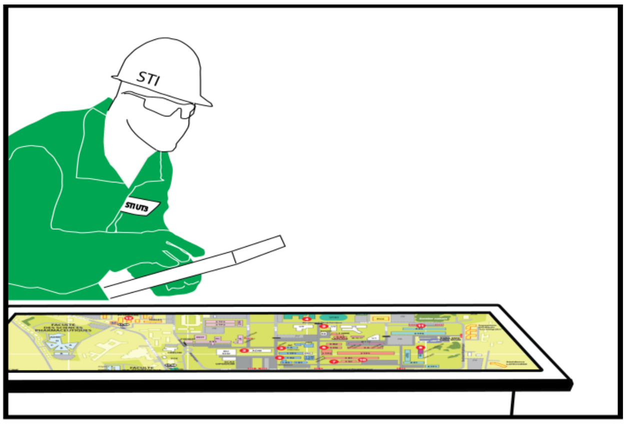


Figure 6.6: the local electrician is diagnosing the failures and preparing his intervention plan

**Scenario C2:** If the local maintenance group is unable to intervene, the Construction and Study Department is contacted (CSD). This service deals with requests related to mandating external companies for services on the university campus. In this case, the service relates to intervening on the electrical failures described previously. Two possible sub-scenarios arise:

- **Scenario C21:** The external company is assisted by the CSD. The CSD completes the external company's electrical expertise with its campus expertise and helps it generate an intervention roadmap (Figure 6.7).

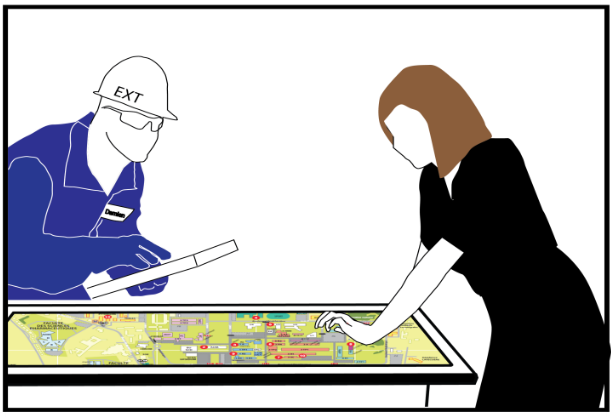


Figure 6.7: the CSD and the external electrician collaborating to diagnose the failures and prepare an intervention plan

- **Scenario C22:** The external company intervenes by itself, without the assistance of the CSD (Figure 6.8). In this case, the company's electrician uses the system to consult the history of failures, the location of the failures, the equipment installed in each one of these locations and the current energy consumption data. Then, he generates an intervention roadmap.

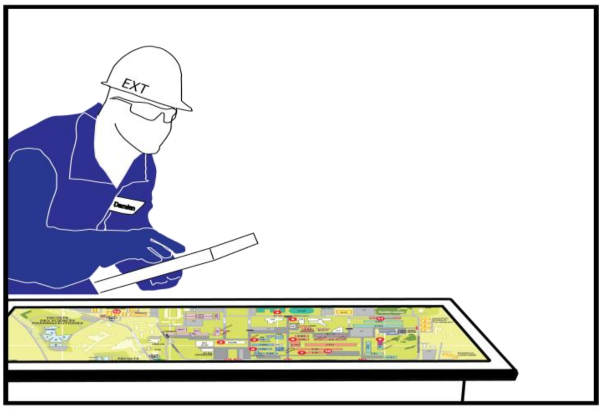


Figure 6.8: the external electrician is diagnosing the failures and preparing his intervention plan without the assistance of the CSD

## Characterization

**User(s):** In scenario C1, in which the local maintenance group intervenes, the electrician uses the system as a daily work tool which makes him a *Frequent* user.

In scenario C21 and C22, the electrician sent by the external company uses the system from time to time making him a *Casual* user. While it is not his daily work tool, the CSD agent uses the system regularly. He is a *Regular* user of the system.

**Service(s) used:** The system allows the users to visualize data (*Visualization*), supports them in the diagnosis of the failures (*Comprehension*) and the joint (*Collaboration*) generation of an intervention itinerary (*Production*).

**Exploited data:** In the two interactive situations, the users manipulate *Incident* data (history of failures), *Ambient* data (locations of the equipment concerned by the failure), *Raw* data (energy consumption data).

**Deployment context:** The access to such a system is not available to the general public. It is a work tool dedicated to the users described above.

**Description diagram:**

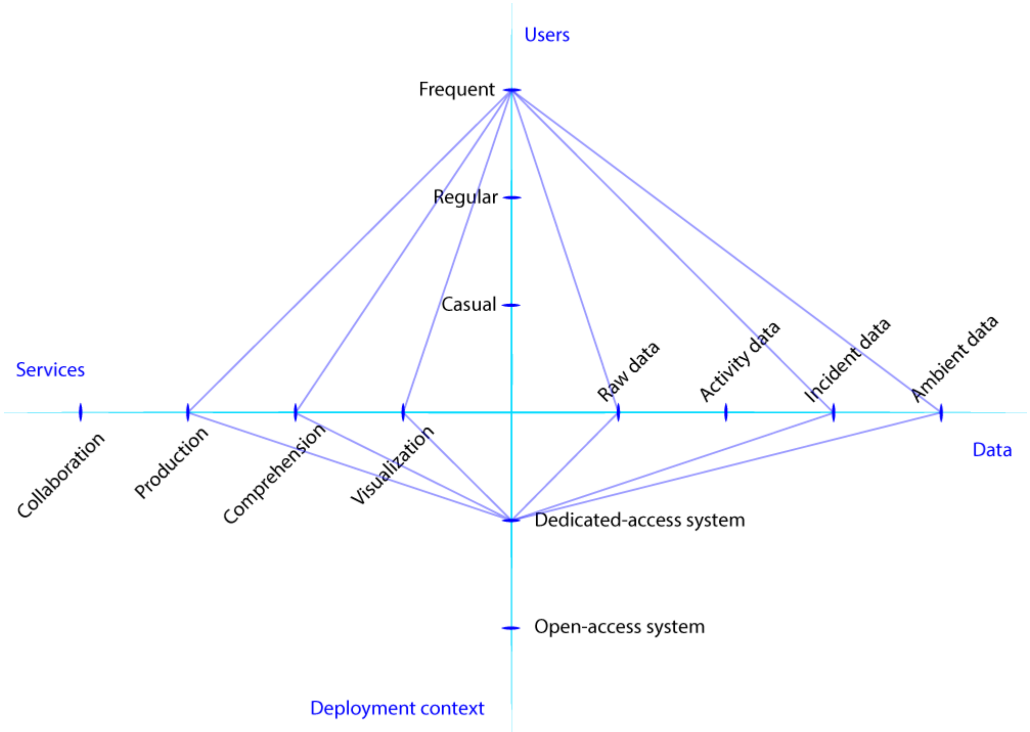


Figure 6.9: Description diagram of scenario C1

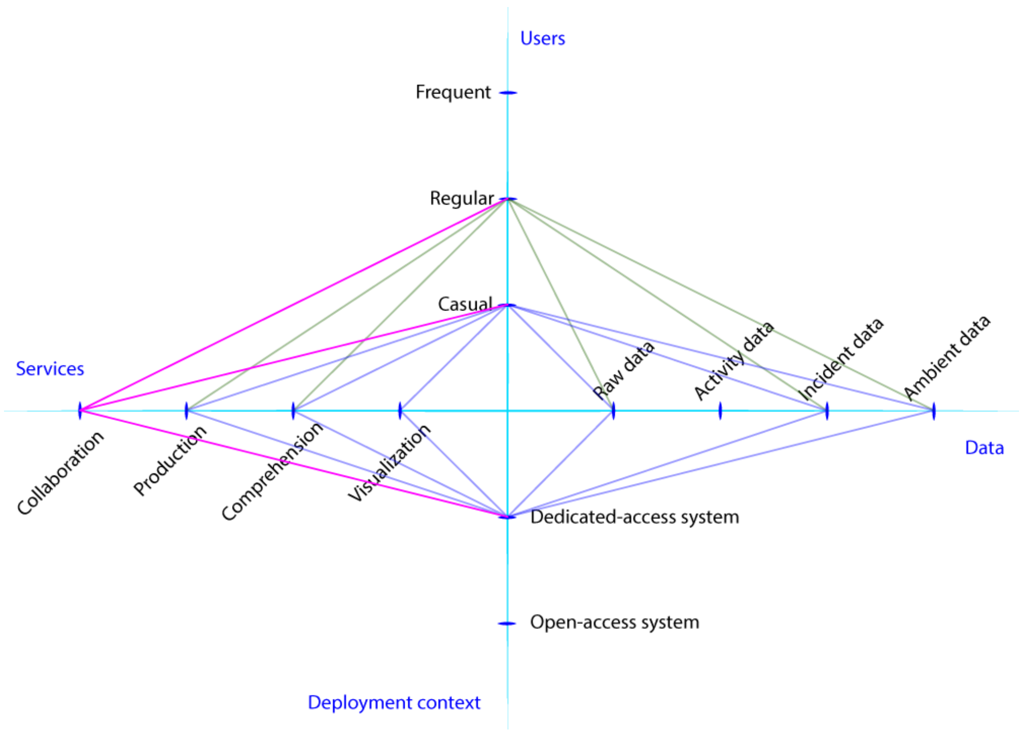


Figure 6.10: Description diagram of scenario C21

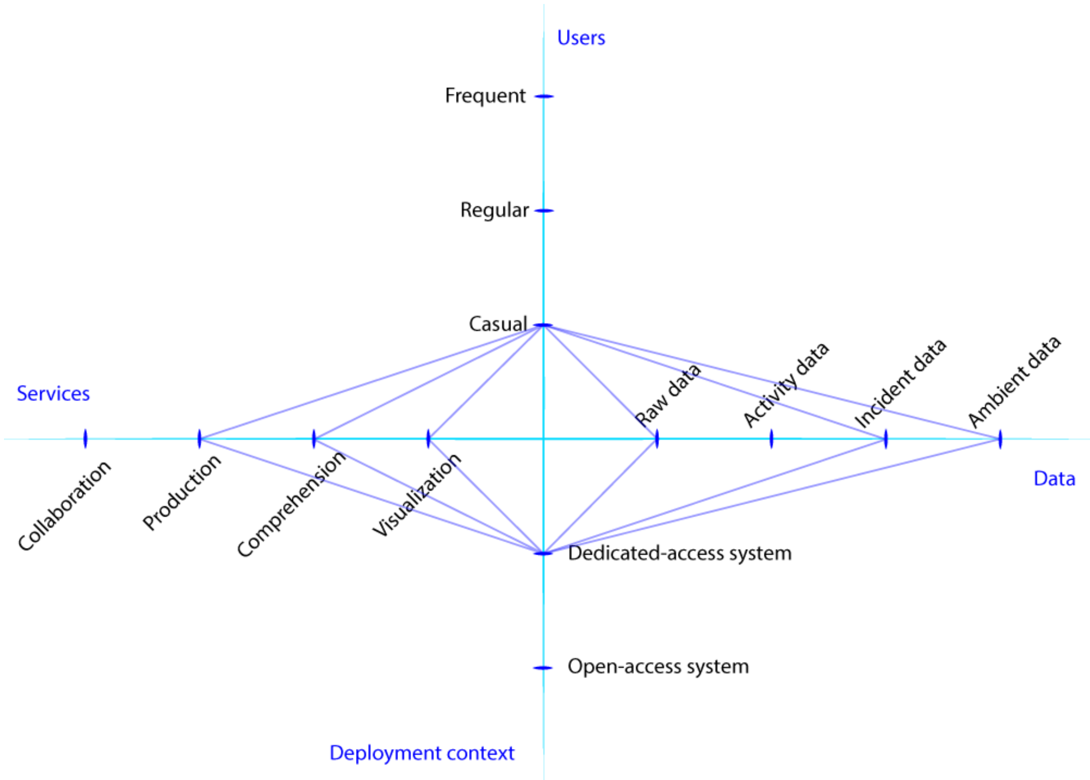


Figure 6.11: Description diagram of scenario C22

This categorization could be used to identify recommendations for the design of interaction techniques for each value and/or dimension of the description space. Moreover, it can be used to consider possible improvements to current interaction techniques over one of the axes like adding a new service, widening the type of data that can be manipulated through it or adapting it to a public usage.

# 6.3 Translating contributions into concrete usages

This section will discuss the contributions proposed in this thesis in relation to the description space introduced previously. Each subsection will focus on one interaction solution and will detail which values of each dimension the interaction solution could cover. That is to say, identify:

- The profile of users it could attend to.
- The types of data it could manipulate.
- The type of service it could provide.
- The type of system it would be suited to.

At the end of each discussion, a concrete example of each solution applied to the neOCampus project will be presented if applicable. Otherwise, a scenario highlighting its potential use will be described.

## 6.3.1 Split-focus: interaction in large displays

### 6.3.1.1. Discussion

The split-focus visualization (Chapter 3) and interaction solution is easy to understand and to use. It does not require training nor an adaptation period which makes it suitable for **all profiles** of users.

In its current version, split-focus does not offer a solution to visualize raw data directly and is used instead to show graphical representations of data similar to the molecular interaction maps described in Chapter 3, 3.1.

Split-focus allows the user to **visualize** and interact with data to better **understand** it. Split-focus was not evaluated nor designed to produce something or to support collaboration.

Although it helps with data visualization thanks to the overview + detail multi-display paradigm it is based on, the interaction solution was designed to address a specific problem: interaction with multiple regions of interest of the same visualization simultaneously. Today, this problem is more pertinent for a professional exploration of data which takes place mainly in a **dedicated-access** system.

