# An interaction Continuum for 3D Dataset Visualization

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Par

**M. Lonni Besançon**

## An Interaction Continuum for 3D Dataset Visualization

**Thèse présentée et soutenue à Gif-sur-Yvette, le 14 décembre 2017 :**

**Composition du Jury :**

| | | |
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# SYNTHÈSE

La récente émergence des smartphones et des systèmes de tracking 3D a permis le développement d'un certains nombre de nouveaux paradigmes d'interaction. Parmis ces nouveaux paradigmes d'interaction, l'interaction tactile et l'interaction tangible ont reçu une attention toute particulière. De nombreuses techniques ont ainsi été développées pour permettre la manipulation de données 3D. Ce développement bénéficie, en particulier, aux domaines scientifiques tels que la visualisation qui s'appuie sur la manipulation de données 3D. Des études comparatives ont démontré les avantages de chacun d'entre eux pour des tâches spécifiques liées à la visualisation. Pourtant, les interfaces utilisateur graphiques classiques ainsi que la souris et les claviers prédominent toujours dans la plupart des environnements interactifs: ils sont toujours utiles pour des tâches spécifiques et facilement accessibles par rapport aux nouveaux paradigmes d'interaction et aux dispositifs innovants.

Contrairement à l'approche habituelle qui consiste à créer ou étudier une nouvelle technique ou un nouveau dispositif d'interaction, les travaux présentés dans cette thèse ouvrent la voie à un continuum d'interaction: la possibilité de passer d'un paradigme d'interaction à l'autre et de combiner deux ou plusieurs paradigmes d'interaction pour en tirer profit. La création de ce continuum repose sur plusieurs étapes.

Tout d'abord, en se basant sur l'observation que la souris et le clavier, l'interaction tactile et l'interaction tangible sont maintenant des normes ou se rapprochent d'être des paradigmes d'interaction standard pour les cas d'utilisation occasionnelle ou spécifique, cette thèse étudie et compare leurs avantages et limites inhérents aux manipulations 3D.

Sur la base de ce travail, nous créons ensuite un paradigme d'interaction hybride tactile et tangible. Basé sur les besoins de la visualisation scientifique pour la mécanique des fluides, nous mettons en oeuvre des techniques spécifiques d'interaction exploratrice 3D avec le paradigme hybride et les évaluons avec des experts du domaine. La mise en oeuvre prototypique de ce paradigme hybride repose sur une tablette tactile capable de se géolocaliser. Sur la base des retours d'expérience des experts du domaine, une telle combinaison est plus flexible que l'état de l'art et permet des manipulations 3D précises.

Avec le potentiel de ce paradigme hybride, nous abordons ensuite la tâche complexe de la sélection des sous-ensembles 3D —une étape initiale majeure pour la compréhension des données. Alors que la sélection de sous-ensembles 3D est généralement effectuée avec une entrée 2D initiale étendue ultérieurement par l'ordinateur, notre combinaison tactile/tangible permet aux utilisateurs d'avoir une technique de sélection entièrement manuelle avec la même tablette: un lasso 2D peut être dessiné avec une entrée tactile qui peut ensuite être étendue en 3D lors du déplacement de la tablette. Non

seulement cette combinaison comble-t-elle un vide dans la taxonomie des techniques de sélection de sous-ensembles 3D, mais elle est également plus précise que les solutions partiellement automatisées, quoique plus lentes.

Enfin, en nous appuyant sur l'observation selon laquelle une interaction tangible avec un dispositif localement couplé pourrait nécessiter des ajustements de facteur de gain, nous proposons d'utiliser un aspect spécifique de l'interaction tactile, la détection de pression, pour contrôler les facteurs de gain des manipulations tangibles.

Les travaux présentés dans cette thèse démontrent donc le potentiel d'un continuum d'interaction pour la visualisation en proposant des paradigmes d'interaction hybrides dans une configuration facile à maintenir, facile à intégrer et abordable. Il fournit les premières étapes nécessaires pour un continuum d'interaction qui, espérons-le, inspirera la création de plus de techniques d'interaction hybrides pour l'interaction de données 3D.