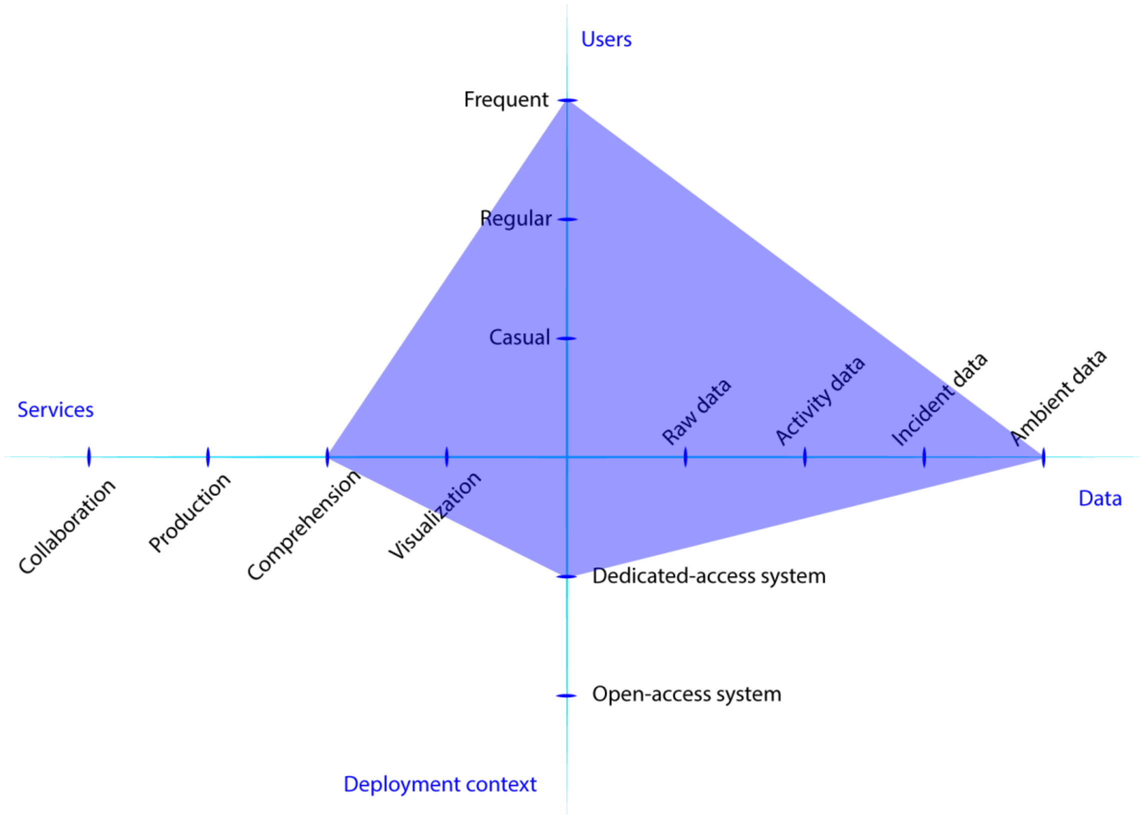


Figure 6.12: Description diagram of the values overed by split-focus

#### 6.3.1.2. Concrete application of split-focus in the neOCampus project

Split-focus (chapter 3) could be used in scenario A. In this scenario, the university receives an elected official from the city. In its bid to promote the project and get more funding from the city council, the university prepared an interactive demonstration of the project. The demonstration includes the real time monitoring of energy consumption data, comparison between the consumption data of multiple buildings.

While the interaction solution has been designed for an MDE composed of a large screen and a tablet, it can be adapted to any combination of displays provided that one of them offers enough screen real estate to display the large overview (map).

We implemented an application using the split-focus approach for a concrete usage in Figure 6.13. A video demonstrating it can be found here[32].


Figure 6.13: A concrete implementation of the split-focus solution in the neOCampus project (2 detailed views configuration)

The implemented solution offers the following:

- The exploration of the map using up to 4 detailed views.
- A circular menu allowing the user to switch between the views and perform additional actions.
- A quick way to translate views from one region to the other: the translation view described in Chapter 3, 3.2.2.3.

[32] https://www.youtube.com/watch?v=E1HxtnfzPB0

- The visualization of energy consumption data: the data is displayed in the colored part at the top of each detailed view. The displayed data is updated when the view is translated.
- The possibility to switch between numerous energy consumption data: water, electricity, gas, etc. Switching between the data displayed is done by performing swipe gestures on the colored part of the detailed view.
- The possibility to keep the views coherent, by locking them in a specific region of the overview.
- The possibility to show different types of data for the same building by linking the translations of two detailed views.
- The possibility to compare energy consumption data for up to 4 regions of the map.

In its actual version, the split-view interface supports visualization and comprehension of data. It can easily be adapted to support the user in producing something from the visualized data by introducing new functions through menus or multitouch gestures.

### 6.3.2 TDome: A multiple degrees of freedom device to interact with multi-display environments

#### 6.3.2.1. Discussion

TDome (Chapter 4) was designed to improve interaction in working multi-display environments. It is most probably a daily working tool that involves **frequent** users. The type of data exploited depends on the task at hand. With its large interaction vocabulary, TDome could be adapted to support numerous tasks. Multi-display environments in a work context are usually **dedicated-access** systems.

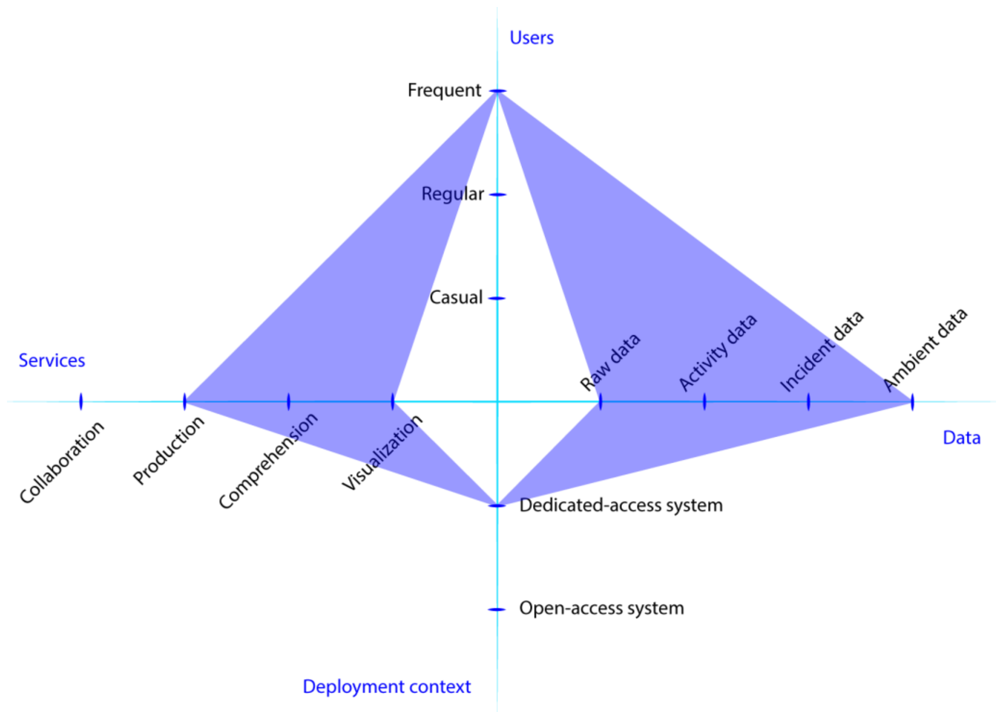


Figure 6.14: Description diagram of the values overed by TDome

#### 6.3.2.2. Concrete use of TDome in the neOCampus project

TDome can be used in scenario B in which the user (LS Agent) interacts with a multi-display environment (MDE) to find a suitable room for a lecture.

The configuration of the working MDE is as follows (Figure 6.15):

- An interactive tabletop displaying a map highlighting the buildings, classrooms, conference rooms.
- A screen displaying the information related to each room's equipment and ambient data (temperature, affluence, etc).
- A third display showing the teaching/lectures schedule and the available rooms.

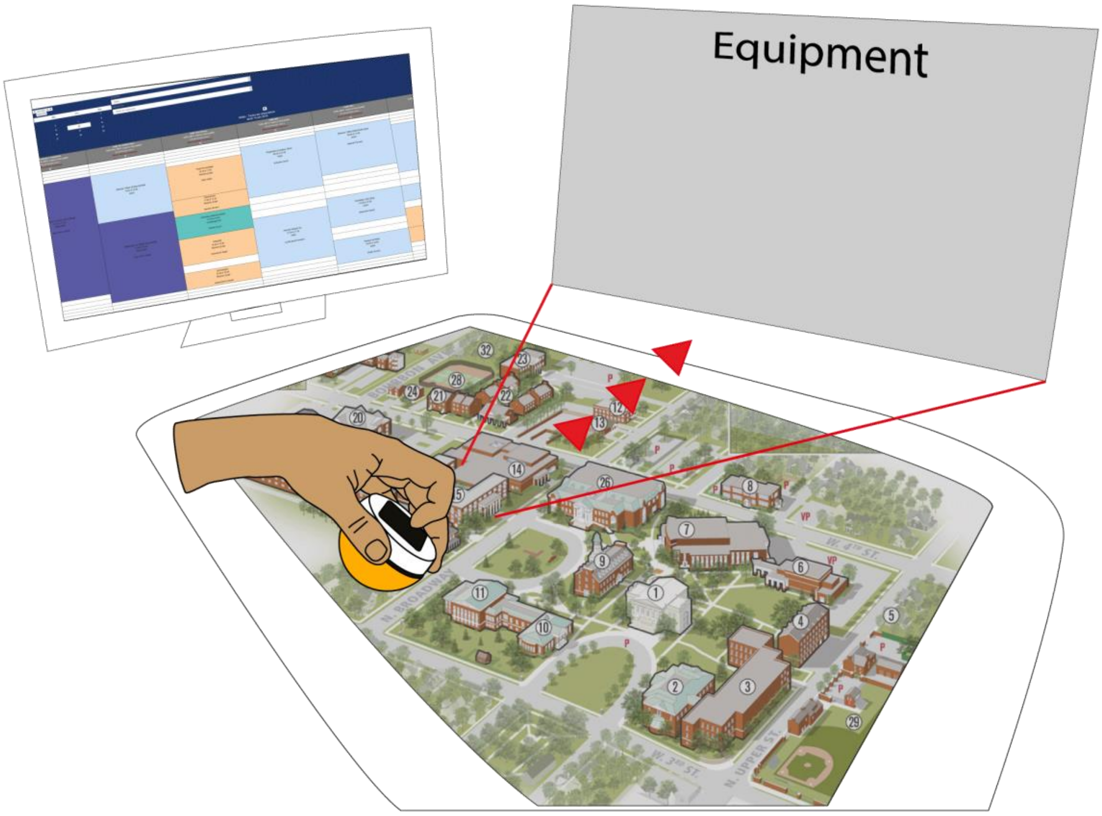


Figure 6.15: A possible use of TDome in the neOCampus project

The steps required to find an available conference room, that is heated and contains the equipment required by the lecturer are as follows:

- Interaction with the interactive tabletop to have a broad idea of the available conference rooms around the position of the lecturer. This task includes:
    - Navigating in a map (pan and zoom)
    - Selecting a region and sending it to the calendar display.
- Redirecting the input to the calendar display and interacting with it.
- Selecting a conference room from the agenda display to visualize the available equipment and the temperature of the conference room.

The tasks described above are common tasks in MDEs. We showed in Chapter 4 that TDome is suitable to perform such tasks. In this context, TDome's translations facilitate panning on the map and the zoom function can be mapped to rotations. Sending the selection from the interactive tabletop to the calendar display involves content transfer between two displays, interacting with the second display involves input redirection. With a good understanding of the displays composing the MDE, TDome's tilting can be used to select the display to interact with. Its tunnel implementation (Chapter 4) can be used to transfer content from one display to the other.

With an affordable and autonomous version of TDome, its use could be extended to open-access systems.

### 6.3.3 On-body tangible interactions for immersive data visualization

#### 6.3.3.1. Discussion

The proposed interaction solution aims to facilitate interaction with complex data visualized in immersive environments (Chapter 5). Due to the requirement of interaction with a multiple degrees of freedom device and the type of tasks performed on complex data, the profiles of users that would use such a system are **regular** or **frequent** users.

The display capabilities of immersive systems allow them to display all types of data. The interaction technique is not designed for data in particular but to interact with the immersive system. Thus, it can cover the **four types of data**.

The interaction technique was designed to support several tasks related to data exploration (**visualization**, **comprehension** and **production**) and interaction with immersive system.

While it may be adapted to other configurations, the current design and study of the approach pertain to a professional, **dedicated-access** system.

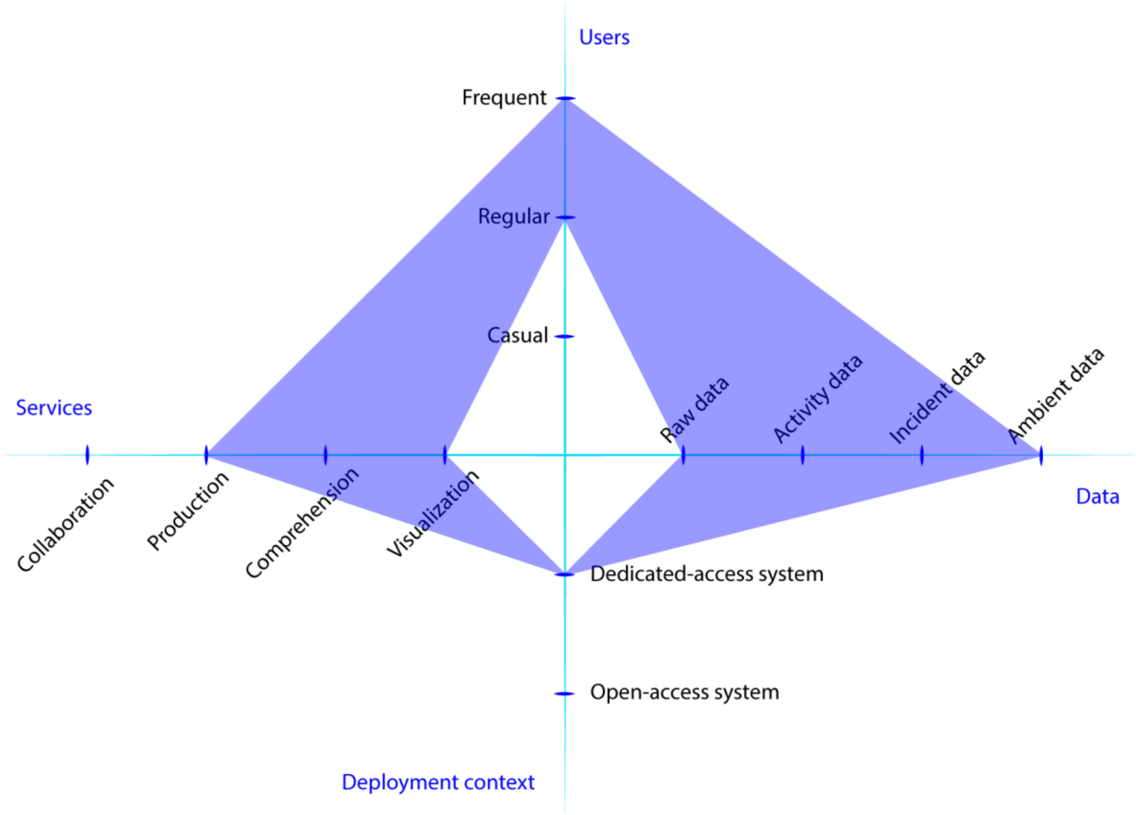


Figure 6.16: Description diagram of the values overed by our on-body tangible interations approach

#### 6.3.3.2. Concrete application of the interactive solution in the neOCampus project

This approach could be used in the activity described in scenario C albeit in a different setup. The local electrician has a list of failures on several sites of the university campus and he wants to visualize the energy consumption data to diagnose the failures. To conduct his task, he exploits the spatial capabilities of a hololens headset and the on-body tangible interaction approach.

The system allows the electrician to display a specific type of data (electricity consumption for example) at a specific point in time and in a specific location. The data is multidimensional. The electrician distributes it spatially over the 3 egocentric axes.

The system allows him to switch the dimension of data attached to each axis and offers him the possibility to anchor the volume of data on a specific physical position which helps him in his understanding of it. Indeed, the electrician can have an overview of the data by moving away from it, or a more detailed view by getting closer. He can also observe data from different angles if necessary.

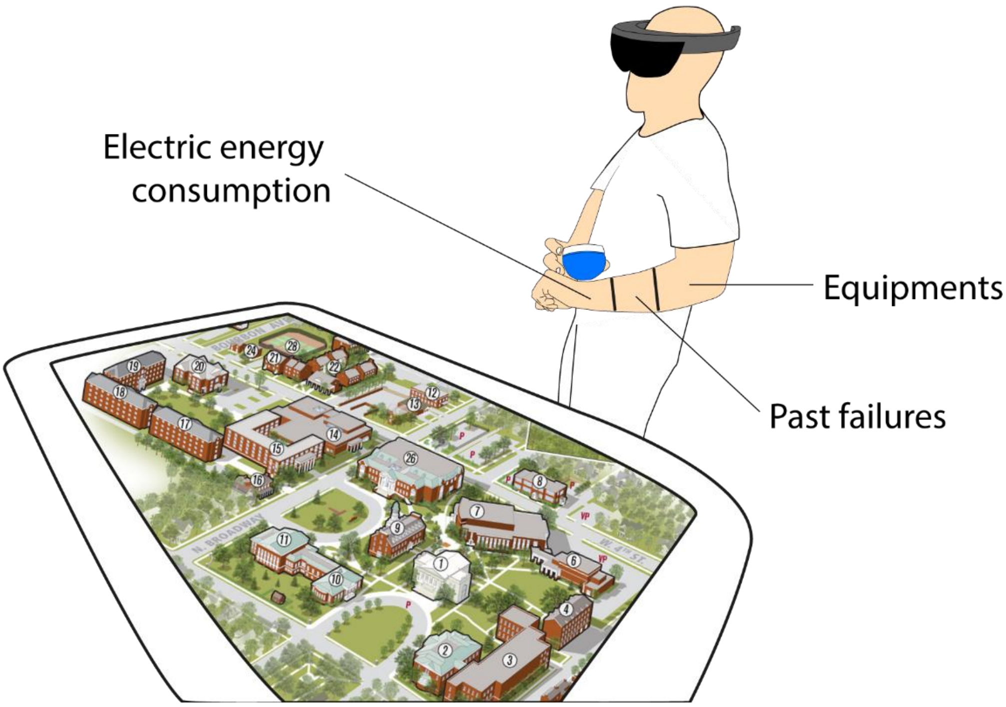


Figure 6.17: A possible use of the On-body tangible interactions approach in the neOCampus project

The on-body tangible interaction approach (Figure 6.17) allows him to interact with the three axes using a multi-degree of freedom device supported by the forearm with efficiency and without dividing his attention between the data and the interaction tool.

The electrician can use the system to select data, apply commands on it, scale it, rotate its visualization, etc. These tasks are mapped to different poses of the forearm, different regions of the forearm and different physical manipulations of the device (translations, tilting, rotations).

Although it has not been evaluated in a collaborative context, the interaction paradigm can support collaboration in several ways: The users can use one device for interaction, passing it from one user to the other or they could use several devices.

## 6.4 Conclusion

In this chapter, we described the neOCampus project and highlighted the related objectives falling in the scope of this thesis. They consist in addressing the challenges of exploration of the complex data provided by the numerous sensors and devices distributed on it.

To illustrate the different aspects of exploration of data in such a large context, we proposed what we called a "description space" which aims to identify and organize the relevant characteristics to consider when designing interactive solutions. In such contexts, the aspects covered by the description space includes the profiles of users the interactive solutions are designed for, the manipulated data, the type of services provided and its context of deployment.

We demonstrated the use of the description space through 3 scenarios representing situations of interest to us and covering the different aspects of interaction with complex data. We demonstrated the potential use of this thesis's contributions in this project by discussing how they could be applied to address the challenges of interaction in the 3 aforementioned scenarios. We detailed the profiles of users each solution targets, the type of data that can be explored through it and the services it provides.

In terms of perspectives, a potential use of the description space resides in identifying recommendations for the design of interaction techniques for each value and/or dimension of the description space.

# Conclusion & Perspectives

# 7 Conclusion & Perspectives

This chapter provides a summary of the main contributions of this thesis and discusses the associated medium-term and long-term perspectives.

## 7.1 Thesis summary

Today, several display spaces are available for data visualization. They offer numerous advantages and introduce new interaction challenges. In this manuscript, we discussed three display environments for data exploration: large displays, multi-display environments (MDEs) and immersive environments. We described them and detailed their characteristics, we presented their advantages and identified the interaction challenges they introduce. In this thesis, our goal was to improve interaction in each one of the previously cited environments. Below, we summarize our main contributions.Our work on large displays consisted in improving interaction with several regions of interest simultaneously. Our proposed approach is based on the use of a multi-view approach. We evaluated the influence of the number of detailed views on the user performance. To this end, we designed a visualization interface that offers multiple detailed views. The interface is based on an Overview+detail approach deployed on two displays: a large display showing the overview and a tablet displaying the detailed view (Figure 7.1). Our design follows Baldonado et al. [10] guidelines for multiple views. Baldonado [10] proposed a set of rules that helps designers assess the adequacy of multi-view systems for their application and make design choices related to the use of the views. They also help usability experts evaluate such systems. Our interface offer two interaction techniques to navigate in the overview: a basic one that consists in regular pan directly on the detailed view; a more advanced one in the form of dedicated view we called the translation view, it allows users to translate the detailed views by manipulating their icons on a mini-map. The translation view allows users to use multitouch to translate several detailed views at the same time.

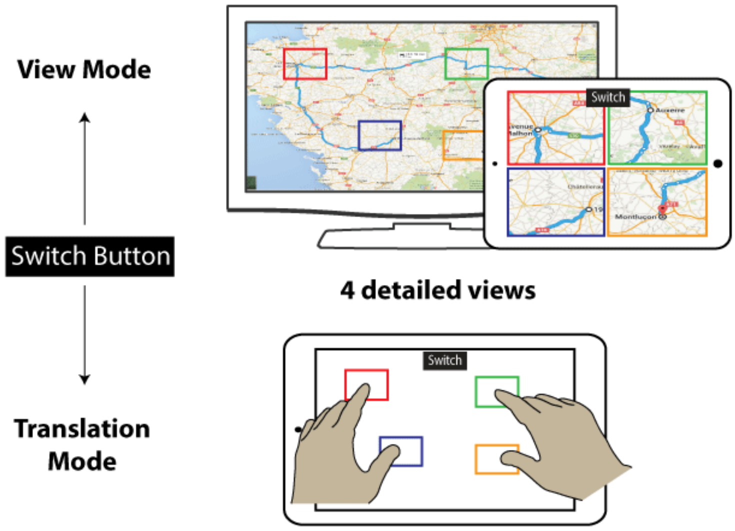


Figure 7.1: the split-focus technique

Using our interface, we experimentally evaluated the effect of the number of detailed views in a task related to the manipulation of large graphs in which users were asked to create a connection between 2, 3 or 4 nodes. We evaluated three multi-view configurations: one view (1V), two split views (2V) and four split views (4V). The results show that for tasks involving 4 regions of interest, 4 detailed views was the most efficient configuration. However, users performed similarly in 2V and 4V for tasks involving 2 regions of interest. The findings related to the use of the translation view, which allowed users to translate the detailed view in parallel through multi-touch interactions, showed that users did not take full benefit of that parallelism.

Next, we focused on multi-display environments (MDEs). We described their characteristics, highlighted their heterogeneous nature as well as the benefits they offer and the challenges they introduce. We identified two types of MDEs: MDEs deployed in a public context and MDEs deployed in a work context. While they share the same characteristics and interaction requirements (input redirection, output redirection, reachability, personal interaction), the profiles of their potential users and the type of tasks performed on them are different. Indeed, the users of public MDEs are usually passers-by, they may not engage in interaction with the MDEs if it's too difficult or takes too long. They may have never used the system before which makes them novice users requiring quick and easy to understand interactions. Moreover, they are mainly used to display data as they offer little or no means of interaction. To improve interaction in public MDEs, we explored the use of everyday objects as tools to perform tangible interactions to interact with these environments. They are always available, they offer easy to perform interactions and their shapes may help suggest their potential use which could translate into easy to understand interactions. We conducted a creativity study to identify the way to use objects of different shapes and materials to perform common tasks in MDE and amended an existing taxonomy to classify the proposed gestures. Among our findings was the fact that participants took benefit of the material of the object when it was soft, rather than its shape with the exception of the spherical object. Indeed, despite the soft nature of the ball, participants preferred exploiting its rounded shape for their proposed gestures.

Building on the findings of the creativity study, we proposed TDome, a rounded device designed to overcome the lack of a unified device or interaction technique dedicated to multi-display environments in a work context. TDome is an input and output device with a semi-spherical base offering multiple degrees of freedom (rolls, rotations and translations). The device is augmented with a touchscreen that allows it to display information and detect touch input. The combination of physical manipulations and touch gestures makes TDome a robust device and increases the number of available gestures. We discussed the suitability of TDome in addressing the main MDEs requirements, while avoiding the need to have more than one device in the workspace, and demonstrated its benefits through a set of interaction techniques (Figure 7.2).

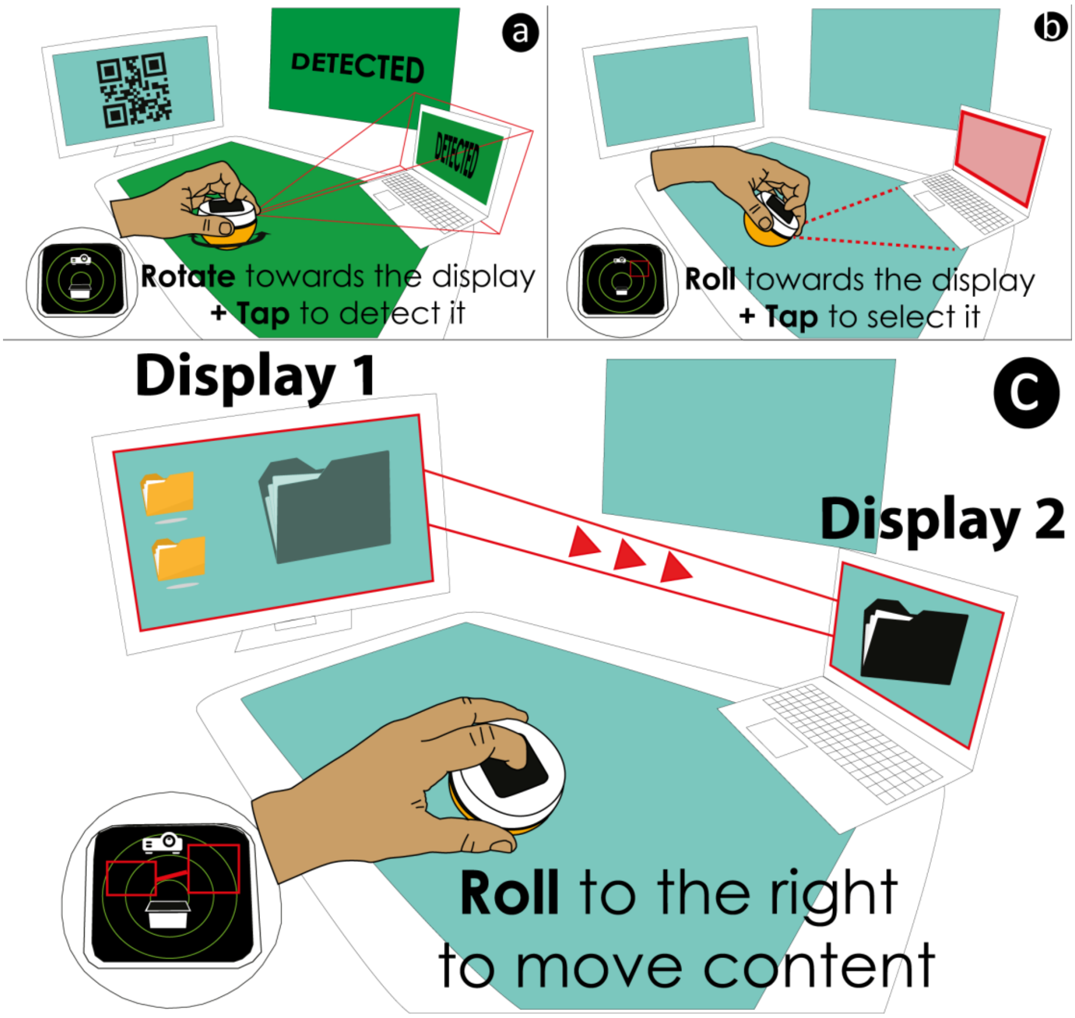


Figure 7.2: a) display registration using its embedded camera, b) device selection and c) cross-display data transfer

We evaluated the usability of the device through an experimental study. The results show that up to 71 combined gestures can be comfortably performed with the device. We explored potential mappings of TDome gestures to MDE's tasks through a user survey. Results show that some combined gestures are more prone to be used in specific tasks than others. In general, we find participants are able to match TDome features to MDE tasks.