# PUBLICATIONS

## Papers in International Conferences

1. Paul Issartel, **Lonni Besançon**, Mehdi Ammi, Tobias Isenberg. Preference Between Allocentric and Egocentric 3D Manipulation in a Locally Coupled Configuration. *ACM Symposium on Spatial User Interaction, Oct 2016, Tokyo, Japan.*
2. Paul Issartel, **Lonni Besançon**, Mehdi Ammi, Tobias Isenberg. A Tangible Volume for Portable 3D Interaction. *2016 IEEE International Symposium on Mixed and Augmented Reality, Sep 2016, Merida, Mexico. pp.5.*
3. **Lonni Besançon**,Paul Issartel, Mehdi Ammi, Tobias Isenberg. Hybrid Tactile/Tangible Interaction for 3D Data Exploration. *IEEE Transactions on Visualization and Computer Graphics, Institute of Electrical and Electronics Engineers, 2017, 23 (1), pp.881-890.*
4. **Lonni Besançon**,Paul Issartel, Mehdi Ammi, Tobias Isenberg. Mouse, Tactile, and Tangible Input for 3D Manipulation. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI), May 2017, Denver, United States. pp.4727-4740.*
5. **Lonni Besançon**, Mehdi Ammi, Tobias Isenberg. Pressure-Based Gain Factor Control for Mobile 3D Interaction using Locally-Coupled Devices. *Proceedings of the ACM Conference on Human Factors in Computing Systems (CHI), May 2017, Denver, United States. pp.1831-1842.* **Best Paper Award Honorable Mention**

## Papers in National Conferences

6. **Lonni Besançon**,Paul Issartel, Mehdi Ammi, Tobias Isenberg. Interactive 3D Data Exploration Using Hybrid Tactile/Tangible Input. *Journees Visu 2017, Jun 2017, Rueil-Malmaison, France*
7. **Lonni Besançon**, Pierre Dragicevic. La Difference Significative entre Valeurs p et Intervalles de Confiance *ACM Alt IHM 2017, August 2017, Poitier, France*

## Extended Abstracts

8. Mickael Sereno, Mehdi Ammi, Tobias Isenberg, **Lonni Besançon** Tangible Brush: Performing 3D Selection with Portable and Position-aware Devices. *IEEE VIS2016, Oct 2016, Baltimore, United States*
9. Mickael Sereno, Mehdi Ammi, Tobias Isenberg, **Lonni Besançon** Interaction Hybride Tactile/Tangible pour la Sélection 3D. *ACM IHM2017, August 2017, Poitier, France*

10. Xiyao Wang, **Lonni Besançon** Mehdi Ammi, Tobias Isenberg Augmenting Tactile 3D Data Exploration With Pressure Sensing *IEEE VIS2017, Oct 2016, Phoenix, United States*

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## CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

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# 1

# INTRODUCTION

*The eye...*
*The window of the soul,*
*Is the principal mean*
*By which the central sense*
*Can most completely and*
*Abundantly appreciate*
*The infinite works of nature.*

Leonardo da Vinci

## 1.1 TOWARD AN INTERACTION CONTINUUM FOR 3D DATA VISUALIZATION

Being able to picture specific concepts has historically helped with discoveries and hypothesis formulation as well as communication of findings. The use of visual representation is particularly effective because vision is human beings' dominant sense. Early examples can be found in early human history, pre-computer depictions and computer generated visualizations. For instance, the English photographer Eadweard Muybridge used an array of 12 cameras to photograph a galloping horse in order to understand whether all four feet of a horse went off the ground at the same time (see Figure 1). Earlier, Da Vincy used sketching in order to communicate on Vitruvius's theories about perfect human proportions in his work the *The Canon of Proportions*, a drawing also known as *The Vitruvian Man*.