Finally, we explored on-body tangible interactions in immersive environments with complex data requiring multiple degrees of freedom. The approach is based on the use of a multi-degrees of freedom device (RPM) supported by a body part (forearm). The use of RPM is motivated by its multiple degrees of freedom and its suitability for interaction with multidimensional data. The use of the forearm as a support is motivated by its social acceptability, its large surface of interaction and its accessibility. The combination of the multi-DOF mouse and the forearm allows the user to move in his environment to explore data, improve the accuracy and avoid the inherent fatigue of mid-air interactions (Figure 7.3).

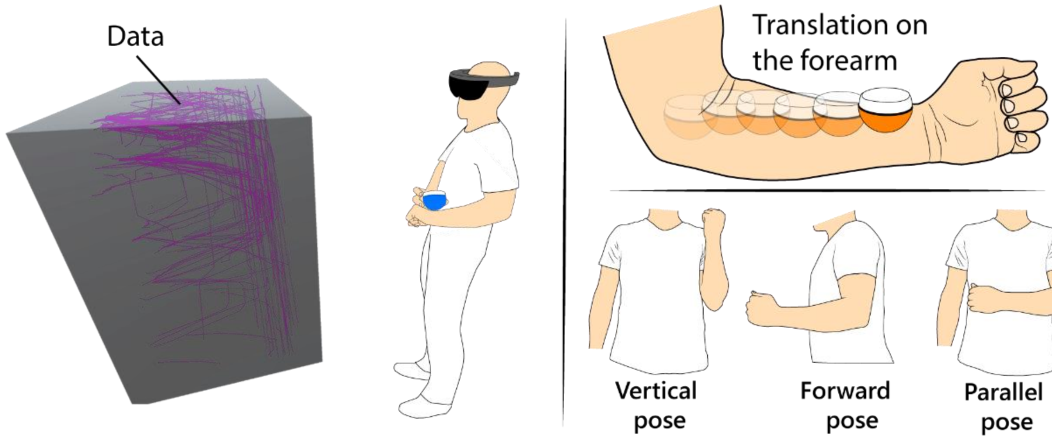


Figure 7.3: On-body tangible interaction for immersive data visualization

We proposed a theoretical contribution in the form of a design space describing the main characteristics of the approach and a practical contribution through its evaluation. To validate the adequacy of such an approach for immersive environments, we conducted an experiment aimed at establishing the range, stability and comfort of gestures performed with the device on the forearm.

The results show that: the forearm is a suitable support for tangible interactions (minimal movement during interaction); the forearm offers a large area where interaction is possible; the device was stable when used to perform physical manipulations on the forearm; no fatigue was reported by the participants when using the approach.

We discussed possible mappings of the tangible gestures on the body to different controls. We highlighted the potential of translations performed on the length of the forearm for controls requiring substantial precision or a great data coverage; we also discussed the possible use of translations performed on the width of the forearm for " Rate control" type controllers.

# 7.2 Future work

In this section, we present and discuss research opportunities and ideas for future work.

## 7.2.1 Medium-term

Below, we present several medium-term perspectives related to the work conducted in this thesis.

### 7.2.1.1. Large displays

In our work on improving interaction with multiple regions of an overview simultaneously, we proposed an overview + detail visualization interface where multiple detailed views are displayed on a tablet. The visualization technique allows the translation of the detailed views in the overview through a view we called "translation view". It allows the users to move up to 4 detailed views simultaneously using multi-touch interactions (Figure 7.1).

One of the findings of our evaluation was that users did not fully exploit the parallel exploration offered by our interface. They found symmetric bimanual multi-touch input difficult to perform. An alternative to the use of all fingers for parallel translations of detailed views is to repurpose the role of unused fingers. They can be used as modifiers for the interaction: to dynamically activate or release locks without using the menu designed for that on the detailed view; to perform quick translation movements like reverting to a previous position, translating to a corner, translating to the closest detailed view (forming a continuous view) …; to increase/decrease the size of the detailed views' icons while translating them; to give a temporary overview of a specific region i.e. while translating a detailed view (DV) with one finger, a touch on the overview (TO) with another finger of the same hand can display temporarily on DV the area pointed by TO. Removing the finger from TO would revert to showing the area covered by the detailed view icon.

It would be interesting to explore these potential uses of unused fingers and evaluate them in further depth through the adequate experimental setup.

#### 7.2.1.2. Multi-display environments

In our implementation of TDome to interact with MDEs (Chapter 4), we used a semi-autonomous version of RPM [140]. Indeed, while the rotations and rolls were detected by the inertial measurement unit equipping it, the translations (positions) of the device were always detected using an external sensor limiting the usage of the device. The TDome prototype used an infrared touch overlay which restricts the use of the device to the surface where it is installed and reduces the benefits of the device. The RPM mouse on which TDome is based on [140] used the mocap system[33]. it offers a more precise detection of translations, rotations and rolls as well as a larger area where it can be used. However, this solution is expensive, cumbersome to implement and difficult to move which hinders the portability of the approach. A next step in the improvement of RPM/TDome consists in studying the possible use of integrated and affordable sensors to detect translations accurately as it is the only barrier to have a fully self-contained device.

A more research-oriented perspective consists in comparing TDome to several baselines in interaction with MDEs. We demonstrated that the device offers a wider variety of interactions than existing solutions support which demonstrates that it has the potential to be suitable for MDEs. However, this potential is hard to validate without any baseline comparison of the device with existing interaction solutions that for example, based on studies reported in the literature, has been shown to provide the best support in MDEs. Our contribution has no such baseline comparison and instead focuses on studying the usability of the device in such context.

Finally, our work focused mainly on stationary MDEs, it would be interesting to study how TDome could be used in more mobile context where smartphones and wearable have been used to compose the MDE [46, 72].

[33] http://optitrack.com/

#### 7.2.1.3. Immersive Environments

Our work on-body tangible interactions was a first step in evaluating the proposed interaction approach. It focused on studying the stability of the forearm and the multi-dof device. This study was limited to the translations of the device. Indeed, we hypothesized that performing translations on the width of the forearm would lead to voluntary rolls due to the cylindrical shape of the forearm. This hypothesis, which was validated by the study results, prompted us to focus on translations first to evaluate the feasibility of the proposed interactions. The next step in this work is to evaluate to remaining physical manipulations allowed by the device in the same circumstances.

Another perspective is to widen the possible use of the forearm for interactions. In our design space, the forearm was restricted to the role of simple support. Another dimension could specify the role it plays in interaction. It could augment the interaction and act as an additional tool of interaction. For instance, the users could move the forearm to choose the granularity of control provided by the device. In this case, it acts as a modifier for the interaction. It would be interesting to explore the combination of support movement (forearm moving) and tangible interactions to construct a bigger interaction vocabulary and larger amplitudes. Similarly, the poses we proposed for the forearm embody the 3 axes of a three-dimensional cartesian coordinate system. Alternative poses could be evaluated to perform interactions.

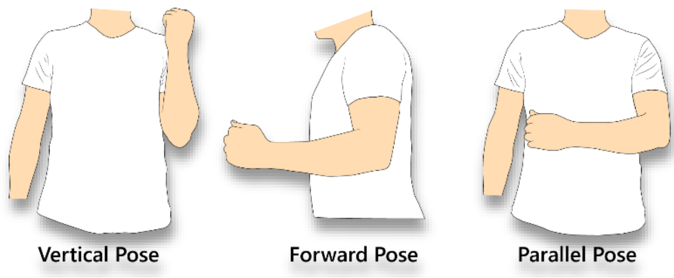


Figure 7.4: Possible poses

As an example, a pose between the forward pose and the parallel pose (Figure 7.4) could allow the interaction with the two controllers/axes mapped to them simultaneously.

## 7.2.2 Long-term

### 7.2.2.1. Displays' positions and rotations in an MDE

We highlighted at several points in this manuscript the heterogenous nature of MDEs. However, in proposing a multi-dof device to interact with these environments, we focused mainly on the device, its suitability for MDEs and its usability in a specific context in which the displays were at fixed positions. The displays composing MDEs can offer most varying characteristics. Some more than others can influence greatly the way we perform interactions with them. The positions and rotations of displays may change frequently in those environments: either involuntarily as displays like smartphones, tablets and wearables in general are meant to be mobile or voluntarily as users can exploit the spatial reconfigurability/flexibility of MDEs to create a work environment in which they feel comfortable. In both cases, the relationship between displays changes which could have an undesirable effect on the flow of the tasks usually performed on the MDE. For instance, the distribution of data between displays may be different in a newly arranged MDE which could have a direct effect on how a content transfer task is performed between displays. It would be interesting to explore how the topology of displays influences the flow of interaction and how TDome is used in different dispositions of displays.

### 7.2.2.2. Physical visualizations

A second long-term perspective consists in exploring interaction with spatial data displayed on three-dimensional physical models. This thesis has so far focused on interaction with display spaces where data is visualized virtually (large displays, MDEs, immersive environments). Recently, growing emphasis has been placed on the physicalisation of data i.e. displaying data in the spatial or physical context that generated it. Such visualizations are becoming possible through the use of spatial augmented reality (SAR) [30]. Several works in HCI are highlighting the benefits of such environments and arguing that today's visualization systems will slowly get enriched with physicalized instruments [95]. This type of physical visualizations allow for in-place or in-situ analytics [62], but also constitute effective communication tools when presenting information to non-expert users [96]. They have been used in multiple contexts: to display air quality measures in the physical context of the sensors [193]; to present traffic flow on city models [74]; to embed data representations on buildings [74,194]. Research for this type of visualizations is still at an early stage and work is still to be done to improve interaction with these environments. Our work for immersive environments which focused on virtual 3d representation of data could be adapted to these environments. It would be interesting to explore it further and evaluate it in such contexts.

#### 7.2.2.3. Integration of the proposed solutions in the neOCampus project

A final long-term perspective consists in integrating the developed interaction techniques on the campus of the University of Toulouse. Indeed, we briefly touched upon potential usages of our contributions on the campus through 3 usage scenarios in Chapter 6 (neOCampus) and described their potential use. However, the pertinence of the designed solutions to the campus's challenges have been discussed and evaluated in controlled laboratory conditions. Any adaptation of the interactive solutions should be evaluated in-situ and in collaboration with the end users.

# References


1. Zahra Shakeri Hossein Abad, Craig Anslow, and Frank Maurer. 2014. Multi Surface Interactions with Geospatial Data: A Systematic Review. In Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14). ACM, New York, NY, USA, 69–78. DOI: https://doi.org/10.1145/2669485.2669505
2. Adalberto L. Simeone, Julian Seifert, Dominik Schmidt, Paul Holleis, Enrico Rukzio, and Hans Gellersen. 2013. A cross-device drag-and-drop technique. In Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia (MUM '13). ACM, New York, NY, USA, Article 10, 4 pages. DOI: https://doi.org/10.1145/2541831.2541848
3. Christopher Andrews, Alex Endert, and Chris North. 2010. Space to think: large high-resolution displays for sensemaking. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10). ACM, New York, NY, USA, 55–64. DOI: https://doi.org/10.1145/1753326.1753336
4. Christopher Andrews, Alex Endert, Beth Yost, and Chris North. 2011. Information visualization on large, high-resolution displays: issues, challenges, and opportunities. Information Visualization 10, 4 (October 2011), 341–355. DOI=http://dx. doi. org/10.1177/1473871611415997
5. Daniel L. Ashbrook, Thad E. Starner, enabling mobile microinteractions, Georgia Institute of Technology, Atlanta, GA, 2010
6. Bach, B., Sicat, R., Beyer, J., Cordeil, M., Pfister, H. The Hologram in My Hand: How Effective is Interactive Exploration of 3D Visualizations in Immersive Tangible Augmented Reality? IEEE Transactions on Visualization and Computer Graphics (TVCG), 2018, IEEE VIS (InfoVis)
7. Gilles Bailly, Robert Walter, Jörg Müller, Tongyan Ning, and Eric Lecolinet. 2011. Comparing free hand menu techniques for distant displays using linear, marking and finger-count menus. In Proceedings of the 13th IFIP TC 13 international conference on Human-computer interaction—Volume Part II (INTERACT'11), Pedro Campos, Nuno Nunes, Nicholas Graham, Joaquim Jorge, and Philippe Palanque (Eds.), Vol. Part II. Springer-Verlag, Berlin, Heidelberg, 248–262.
8. Ravin Balakrishnan, Thomas Baudel, Gordon Kurtenbach, George Fitzmaurice, The Rockin'Mouse: integral 3D manipulation on a plane, Proceedings of the ACM SIGCHI Conference on Human factors in computing systems, p.311-318, March 22–27, 1997, Atlanta, Georgia, USA [doi¿10.1145/258549.258778]
9. Ravin Balakrishnan, Ken Hinckley, Symmetric bimanual interaction, Proceedings of the SIGCHI conference on Human Factors in Computing Systems, p.33-40, April 01–06, 2000, The Hague, The Netherlands [doi¿10.1145/332040.332404]

10. Baldonado, M., Woodruff, A., Kuchinsky, A. 2000. Guidelines for using multiple views in information visualization, In AVI'00. ACM, pp.110-119.