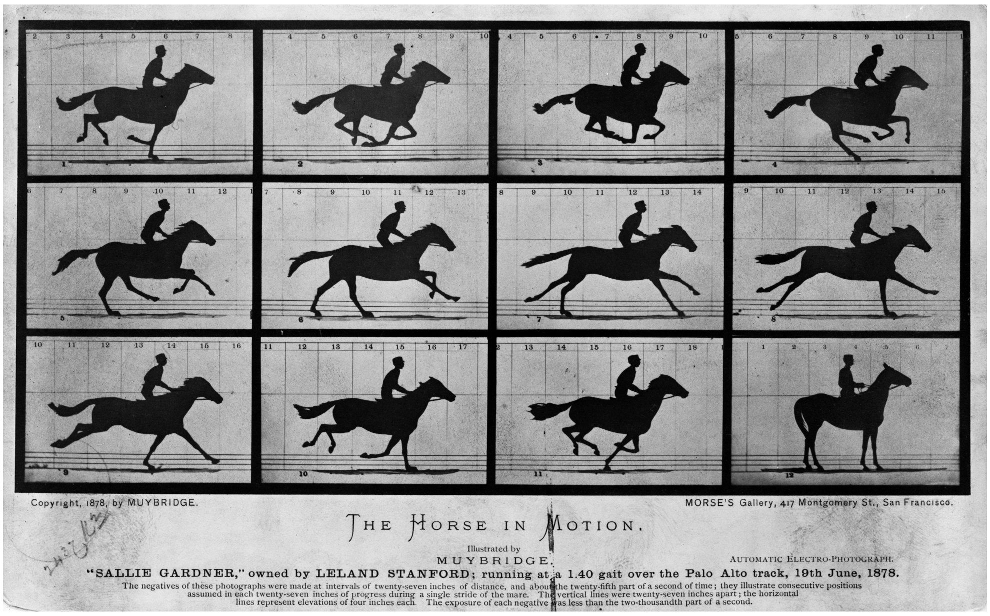


Figure 1: The horse in motion by Eadweard Muybridge, 1878 (Public Domain)

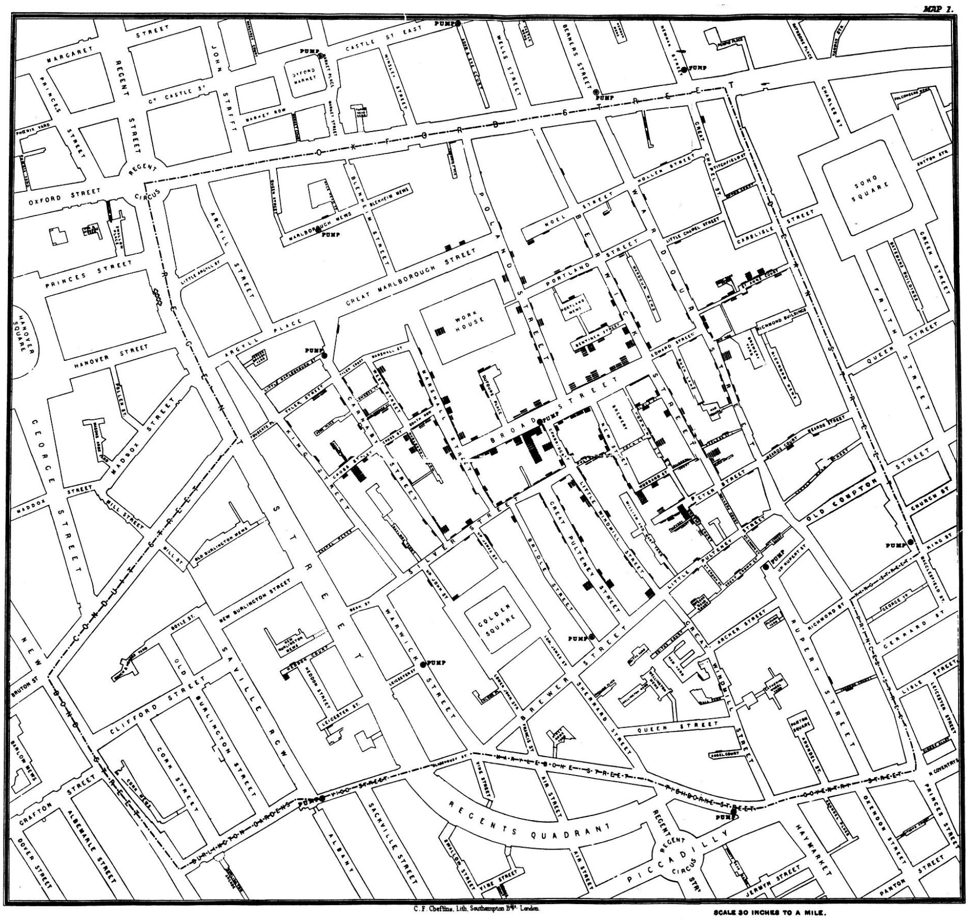


Figure 2: John Snow's map of the cholera outbreak in the streets of London, 1878 (Public Domain)

Other famous examples of illustrations can be found, for instance, in John Snow's map of the cholera outbreak (see Figure 2), Gantt charts for project management, or network maps. The scientific field behind this use of illustration to assist scientific thinking is called visualization. It thus led to the creation of an independent scientific branch specialized in the making of visual data representations. Visualization is an interdisciplinary branch of science that creates depictions of specific phenomena or data. Its purpose is to illustrate graphically phenomena, abstract or scientific datasets in order to help experts of different fields understand and gather qualitative and/or quantitative insights from the data/phenomena they are studying.