11. Robert Ball, Chris North, and Doug A. Bowman. 2007. 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). ACM, New York, NY, USA, 191–200. DOI: https://doi.org/10.1145/1240624.1240656

12. Jakob E. Bardram, Jonathan Bunde-Pedersen, Afsaneh Doryab, and Steffen Sørensen. 2009. CLINICAL SURFACES—

13. Patrick Baudisch, Nathaniel Good, and Paul Stewart. 2001. Focus plus context screens: combining display technology with visualization techniques. In Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01). ACM, New York, NY, USA, 31-40. DOI=http://dx.doi.org/10.1145/502348.502354

14. Baudisch, Patrick & Cutrell, Edward & Czerwinski, Mary & Robbins, Daniel & Tandler, Peter & Bederson, Ben & Zierlinger, A. (2003). Drag-and-Pop and Drag-and-Pick: Techniques for Accessing Remote Screen Content on Touch- and Pen-Operated Systems.

15. Patrick Baudisch, Edward Cutrell, Ken Hinckley, and Robert Gruen. 2004. Mouse ether: accelerating the acquisition of targets across multi-monitor displays. In CHI '04 Extended Abstracts on Human Factors in Computing Systems (CHI EA '04). ACM, New York, NY, USA, 1379–1382. DOI: https://doi.org/10.1145/985921.986069

16. Dominikus Baur, Sebastian Boring, Steven Feiner, Virtual projection: exploring optical projection as a metaphor for multi-device interaction, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, May 05–10, 2012, Austin, Texas, USA [doi¿10.1145/2207676.2208297]

17. Michel Beaudouin-Lafon. 2000. Instrumental interaction: an interaction model for designing post-WIMP user interfaces. In Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI '00). ACM, New York, NY, USA, 446–453. DOI=http://dx. doi. org/10.1145/332040.332473

18. Michel Beaudouin-Lafon, Stephane Huot, Mathieu Nancel, Wendy Mackay, Emmanuel Pietriga, Romain Primet, Julie Wagner, Olivier Chapuis, Clement Pillias, James Eagan, Tony Gjerlufsen, and Clemens Klokmose. 2012. Multisurface Interaction in the WILD Room. Computer 45, 4 (April 2012), 48–56. DOI=http://dx. doi. org/10.1109/MC.2012.110

19. Benjamin B. Bederson, Interfaces for staying in the flow, Ubiquity, v.2004 n.September, p.1-1 [doi¿10.1145/1074068.1074069]

20. Hrvoje Benko and Steven Feiner. 2005. Multi-monitor mouse. In CHI '05 Extended Abstracts on Human Factors in Computing Systems (CHI EA '05). ACM, New York, NY, USA, 1208–1211. DOI=http://dx. doi. org/10.1145/1056808.1056878

21. Hrvoje Benko and Andrew D. Wilson. 2010. Multi-point interactions with immersive omnidirectional visualizations in a dome. In ACM International Conference on Interactive Tabletops and Surfaces (ITS '10). ACM, New York, NY, USA, 19–28. DOI: https://doi.org/10.1145/1936652.1936657

22. Hrvoje Benko, Shahram Izadi, Andrew D. Wilson, Xiang Cao, Dan Rosenfeld, Ken Hinckley, Design and evaluation of interaction models for multi-touch mice, Proceedings of Graphics Interface 2010, May 31-June 02, 2010, Ottawa, Ontario, Canada

23. Amal Benzina, Arindam Dey, Marcus Toennis, and Gudrun Klinker. 2012. Empirical evaluation of mapping functions for navigation in virtual reality using phones with integrated sensors. In Proceedings of the 10th asia pacific conference on Computer human interaction (APCHI '12). ACM, New York, NY, USA, 149–158. DOI: https://doi.org/10.1145/2350046.2350078

24. Louis-Pierre Bergé, Marcos Serrano, Gary Perelman, and Emmanuel Dubois. 2014. Exploring smartphone-based interaction with overview+detail interfaces on 3D public displays. In Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services (MobileHCI '14). ACM, New York, NY, USA, 125–134. DOI: https://doi.org/10.1145/2628363.2628374

25. Louis-Pierre Bergé, Emmanuel Dubois, and Mathieu Raynal. 2015. Design and Evaluation of an "Around the SmartPhone" Technique for 3D Manipulations on Distant Display. In Proceedings of the 3rd ACM Symposium on Spatial User Interaction (SUI '15). ACM, New York, NY, USA, 69–78. DOI: https://doi.org/10.1145/2788940.2788941

26. Lonni Besançon, Paul Issartel, Mehdi Ammi, and Tobias Isenberg. 2017. Mouse, Tactile, and Tangible Input for 3D Manipulation. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). ACM, New York, NY, USA, 4727–4740. DOI: https://doi.org/10.1145/3025453.3025863

27. Shruti Bhandari and Youn-Kyung Lim, "Exploring gestural mode of interaction with mobile phones," in CHI '08 Extended Abstracts on Human Factors in Computing Systems, Florence, Italy, 2008, pp. 2979–2984

28. Xiaojun Bi, Yuanchun Shi, Xiaojie Chen, and Peifeng Xiang. 2005. Facilitating interaction with large displays in smart spaces. In Proceedings of the 2005 joint conference on Smart objects and ambient intelligence: innovative context-aware services: usages and technologies (sOc-EUSAI'05). ACM, New York, NY, USA, 105–110. DOI: https://doi.org/10.1145/1107548.1107579

29. Bi X and Balakrishnan R. Comparing usage of a large high-resolution display to single or dual desktop displays for daily work. Proceedings of the 27th International Conference on Human Factors in Computing Systems, ACM: Boston, MA, 2009; 1005–1014

30. Oliver Bimber and Ramesh Raskar. 2005. Spatial Augmented Reality Merging Real and Virtual Worlds. https://doi.org/10.1260/147807708784640126

31. Kellogg S. Booth, Brian D. Fisher, Chi Jui Raymond Lin, and Ritchie Argue. 2002. The "mighty mouse" multi-screen collaboration tool. In Proceedings of the 15th annual ACM symposium on User interface software and technology (UIST '02). ACM, New York, NY, USA, 209–212. DOI: https://doi.org/10.1145/571985.572016

32. Borg, G. Borg's Perceived Exertion and Pain Scales. Human Kinetics (1998), viii 104pp

33. Boring, S. 2007. Interacting in Multi-Display Environments. In DC Ubicomp'07. ACM.

34. Sebastian Boring, Marko Jurmu, Andreas Butz, Scroll, tilt or move it: using mobile phones to continuously control pointers on large public displays, Proceedings of the 21st Annual Conference of the Australian Computer-Human Interaction Special Interest Group: Design: Open 24/7, November 23–27, 2009, Melbourne, Australia [doi¿10.1145/1738826.1738853]

35. Sebastian Boring, Dominikus Baur, Andreas Butz, Sean Gustafson, and Patrick Baudisch. 2010. Touch projector: mobile interaction through video. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10). ACM, New York, NY, USA, 2287–2296. DOI=http://dx. doi. org/10.1145/1753326.1753671

36. Christophe Bortolaso, Matthew Oskamp, T.C. Nicholas Graham, Doug Brown, OrMiS: a tabletop interface for simulation-based training, Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces, October 06–09, 2013, St. Andrews, Scotland, United Kingdom

37. Doug Bowman, Chadwick Wingrave, Joshua Campbell, Vinh Q Ly. Using pinch gloves (tm) for both natural and abstract interaction techniques in virtual environments. In Proc. of HCI International, no. 0106, 629–633

38. Frederik Brudy, Joshua Kevin Budiman, Steven Houben, and Nicolai Marquardt. 2018. Investigating the Role of an Overview Device in Multi-Device Collaboration. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). ACM, New York, NY, USA, Paper 300, 13 pages. DOI: https://doi.org/10.1145/3173574.3173874

39. Buntarou Shizuki, Takaomi Hisamatsu, Shin Takahashi, Jiro Tanaka, Laser pointer interaction techniques using peripheral areas of screens, Proceedings of the working conference on Advanced visual interfaces, May 23–26, 2006, Venezia, Italy

40. Robin Burgess, António J. Falcão, Tiago Fernandes, Rita A. Ribeiro, Miguel Gomes, Alberto Krone-Martins, André Moitinho de Almeida. Selection of large-scale 3d point cloud data using gesture recognition. In Doctoral Conference on Computing, Electrical and Industrial Systems, pages 188–195. Springer, 2015

41. Simon Butscher, Kasper Hornbæk, and Harald Reiterer. 2014. SpaceFold and PhysicLenses: simultaneous multifocus navigation on touch surfaces. In Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces (AVI '14). ACM, New York, NY, USA, 209–216. DOI: https://doi.org/10.1145/2598153.2598177

42. Jessica R. Cauchard, Markus Löchtefeld, Pourang Irani, Johannes Schoening, Antonio Krüger, Mike Fraser, and Sriram Subramanian. 2011. Visual separation in mobile multi-display environments. In Proceedings of the 24th annual ACM symposium on User interface software and technology (UIST '11). ACM, New York, NY, USA, 451–460. DOI: https://doi.org/10.1145/2047196.2047256

43. Tsung-Hsiang Chang, Yang Li, Deep shot: a framework for migrating tasks across devices using mobile phone cameras, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, May 07–12, 2011, Vancouver, BC, Canada [doi¿10.1145/1978942.1979257]

44. Olivier Chapuis, Anastasia Bezerianos, Stelios Frantzeskakis, Smarties: an input system for wall display development, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 26-May 01, 2014, Toronto, Ontario, Canada [doi¿10.1145/2556288.2556956]

45. Chen, X., Davis, J. (2001). Lumipoint: Multi-user laser-based interaction on large tiled displays. Displays. 23. 205–211.

46. Xiang "Anthony" Chen, Tovi Grossman, Daniel J. Wigdor, and George Fitzmaurice. 2014. Duet: exploring joint interactions on a smart phone and a smart watch. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 159–168. DOI: https://doi.org/10.1145/2556288.2556955

47. Kelvin Cheng and Dingyun Zhu. 2014. Tablet interaction techniques for viewport navigation on large displays. In CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14). ACM, New York, NY, USA, 2029–2034. DOI: https://doi.org/10.1145/2559206.2581148

48. Samuel Clarke, Nathan Dass, Duen Horng (Polo) Chau. Naturalmotion: Exploring gesture controls for visualizing time-evolving graphs. Proceedings of IEEE VIS (poster session), 2016

49. COCKBURN, A. AND SAVAGE, J. 2003. Comparing speed-dependent automatic zooming with traditional scroll, pan and zoom methods. In Proceedings of the British Computer Society Conference on Human-Computer Interaction, People and Computers XVII, 87–102.

50. Cockburn, A., Karlson, A., and Bederson, B.B. 2008. A Review of Overview+Detail, Zooming, and Focus+Context Interfaces. ACM CSUR, 41, 1.

51. Andy Cockburn, Philip Quinn, Carl Gutwin, Gonzalo Ramos, and Julian Looser. 2011. Air pointing: Design and evaluation of spatial target acquisition with and without visual feedback. Int. J. Hum.-Comput. Stud. 69, 6:401–414.

52. Andy Cockburn, Carl Gutwin, Joey Scarr, Sylvain Malacria, Supporting Novice to Expert Transitions in User Interfaces, ACM Computing Surveys (CSUR), v.47 n.2, p.1-36, January 2015 [doi¿10.1145/2659796]

53. Peter Cook, Clarence Ellis, Mike Graf, Gail Rein, and Tom Smith, "Project Nick: meetings augmentation and analysis," ACM Transactions on Information Systems (TOIS), vol. 5, no. 2, pp.132-146, April 1987

54. Maxime Cordeil, Tim Dwyer, and Christophe Hurter. 2016. Immersive solutions for future Air Traffic Control and Management. In Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces (ISS Companion '16). ACM, New York, NY, USA, 25–31. DOI: https://doi.org/10.1145/3009939.3009944

55. Cordeil, M., Bach, B., Li, Y., Wilson, E., and Dwyer, T. A design space for spatio-data coordination: Tangible interaction devices for immersive information visualisation. In Proceedings of the 10th IEEE Pacific Visualization Symposium (PacificVis) (2017)

56. Czerwinski M, Tan D and Robertson G. Women take a wider view. CHI '02. Minneapolis, MN: ACM, 2002, pp. 195–202.

57. Raimund Dachselt and Robert Buchholz, "Natural throw and tilt interaction between mobile phones and distant displays," in CHI '09 Extended Abstracts on Human Factors in Computing Systems, Boston, MA, USA, 2009, pp. 3253–3258.

58. Coffey, Dane et al. (2012). "Interactive Slice WIM: Navigating and Interro- gating Volume Datasets Using a Multi-Surface, Multi-Touch VR Inter- face." In: IEEE Transactions on Visualization and Computer Graphics 18.10, pp. 1614–1626. doi: http://dx.doi.org/10.1109/TVCG.2011.283

59. David Dobbelstein, Philipp Hock, and Enrico Rukzio. 2015. Belt: An Unobtrusive Touch Input Device for Head-worn Displays. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 2135–2138. DOI: https://doi.org/10.1145/2702123.2702450

60. Tanja Döring, Alireza Sahami Shirazi, and Albrecht Schmidt. 2010. Exploring gesture-based interaction techniques in multi-display environments with mobile phones and a multi-touch table. In Proceedings of the International Conference on Advanced Visual Interfaces (AVI '10), Giuseppe Santucci (Ed.). ACM, New York, NY, USA, 419-419. DOI: https://doi.org/10.1145/1842993.1843097

61. Elmqvist, N., Nathalie Henry, Yann Riche, Jean-Daniel Fekete. 2008. Melange: space folding for multi-focus interaction. In CHI'08. ACM, pp. 1333–1342

62. Niklas Elmqvist and Pourang Irani. 2013. Ubiquitous analytics: Interacting with big data anywhere, anytime. Computer 46, 4:86–89. https://doi.org/10.1109/MC.2013.147

63. Andreas Fender, David Lindlbauer, Philipp Herholz, Marc Alexa, and Jörg Müller. 2017. HeatSpace: Automatic Placement of Displays by Empirical Analysis of User Behavior. In Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology (UIST '17). ACM, New York, NY, USA, 611–621. DOI: https://doi.org/10.1145/3126594.3126621

64. Furnas, G. W. 1986. Generalized fisheye views, In CHI'86. ACM, pp.16-23.

65. Furnas GW and Bederson BB. Space-scale diagrams: Understanding multiscale interfaces. Human Factors in Computing Systems (CHI '95), ACM, Denver, Colorado, 1995; 234–241

66. Furnas, George W. 2006. A fisheye follow-up: further reflections on focus + context. In CHI'06. ACM, pp. 999–1008.

67. Gallo, L., and Minutolo, A. Design and comparative evaluation of smoothed pointing: A velocity-oriented remote pointing enhancement technique. IJHCS 70, 4 (2012), 287–300.

68. Geyer, F., Höchtl, A., and Reiterer, H. 2012. Harnessing the benefits of bimanual and multi-finger input for supporting grouping tasks on interactive tabletops. In NordiCHI'12. pp. 496–499.

69. Gleizes, M. P., Boes, J., Lartigue, B., & Thiébolt, F. (2017, June). neocampus: A demonstrator of connected, innovative, intelligent and sustainable campus. In International Conference on Intelligent Interactive Multimedia Systems and Services (pp. 482-491). Springer, Cham.

70. Roswitha Gostner, Enrico Rukzio, and Hans Gellersen, "Usage of spatial information for selection of co-located devices," in Proceedings of the 10th international conference on Human computer interaction with mobile devices and services (MobileHCI'08), Amsterdam, the Netherlands, 2008, pp. 427–430

71. Jakob E. Bardram, Jonathan Bunde-Pedersen, Afsaneh Doryab, and Steffen Sørensen. 2009. CLINICAL SURFACES—Activity-Based Computing for Distributed Multi-Display Environments in Hospitals. In *Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part II* (INTERACT '09), Tom Gross, Jan Gulliksen, Paula Kotzé, Lars Oestreicher, Philippe Palanque, Raquel Oliveira Prates, and Marco Winckler (Eds.). Springer-Verlag, Berlin, Heidelberg, 704–717. DOI: https://doi.org/10.1007/978-3-642-03658-3˙76

72. Grubert, J., Heinisch, M., Quigley, A., & Schmalstieg, D. (2015, April). Multifi: Multi fidelity interaction with displays on and around the body. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (pp. 3933–3942). ACM

73. Gun A. Lee, Jonathan Wong, Hye Sun Park, Jin Sung Choi, Chang Joon Park, and Mark Billinghurst. 2015. User Defined Gestures for Augmented Virtual Mirrors: A Guessability Study. In Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '15). ACM, New York, NY, USA, 959–964. DOI: https://doi.org/10.1145/2702613.2732747

74. Mohammad Hadhrawi and Kent Larson. 2016. Illuminating LEGOs with Digital Information to Create Urban Data Observatory and Intervention Simulator. Proceedings of the 2016 ACM Conference Companion Publication on Designing Interactive Systems—DIS '16 Companion: 105–108. https://doi.org/10.1145/2908805. 2909400

75. Hancock, Mark, Sheelagh Carpendale, and Andy Cockburn. 2007. "Shallow-Depth 3D Interaction: Design and Evaluation of One-, Two- and Three-Touch Techniques." In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems—CHI '07, 1147–56. ACM Press.

76. F. Haque, M. Nancel and D. Vogel. 2015. Myopoint: Pointing and Clicking Using Forearm Mounted Electromyography and Inertial Motion Sensors. In Proceedings of the 33rd Annual ACM Conference on Human Facto rs in Computing Systems, ACM, 3653–3656. 10.1145/2702123.2702133

77. Chris Harrison, Desney Tan, and Dan Morris. 2010. Skinput: appropriating the body as an input surface. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10). ACM, New York, NY, USA, 453–462. DOI: https://doi.org/10.1145/1753326.1753394

78. Nabeel Hassan, Md. Mahfuzur Rahman, Pourang Irani, and Peter Graham, "Chucking: A OneHanded Document Sharing Technique," in Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part II, Uppsala, Sweden, 2009, pp. 264–278.

79. Christian Heath, Paul Luff, and Abigail Sellen, "Reconsidering the virtual workplace: flexible support for collaborative activity," in Proceedings of the fourth conference on European Conference on Computer-Supported Cooperative Work, Stockholm, Sweden, 1995, pp. 83–99.

80. HERMAN, I., MELANCON, G., AND MARSHALL, M. 2000. Graph visualization and navigation in information visualization: A survey. IEEE Trans. Visual. Comput. Graph. 6, 1, 24–43.

81. L. Hespanhol, M. Tomitsch, K. Grace, A. Collins, and J. Kay. Investigating intuitiveness and effectiveness of gestures for free spatial interaction with large displays. In Proc. of PerDis, pp. 6:1–6:6. ACM, 2012.

82. Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, Pourang Irani, Consumed endurance: a metric to quantify arm fatigue of mid-air interactions, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 26-May 01, 2014, Toronto, Ontario, Canada [doi¿10.1145/2556288.2557130]

83. Hinckley, K., Wigdor, D., Input Technologies and Techniques. Chap. 9 in The HCI Handbook, 3rd Edition, Taylor & Francis

84. Ken Hinckley, Mike Sinclair, Erik Hanson, Richard Szeliski, Matt Conway, The VideoMouse: a camera-based multi-degree-of-freedom input device, Proceedings of the 12th annual ACM symposium on User interface software and technology, p.103-112, November 07–10, 1999, Asheville, North Carolina, USA [doi¿10.1145/320719.322591]

85. HORNBÆK, K. AND FRØKJÆR, E., 2001. Reading of Electronic Documents: The Usability of Linear, Fisheye, and Overview + Detail Interfaces. In CHI'01. pp. 293–300.

86. Kasper Hornbæk, Benjamin B. Bederson, and Catherine Plaisant. 2002. Navigation patterns and usability of zoomable user interfaces with and without an overview. ACM Trans. Comput.-Hum. Interact. 9, 4 (December 2002), 362–389. DOI=http://dx. doi. org/10.1145/586081.586086

87. Steven Houben, Nicolai Marquardt, WatchConnect: A Toolkit for Prototyping Smartwatch-Centric Cross-Device Applications, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, April 18–23, 2015, Seoul, Republic of Korea [doi¿10.1145/2702123.2702215]

88. Huber, P. J. (1992), "Issues in computational data analysis," in Computational Statistics, Vol.2 (Y. Dodge and J. Whittaker, eds.), Physica Verlag, Heidelberg.

89. Hürst, Wolfgang, and Matthias Helder. 2011. "Mobile 3D Graphics and Virtual Reality Interaction." In Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology—ACE '11, 28–36. ACM Press.

90. Christophe Hurter, Benjamin Tissoires, and Stéphane Conversy. 2009. FromDaDy: Spreading Aircraft Trajectories Across Views to Support Iterative Queries. IEEE Transactions on Visualization and Computer Graphics 15, 6 (November 2009), 1017–1024. DOI=http://dx. doi. org/10.1109/TVCG.2009.145

91. Issartel, Paul, Florimond Guéniat, and Mehdi Ammi (2014). "A Portable Interface for Tangible Exploration of Volumetric Data." In: Proc. VRST. Edinburgh, Scotland: ACM, pp. 209–210. isbn: 978-1-4503-3253-8. doi: 10.1145/2671015.2671130. url: http://doi.acm.org/10.1145/2671015. 2671130

92. Jackson, Brian et al. (2013). "A Lightweight Tangible 3D Interface for Interactive Visualization of Thin Fiber Structures." In: IEEE Transactions on Visualization and Computer Graphics 19.12, pp. 2802–2809. doi: 10.1109/ TVCG.2013.121. url: http://ieeexplore.ieee.org/xpls/abs˙all.jsp? arnumber=6651934

93. JACOB, R. J. What You Look at is What You Get: Eye Movement-Based Interaction Techniques. In CHI '90 Proceedings (1990), ACM, pp. 11–18

94. Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2012. Tangible remote controllers for wall-size displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY, USA, 2865–2874. DOI: http://dx.doi.org/10.1145/2207676.2208691

95. Jansen Y. Physical and Tangible Information Visualization. PhD thesis. 2014. University Paris-Sud: France

96. Yvonne Jansen, Pierre Drag icevic, and Jean-Daniel Fekete. 2013. Evaluating the efficiency of physical visualizations. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems—CHI '13 : 2593. https://doi.org/10.1145/2470654.2481359

97. Javed, W., Ghani, S., Elmqvist, N. 2012. Polyzoom: multiscale and multifocus exploration in 2d visual spaces. In Proc. of CHI'12. ACM, pp. 287–296.

98. Kim, Ji Sun, Denis Gračanin, Krešimir Matković, and Francis Quek. 2008. "Finger Walking in Place (FWIP): A Traveling Technique in Virtual Environments." Smart Graphics LNCS 5166:58–69. doi:10.1007/978-3-540-85412-8˙6

99. Yucheng Jin, Chi Tai Dang, Christian Prehofer, and Elisabeth André. 2014. A Multi-Display System for Deploying and Controlling Home Automation. In Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14). ACM, New York, NY, USA, 399–402. DOI: https://doi.org/10.1145/2669485.2669553

100. Liu, Jingbo, Oscar Kin-Chung Au, Hongbo Fu, and Chiew-Lan Tai. 2012. "Shallow-Depth 3D Interaction: Design and Evaluation of One-, Two- and Three-Touch Techniques." Computer Graphics Forum 31 (7). John Wiley & Sons, Inc.: 2047–55.

101. Johanson, B., Hutchins, G., Winograd, T., Stone, M.: PointRight: experience with fl exible input redirection in interactive workspaces. In: Proceedings of the ACM Symposium on User Interface Software and Technology, pp. 227–234. ACM, New York (2002)

102. Tero Jokela, Jarno Ojala, Guido Grassel, Petri Piippo, and Thomas Olsson. 2015. A Comparison of Methods to Move Visual Objects Between Personal Mobile Devices in Different Contexts of Use. In Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '15). ACM, New York, NY, USA, 172–181. DOI: https://doi.org/10.1145/2785830.2785841

103. Jota, R., Nacenta, M. A., Jorge, J. A., Carpendale, S., and Greenberg, S. A comparison of ray pointing techniques for very large displays. In Proc. GI '10, CIPS (2010), 269–276.

104. Wendy Ju, David Sirkin, Animate objects: how physical motion encourages public interaction, Proceedings of the 5th international conference on Persuasive

Technology, p.40-51, June 07–10, 2010, Copenhagen, Denmark. DOI=http://dx. doi. org/10.1007/978-3-642-13226-1˙6

105. Thorsten Karrer, Moritz Wittenhagen, Leonhard Lichtschlag, Florian Heller, and Jan Borchers. 2011. Pinstripe: eyes-free continuous input on interactive clothing. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). ACM, New York, NY, USA, 1313–1322. DOI: https://doi.org/10.1145/1978942.1979137

106. KEAHEY, T. 1998. The generalized detail-in-context problem. In Proceedings of the IEEE Symposium on Information Visualization. IEEE Press, 44–51.

107. Daniel Kharlamov, Brandon Woodard, Liudmila Tahai, and Krzysztof Pietroszek. 2016. TickTockRay: smartwatch-based 3D pointing for smartphone-based virtual reality. In Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology (VRST '16). ACM, New York, NY, USA, 365–366. DOI: https://doi.org/10.1145/2993369.2996311

108. Chang-Min Kim, Tek-Jin Nam, G-raff: An Elevating Tangible Block for Spatial Tabletop Interaction, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, April 18–23, 2015, Seoul, Republic of Korea [doi¿10.1145/2702123.2702444]

109. Kirstein, C., and Muller, H. Interaction with a projection screen using a camera-tracked laser pointer. In Proc. MMM '98, IEEE (1998), 191–192.

110. T. Klein, F. Guéniat, L. Pastur, F. Vernier, and T. Isenberg. A design study of direct-touch interaction for exploratory 3d scientific visualization. In Computer Graphics Forum, volume 31, pages 1225–1234. Wiley Online Library, 2012

111. Kobayashi, M., Igarashi, T.: Ninja cursors: using multiple cursors to assist target acquisition on large screens. In: Proceedings of the ACM CHI Conference on Human Factors in Computing Systems, pp. 949–958. ACM, New York (2008)

112. Kohn KW. Molecular interaction map of the mammalian cell cycle control and DNA repair systems. Mol Biol Cell. 1999; 10 (8):2703–2734.

113. B. Kollee, S. Kratz, and A. Dunnigan. Exploring gestural interaction in smart spaces using head mounted devices with ego-centric sensing. In SUI, pages 40–49, 2014

114. Y. K. Leung and M. D. Apperley. 1994. A review and taxonomy of distortion-oriented presentation techniques. ACM Trans. Comput.-Hum. Interact. 1, 2 (June 1994), 126–160. DOI=http://dx. doi. org/10.1145/180171.180173

115. Ioannis Giannopoulos, Andreas Komninos, and John Garofalakis. 2017. Natural interaction with large map interfaces in VR. In Proceedings of the 21st Pan-Hellenic Conference on Informatics (PCI 2017). ACM, New York, NY, USA, Article 56, 6 pages. DOI: https://doi.org/10.1145/3139367.3139424

116. D. Lopez, L. Oehlberg, C. Doger, and T. Isenberg. Towards An Un- derstanding of Mobile Touch Navigation in a Stereoscopic Viewing Environment for 3d Data Exploration. IEEE Transactions on Visual—ization and Computer Graphics, 22 (5):1616–1629, May 2016

117. Paul Luff and Christian Heath, "Mobility in collaboration," in Proceedings of the 1998 ACM conference on Computer supported cooperative work CSCW'98), Seattle, Washington, USA, 1998, pp. 305–314.

118. Lundström, Claes et al. (2011). "Multi-Touch Table System for Medical Visualization: Application to Orthopedic Surgery Planning." In: IEEE Transactions on Visualization and Computer Graphics 17.12. doi: 10.1109/TVCG. 2011.224

119. Shahzad Malik, Abhishek Ranjan, Ravin Balakrishnan, Interacting with large displays from a distance with vision-tracked multi-finger gestural input, Proceedings of the 18th annual ACM symposium on User interface software and technology, October 23–26, 2005, Seattle, WA, USA

120. Thomas Marrinan, Arthur Nishimoto, Joseph A. Insley, Silvio Rizzi, Andrew Johnson, and Michael E. Papka. 2016. Interactive Multi-Modal Display Spaces for Visual Analysis. In Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces (ISS '16). ACM, New York, NY, USA, 421-426. DOI: https://doi.org/10.1145/2992154.2996792

121. Martinet, Anthony, Géry Casiez, and Laurent Grisoni. 2010. "The Effect of DOF Separation in 3D Manipulation Tasks with Multi-Touch Displays." In Proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology—VRST '10, 111–18. ACM Press.

122. Fabrice Matulic and Daniel Vogel. 2018. Multiray: Multi-Finger Raycasting for Large Displays. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18). ACM, New York, NY, USA, Paper 245, 13 pages. DOI: https://doi.org/10.1145/3173574.3173819

123. Mccallum, D. C., and Irani, P. Arc-pad: absolute+relative cursor positioning for large displays with a mobile touchscreen. In Proc. UIST '09, ACM (2009), 153–156

124. J. P. McIntire and K. K. Liggett. The (possible) utility of stereoscopic 3d displays for information visualization: The good, the bad, and the ugly. In IEEE VIS International Workshop on 3DVis (3DVis), pp. 1–9. IEEE, 2014

125. P. Milgram and H. Colquhoun. A taxonomy of real and virtual world display integration. Mixed reality: Merging real and virtual worlds, 1:1–26, 1999

126. B. P. Miranda, N. J. S. Carneiro, C. G. R. dos Santos, A. A. de Freitas, J. Magalhães, B. S. Meiguins, et al. Categorizing issues in mid-airinfovis interaction. In Information Visualization (IV), 2016 20th International Conference, pages 242–246. IEEE, 2016

127. Moscovich, T., Hughes, J.F. 2008. Indirect mappings of multi-touch input using one and two hands, In CHI'08. ACM, pp. 1275–1284.

128. Moscovich, T., Chevalier, F., Henry, N., Pietriga, E., and Fekete, J-D. 2009. Topology-aware navigation in large networks. In CHI '09. ACM, 2319–2328.

129. Nacenta, M.A., Aliakseyeu, D., Subramanian, S., Gutwin, C.: A comparison of techniques for multi-display reaching. In: Proceedings of the ACM CHI Conference on Human Factors in Computing Systems, pp. 371–380. Association for Computing Machinery, New York (2005)

130. Nacenta, M.A., Sallam, S., Champoux, B., Subramanian, S., Gutwin, C.: Perspective cursor: perspective-based interaction for multi-display environments. In: Proceedings of the ACM CHI Conference on Human Factors in Computing Systems, pp. 289–298. Association for Computing Machinery, New York (2006)

131. Nancel, M., Pietriga, E., and Beaudouin-Lafon, M. Precision pointing for ultra-high-resolution wall displays. Technical Report RR-7624, INRIA, 2011

132. M. Nancel, J. Wagner, E. Pietriga, O. Chapuis, and W. Mackay. Mid-air pan-and-zoom on wall-sized displays. In Proc. of CHI, pp. 177–186. ACM, 2011.

133. Mathieu Nancel, Olivier Chapuis, Emmanuel Pietriga, Xing-Dong Yang, Pourang P. Irani, Michel Beaudouin-Lafon, High-precision pointing on large wall displays using small handheld devices, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 27-May 02, 2013, Paris, France [doi¿10.1145/2470654.2470773]

134. Mathieu Nancel, Emmanuel Pietriga, Olivier Chapuis, and Michel Beaudouin-Lafon. 2015. Mid-Air Pointing on Ultra-Walls. ACM Trans. Comput.-Hum. Interact. 22, 5 : 21:1 — 21:62. http://doi.org/10.1145/2766448

135. Ni T, et al. A survey of large high-resolution display technologies, techniques, and applications. IEEE Virtual Reality, IEEE Computer Society, Alexandria, VA, 2006; 223–234.

136. Ji-Young Oh, Wolfgang Stuerzlinger. (2002) Laser Pointers as Collaborative Pointing Devices, Graphics Interfaces 2002, p. 141–149

137. Timo Ojala, Vassilis Kostakos, Hannu Kukka, Tommi Heikkinen, Tomas Linden, Marko Jurmu, Simo Hosio, Fabio Kruger, Daniele Zanni, Multipurpose Interactive Public Displays in the Wild: Three Years Later, Computer, v.45 n.5, p.42-49, May 2012. DOI=http://dx. doi. org/10.1109/MC.2012.115

138. Michael Ortega and Laurence Nigay. 2009. AirMouse: Finger Gesture for 2D and 3D Interaction. In Proceedings of the 12th IFIP TC 13 International Conference on Human-Computer Interaction: Part II (INTERACT '09), Tom Gross, Jan Gulliksen, Paula Kotzé, Lars Oestreicher, Philippe Palanque, Raquel Oliveira Prates, and Marco Winckler (Eds.). Springer-Verlag, Berlin, Heidelberg, 214–227. DOI: https://doi.org/10.1007/978-3-642-03658-3˙28

139. Peter Peltonen, Esko Kurvinen, Antti Salovaara, Giulio Jacucci, Tommi Ilmonen, John Evans, Antti Oulasvirta, Petri Saarikko, It’s Mine, Don’t Touch! : interactions at a large multi-touch display in a city centre, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 05–10, 2008, Florence, Italy. DOI=http://dx. doi. org/10.1145/1357054.1357255

140. Gary Perelman, Marcos Serrano, Mathieu Raynal, Celia Picard, Mustapha Derras, Emmanuel Dubois, The Roly-Poly Mouse: Designing a Rolling Input Device Unifying 2D and 3D Interaction, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, April 18–23, 2015, Seoul, Republic of Korea [doi¿10.1145/2702123.2702244]

141. Gary Perelman, Marcos Serrano, Mathieu Raynal, Celia Picard, Mustapha Derras, Emmanuel Dubois, DECO: A Design Space for Device Composition, Proceedings of the 2016 ACM Conference on Designing Interactive Systems, June 04–08, 2016, Brisbane, QLD, Australia [doi¿10.1145/2901790.2901893]

142. Piumsomboon, T., A. Clark, M. Billinghurst, and A. Cockburn (2013). User-defined gestures for augmented reality. In Proc. of Interact, pp. 282–299. Springer

143. Henning Pohl, Michael Rohs, Around-device devices: my coffee mug is a volume dial, Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services, September 23–26, 2014, Toronto, ON, Canada. DOI=http://dx. doi. org/10.1145/2628363.2628401

144. Arnaud Prouzeau, Anastasia Bezerianos, and Olivier Chapuis. 2016. Towards Road Traffic Management with Forecasting on Wall Displays. In Proceedings of the 2016 ACM International Conference on Interactive Surfaces and Spaces (ISS ’16). ACM, New York, NY, USA, 119–128. DOI: https://doi.org/10.1145/2992154.2992158

145. R. Radkowski and C. Stritzke. Interactive Hand Gesture—based Assembly for Augmented Reality Applications. In Proc. of Advances in Computer-Human Interactions (ACHI), pp.303–308. IARIA, 2012

146. Roman Rädle , Hans-Christian Jetter , Nicolai Marquardt , Harald Reiterer , Yvonne Rogers, HuddleLamp: Spatially-Aware Mobile Displays for Ad-hoc Around-the-Table Collaboration, Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces, November 16–19, 2014, Dresden, Germany [doi¿10.1145/2669485.2669500]

147. Axel Radloff, Christian Tominski, Thomas Nocke, Heidrun Schumann, Supporting presentation and discussion of visualization results in smart meeting rooms, The Visual Computer: International Journal of Computer Graphics, v.31 n.9, p.1271-1286, September 2015

148. Rebecca Randell, Gordon Hutchins, John Sandars, Thilina Ambepitiya, Darren Treanor, Rhys Thomas, and Roy Ruddle. 2012. Using a high-resolution wall-sized virtual microscope to teach undergraduate medical students. In CHI ’12 Extended

Abstracts on Human Factors in Computing Systems (CHI EA '12). ACM, New York, NY, USA, 2435–2440. DOI: https://doi.org/10.1145/2212776.2223815

149. Rashid, U., Miguel A. Nacenta, and Aaron Quigley. 2012. The cost of display switching: a comparison of mobile, large display and hybrid UI configurations. In Proc. of AVI '12. ACM, 99–106.

150. Ramesh Raskar, Greg Welch, Matt Cutts, Adam Lake, Lev Stesin, Henry Fuchs, The office of the future: a unified approach to image-based modeling and spatially immersive displays, Proceedings of the 25th annual conference on Computer graphics and interactive techniques, p.179-188, July 1998 [doi¿10.1145/280814.280861]

151. Rautaray, Siddharth S. "Real Time Hand Gesture Recognition System for Dynamic Applications." IJU International Journal of UbiComp 3.1 (2012): 21–31. Web

152. Jun Rekimoto, Pick-and-drop: a direct manipulation technique for multiple computer environments, Proceedings of the 10th annual ACM symposium on User interface software and technology, p.31-39, October 14–17, 1997, Banff, Alberta, Canada [doi¿10.1145/263407.263505]

153. Jun Rekimoto, Masanori Saitoh, Augmented surfaces: a spatially continuous work space for hybrid computing environments, Proceedings of the SIGCHI conference on Human Factors in Computing Systems, p.378-385, May 15–20, 1999, Pittsburgh, Pennsylvania, USA [doi¿10.1145/302979.303113]

154. Rodrigues, F., Seyed, T., Maurer, F., and Carpendale, S. 2014. Bancada: Using Mobile Zoomable Lenses for Geospatial Exploration. In ITS '14. ACM, 409–414.

155. Rogers, Y., Lindley, S.E.: Collaborating around vertical and horizontal large interactive displays: which way is best? Interact. Comput. 16 (6), 1133–1152 (2004)

156. David Rudi, Ioannis Giannopoulos, Peter Kiefer, Christian Peier, and Martin Raubal. 2016. Interacting with Maps on Optical Head-Mounted Displays. In Proceedings of the 2016 Symposium on Spatial User Interaction (SUI '16). ACM, New York, NY, USA, 3–12. DOI: https://doi.org/10.1145/2983310.2985747

157. Houssem Saidi, Marcos Serrano, and Emmanuel Dubois. 2016. Investigating the effects of splitting detailed views in Overview+Detail interfaces. In Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI '16). ACM, New York, NY, USA, 180-184. DOI: https://doi.org/10.1145/2935334.2935341

158. Houssem Saidi, Marcos Serrano, Pourang Irani, and Emmanuel Dubois. 2017. TDome: A Touch-Enabled 6DOF Interactive Device for Multi-Display Environments. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). ACM, New York, NY, USA, 5892–5904. DOI: https://doi.org/10.1145/3025453.3025661

159. H. Saidi, E. Dubois, and M. Serrano. 2017. Using everyday objects to interact with multi-display environments. In Proceedings of the 29th Conference on l'Interaction

Homme-Machine (IHM '17). ACM, New York, NY, USA, 253-262. DOI: https://doi.org/10.1145/3132129.3132155

160. Houssem Saidi, Marcos Serrano, Pourang Irani, Christophe Hurter, Emmanuel Dubois. On-body tangible interactions for immersive visualisations. In Proceedings of the 30th Conference on l'Interaction Homme-Machine (IHM '19), Brest, 23/10/2018-26/10/2018.

161. M. Sarkar and M. H. Brown. Graphical fisheye views of graphs. CHI '92: Proceedings of the SIGCHI conference on Human factors in computing systems, pages 83–91, 1992.

162. Schkolne, Steven, Hiroshi Ishii, and Peter Schroder (2004). "Immersive design of DNA molecules with a tangible interface." In: Proc. Visualization. Los Alamitos: IEEE Computer Society, pp. 227–234. doi: 10.1109/ VISUAL.2004.47

163. Dominik Schmidt, Corina Sas, Hans Gellersen, Personal clipboards for individual copy-and-paste on shared multi-user surfaces, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 27-May 02, 2013, Paris, France [doi¿10.1145/2470654.2466457]

164. Stefan Schneegass, There is more to Interaction with Public Displays than Kinect: Using Wearables to Interact with Public Displays, Proceedings of the 4th International Symposium on Pervasive Displays, June 10–12, 2015, Saarbruecken, Germany. DOI: http://dx.doi.org/10.1145/2757710.2776803

165. Shneiderman, B. 1997. Designing the User Interface: Strategies for Effective Human-Computer Interaction (3rd ed.). Addison-Wesley, Boston, MA, USA.

166. Julian Seifert, Sebastian Boring, Christian Winkler, Florian Schaub, Fabian Schwab, Steffen Herrdum, Fabian Maier, Daniel Mayer, Enrico Rukzio, Hover Pad: interacting with autonomous and self-actuated displays in space, Proceedings of the 27th annual ACM symposium on User interface software and technology, October 05–08, 2014, Honolulu, Hawaii, USA [doi¿10.1145/2642918.2647385]

167. Marcos Serrano, Barrett M. Ens, and Pourang P. Irani. 2014. Exploring the use of hand-to-face input for interacting with head-worn displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 3181–3190. DOI: https://doi.org/10.1145/2556288.2556984

168. Marcos Serrano, Barrett Ens, Xing-Dong Yang, Pourang Irani, Gluey: Developing a Head-Worn Display Interface to Unify the Interaction Experience in Distributed Display Environments, Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services, August 24–27, 2015, Copenhagen, Denmark [doi¿10.1145/2785830.2785838]

169. MRI Table Kinect: A multi-surface application for exploring volumetric medical imagery. Teddy Seyed, Chris Burns, Patrick King, Francisco Marinho Rodrigues, Mario Costa Sousa, Frank Maurer. In proceedings of the Workshop on Safer Interaction in Medical Devices (MediCHI'13), Paris, France, 2013

170. Alemayehu Seyed (2013). Examining User Experience in Multi-Display Environments

171. Orit Shaer, Eva Hornecker (2010), "Tangible User Interfaces: Past, Present, and Future Directions", Foundations and Trendsff in Human—Computer Interaction: Vol. 3: No. 1–2, pp 4–137. DOI=http://dx. doi. org/10.1561/1100000026

172. Shupp L, et al. Shaping the display of the future: The effects of display size and curvature on user performance and insights. Hum Comput Interact 2009; 24 (1): 230–272.

173. Sollich, Hendrik et al. (2016). "Exploring Time-dependent Scientific Data Using Spatially Aware Mobiles and Large Displays." In: Proceedings of the 2016 ACM on Interactive Surfaces and Spaces. ISS '16. Niagara Falls, Ontario, Canada: ACM, pp. 349–354. isbn: 978-1-4503-4248-3. doi: 10. 1145/2992154.2996779. url: http://doi.acm.org/10.1145/2992154. 2996779.

174. Peng Song, Wooi Boon Goh, Chi-Wing Fu, Qiang Meng, and Pheng-Ann Heng. 2011. WYSIWYF: exploring and annotating volume data with a tangible handheld device. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). ACM, New York, NY, USA, 1333–1342. DOI: https://doi.org/10.1145/1978942.1979140

175. T. Sousa, I. Cardoso, J. Parracho, P. Dias, and B. S. Santos. DETI-Interact: Interaction with Large Displays in Public Spaces Using Kinect. In Proc. of Distributed, Ambient, and Pervasive Interactions (DAPI), pp. 196–206. Springer, 2014

176. Mark Stefik et al., "Beyond the chalkboard: computer support for collaboration and problem solving in meetings," Communications of the ACM, vol. 30, no. 1, pp. 32–47, January 1987.

177. Stoakley, Richard, Matthew J. Conway, and Randy Pausch (1995). "Virtual Reality on a WIM: Interactive Worlds in Miniature." In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. CHI '95. Denver, Colorado, USA: ACM Press/Addison-Wesley Publishing Co., pp. 265–272. isbn: 0-201-84705-1. doi: 10. 1145 / 223904. 223938. url: http://dx.doi.org/10.1145/223904.223938.

178. Su, R.E., & Bailey, B.P. (2005). Put Them Where? Towards Guidelines for Positioning Large Displays in Interactive Workspaces. Proc. INTERACT, 337–349.

179. Tan DS, Gergle D, Scupelli P and Pausch R. Physically large displays improve performance on spatial tasks. ACM Trans Comput Hum Interact 2006; 13 (1): 71–99.

180. Sheng Kai Tang, Yusuke Sekikawa, Daniel Leithinger, Follmer Sean, and Hiroshi Ishii. 2013. Tangible CityScape. Retrieved February 4, 2018 from http://tangible.media.mit.edu/project/tangible—cityscape/

181. Dong-Bach Vo, Eric Lecolinet, and Yves Guiard. 2014. Belly gestures: body centric gestures on the abdomen. In Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational (NordiCHI '14). ACM, New York, NY, USA, 687–696. DOI: https://doi.org/10.1145/2639189.2639210

182. Daniel Vogel and Ravin Balakrishnan. 2005. Distant freehand pointing and clicking on very large, high-resolution displays. Proceedings of the 18th annual ACM symposium on User interface software and technology, ACM, 33–42. http://doi.org/10.1145/1095034.1095041

183. Julie Wagner. A bodycentric framework for generating and evaluating novel interaction techniques. UniversitéParis Sud - Paris XI, 2012. https://tel.archives-ouvertes.fr/tel-00772138

184. Julie Wagner, Mathieu Nancel, Sean G. Gustafson, Stephane Huot, and Wendy E. Mackay. 2013. Body-centric design space for multi-surface interaction. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). ACM, New York, NY, USA, 1299–1308. DOI: https://doi.org/10.1145/2470654.2466170

185. Manuela Waldner, Ernst Kruijff, Dieter Schmalstieg, Bridging gaps with pointer warping in multi-display environments, Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries, October 16–20, 2010, Reykjavik, Iceland [doi¿10.1145/1868914.1869036]

186. James R. Wallace, Regan L. Mandryk, and Kori M. Inkpen. 2008. Comparing content and input redirection in MDEs. In Proceedings of the 2008 ACM conference on Computer supported cooperative work (CSCW '08). ACM, New York, NY, USA, 157-166. DOI=http://dx.doi.org/10.1145/1460563.1460588

187. James R. Wallace, Stacey D. Scott, Eugene Lai, and Deon Jajalla. 2011. Investigating the Role of a Large, Shared Display in Multi-Display Environments. Comput. Supported Coop. Work 20, 6 (December 2011), 529-561. DOI=http://dx.doi.org/10.1007/s10606-011-9149-8

188. Robert Walter , Gilles Bailly , Jörg Müller, StrikeAPose: revealing mid-air gestures on public displays, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 27-May 02, 2013, Paris, France [doi¿10.1145/2470654.2470774]

189. Robert Walter, Gilles Bailly, Nina Valkanova, and Jörg Müller. 2014. Cuenesics: using mid-air gestures to select items on interactive public displays. In Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services (MobileHCI '14). ACM, New York, NY, USA, 299–308. DOI: https://doi.org/10.1145/2628363.2628368

190. Wang, J. and R. W. Lindeman (2015). "Object impersonation: Towards effective interaction in tablet and HMD-based hybrid virtual

191. Cheng-YaoWang, Wei-Chen Chu, Po-Tsung Chiu, Min-Chieh Hsiu, Yih-Harn Chiang, and Mike Y. Chen. 2015. PalmType: Using palms as keyboards for smart

glasses. In Proceedings of the SIGCHI Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI'15). 153–160. DOI: http://dx.doi.org/10.1145/2785830.2785886

192. Wegman, E. J. 1988, 'A view of computational statistics and its curriculum,' Am. Statist. Assoc. Proc. Sect. Statist. Educat. 1–6.

193. Sean White and Steven Fe iner. 2009. SiteLens: Situated Visualization Techniques for Urban Site Visits. Proceedings of the 2009 ACM CHI Conference on Human Factors in Computing Systems: 1117–1120. https://doi.org/10.1145/1518701.1518871

194. Winder, James Ira and Kent Larson. "Bits and Bricks Tangible Interactive Matrix for Real-time Computation and 3 D Projection Mapping." (2017)

195. Wobbrock, J.O., Aung, H.H., Rothrock, B. and Myers, B.A. (2005) Maximizing the guessability of symbolic input. Ext. Abstracts CHI '05. New York: ACM Press, 1869-1872.

196. Jacob O. Wobbrock, Meredith Ringel Morris, Andrew D. Wilson, User-defined gestures for surface computing, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 04–09, 2009, Boston, MA, USA [doi¿10.1145/1518701.1518866]

197. Xing-Dong Yang , Edward Mak , David McCallum , Pourang Irani , Xiang Cao , Shahram Izadi, LensMouse: augmenting the mouse with an interactive touch display, Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 10–15, 2010, Atlanta, Georgia, USA [doi¿10.1145/1753326.1753695]

198. Dianna Yim, Garance Nicole Loison, Fatemeh Hendijani Fard, Edwin Chan, Alec McAllister, and Frank Maurer. 2016. Gesture-driven Interactions on a Virtual Hologram in Mixed Reality. In Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces (ISS Companion '16). ACM, New York, NY, USA, 55–61. DOI: https://doi.org/10.1145/3009939.3009948

199. Yost B, Haciahmetoglu Y and North C. Beyond visual acuity: The perceptual scalability of information visualizations for large displays. CHI 2007. San Jose, CA: ACM, 2007, pp. 101–110.

200. Shumin Zhai and Paul Milgram. 1998. Quantifying coordination in multiple DOF movement and its application to evaluating 6 DOF input devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '98), Clare-Marie Karat, Arnold Lund, Joëlle Coutaz, and John Karat (Eds.). ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 320–327. DOI=http://dx. doi. org/10.1145/274644.274689

201. Shengdong Zhao, Ravin Balakrishnan, Simple vs. compound mark hierarchical marking menus, Proceedings of the 17th annual ACM symposium on User interface software and technology, October 24–27, 2004, Santa Fe, NM, USA [doi¿10.1145/1029632.1029639]

# Design and Evaluation of Interaction Techniques for exploring Complex Data in Large Display-Spaces


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## Abstract


Today's ever-growing data is becoming increasingly complex due to its large volume and high dimensionality: it thus becomes crucial to explore interactive visualization environments that go beyond the traditional desktop in order to provide a larger display area and offer more efficient interaction techniques to manipulate the data. The main environments fitting the aforementioned description are: large displays, i.e. an assembly of displays amounting to a single space; Multi-display Environments (MDEs), i.e. a combination of heterogeneous displays (monitors, smartphones/tablets/wearables, interactive tabletops…) spatially distributed in the environment; and immersive environments, i.e. systems where everything can be used as a display surface, without imposing any bound between displays and immersing the user within the environment. The objective of our work is to design and experiment original and efficient interaction techniques well suited for each of the previously described environments.

First, we focused on the interaction with large datasets on large displays. We specifically studied simultaneous interaction with multiple regions of interest of the displayed visualization. We implemented and evaluated an extension of the traditional overview+detail interface to tackle this problem: it consists of an overview+detail interface where the overview is displayed on a large screen and multiple detailed views are displayed on a tactile tablet. The interface allows the user to have up to four detailed views of the visualization at the same time. We studied its usefulness as well as the optimal number of detailed views that can be used efficiently.

Second, we designed a novel touch-enabled device, TDome, to facilitate interactions in Multi-display environments. The device is composed of a dome-like base and provides up to 6 degrees of freedom, a touchscreen and a camera that can sense the environment. Having a unique device for interaction in these environments limits the homing effect when switching from one device to another and leads to a coherent set of interactions with the MDE, contributing to a more fluid task flow, a key element in such environments.

Finally, we introduced a new approach to interact in immersive environments with complex data. It is based on the use of the forearm as a physical support to assist tangible interactions with a multi-degrees of freedom device. We proposed a design space for this approach and we validated its feasibility through an experiment aimed at establishing the range, stability and comfort of gestures performed in this new paradigm.

All along this research work, resulting interaction techniques and environments have been concretely illustrated for exploring energy consumption data in the context of neOCampus, a project of the University of Toulouse 3 that aims at exploring the Campus of the Future, i.e. a smart, innovative and sustainable campus.

# Keywords

Human-computer interaction; Complex Data; Large displays; Multi-display environments; Immersive environments; Multi-degrees of freedom devices.

Discipline: Computer Science

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# Conception et évaluation de techniques d'interaction pour l'exploration de données complexes dans de larges espaces d'affichage

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## Résumé

Les données d'aujourd'hui deviennent de plus en plus complexes à cause de la forte croissance de leurs volumes ainsi que leur multidimensionnalité. Il devient donc nécessaire d'explorer des environnements d'affichage qui aillent au-delà du simple affichage de données offert par les moniteurs traditionnels et ce, afin de fournir une plus grande surface d'affichage ainsi que des techniques d'interaction plus performantes pour l'exploration de données. Les environnements correspondants à cette description sont les suivants : Les écrans large ; les environnements multi-écrans (EME) composés de plusieurs écrans hétérogènes spatialement distribués (moniteurs, smartphones, tablettes, table interactive …) ; les environnements immersifs.

Dans ce contexte, l'objectif de ces travaux de thèse est de concevoir et d'évaluer des solutions d'interaction originales, efficaces et adaptées à chacun des trois environnements cités précédemment.

Une première contribution de nos travaux consiste en Split-focus : une interface de visualisation et d'interaction qui exploite les facilités offertes par les environnements multi-écrans dans la visualisation de données multidimensionnelles au travers d'une interface overview + multi-detail multi-écrans. Bien que plusieurs techniques d'interaction offrent plus d'une vue détaillée en simultané, le nombre optimal de vues détaillées n'a pas été étudié. Dans ce type d'interface, le nombre de vues détaillées influe grandement sur l'interaction : avoir une seule vue détaillée offre un grand espace d'affichage mais ne permet qu'une exploration séquentielle de la vue d'ensemble ; avoir plusieurs vues détaillées réduit l'espace d'affichage dans chaque vue mais permet une exploration parallèle de la vue d'ensemble. Ce travail explore le bénéfice de diviser la vue détaillée d'une interface overview + detail pour manipuler de larges graphes à travers une étude expérimentale utilisant la technique Split-focus. Split-focus est une interface overview + multi-détails permettant d'avoir une vue d'ensemble sur un grand écran et plusieurs vues détaillées (1,2 ou 4) sur une tablette.

Une seconde contribution de nos travaux consiste en TDome : un dispositif d'interaction en entrée et sortie conçu pour pallier le manque de techniques d'interaction dédiées aux environnements multi-écrans. Sa base semi-sphérique lui permet d'offrir plusieurs degrés de liberté sous la forme de manipulations physiques (inclinaison, rotation, translation). Le dispositif est augmenté d'un écran tactile qui lui permet d'afficher de l'information et de détecter des entrées tactiles. La combinaison de manipulations physiques et de gestes tactiles fait de lui un dispositif robuste et augmente l'espace de gestes qu'il offre. Ceci lui permet de répondre aux multiples besoins des environnements multi-écrans tout en évitant la multiplication de dispositifs dans l'espace de travail et, notamment, la détection des écrans dans l'espace de travail, la sélection d'écrans, le transfert de données entre écrans et l'interaction avec des écrans distants.

Enfin, une troisième contribution de ces travaux consiste en l'introduction d'une nouvelle approche d'interaction avec des visualisations immersives. L'approche combine 1) l'usage d'un dispositif sans-fils de type souris multi-DOF, alliant la précision inhérente à une souris, la souplesse d'utilisation du tangible et les larges capacités de contrôle propres aux dispositifs à multiples degrés de liberté et 2) l'utilisation du corps de l'utilisateur pour guider les déplacements du dispositif et exploiter ainsi la proprioception de l'utilisateur, tout en limitant la fatigue musculaire propre aux interactions en l'air.

Tout au long de ce travail de recherche, les techniques d'interaction conçues ont été concrètement illustrées pour l'exploration de données de consommation énergétique dans le contexte de neOCampus, un projet de l'université Paul Sabatier qui a pour objectif d'améliorer le confort au quotidien pour la communauté universitaire tout en diminuant l'empreinte écologique des bâtiments et en réduisant les coûts de fonctionnement (fluide, eau, électricité…).

## Mots-clés

Interaction Homme-Machine ; Données complexes ; Ecrans larges ; Environnements multi-surfaces ; Environnements immersifs ; Dispositif à plusieurs degrés de liberté.

Discipline: Computer Science

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