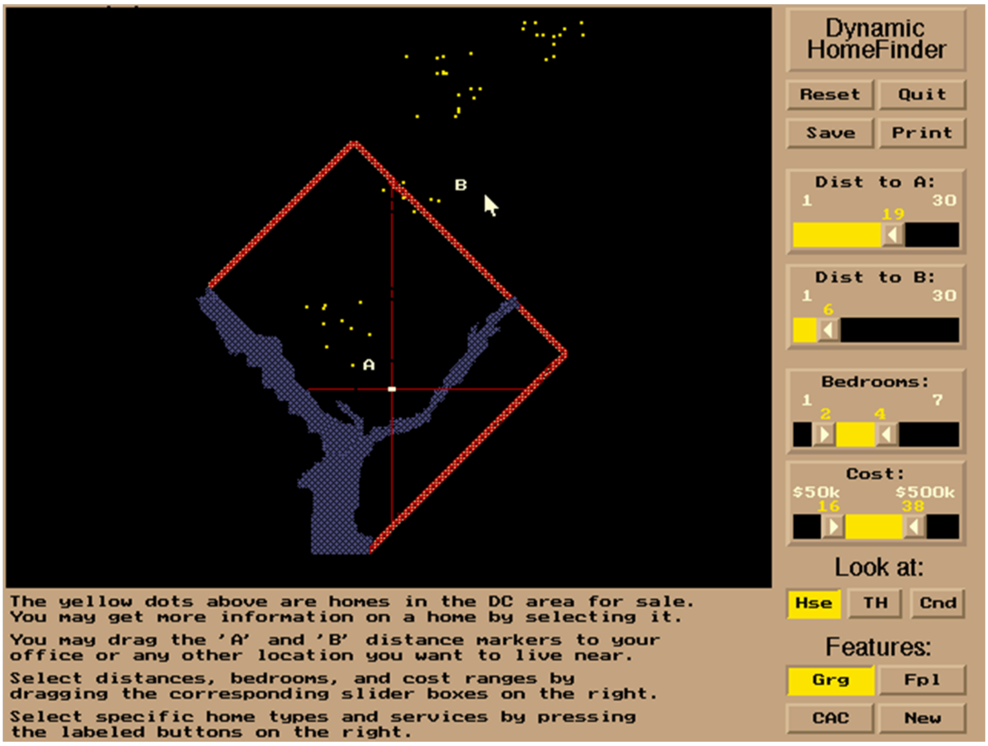
The invention of computer graphics during the twentieth century led to new advances in visualization, which can now refer to a wide variety of different visualization domains. Indeed, the visualization field now gathers techniques and knowledge from flow visualization, medical visualization, graph visualization, text visualization, network visualization...

While the generic end goal of each visualization subfield is always to gather insights on data, different data type call for different problems and thus to different problem-solving needs. For instance, with a map (which is two dimensional), viewers are either looking for a specific point or trying to figure out a path between two of them while with a network/graph, viewers can be interested in specific relationships between nodes, the shortest-path between two nodes, the minimum spanning tree of the network... Ben Shneiderman (1996) thus distinguishes between seven types of data:

1. One-dimensional (1D) data: that is linear data types. This includes code, textual documents, list of things or names.
2. Two-dimensional (2D) data: that is planar or map data. This includes geographic maps, or layouts.
3. Three-dimensional (3D) data: that is real-world object or simulation of the real-world object or phenomena. It is usually, but not necessarily, data that has inherent spatial attribute. This includes for instance the human body, the simulation of flows under an aircraft or molecules.
4. Temporal data: that is time lines which are extremely useful for historical timeline or medical records.
5. Multi-dimensional data: that is items with n attributes that can become points in a n-dimensional space. This can include phenomena simulation, statistical databases, demographics... The representation can be done either in 2D or 3D, depending on the data. Obviously, if the data has inherent spatial attributes, the representation should be in 3D.
6. Tree data: that is collection of items which all (except one, the root) have a link to a parent. This include hierarchical data or operating system's arborescence.
7. Network data: that is a collection of item which structure (relationship between its items) cannot be correctly represented with the simple tree structure as the number of link to parents or children node is unlimited. This includes network topology maps or social network relationship maps.

In this thesis, we focus in particular on three-dimensional data or at least on data that is rendered with a volumetric/spatial representation. This includes plain 3D data as well as higher-dimensional data that is better visualized in 3D. The former is, for instance, object rendering or product simulation or virtual environments which aim at representing a specific spatial project. The latter is oriented towards datasets that have many dimensions but an inherent spatial attribute or that can be represented with a volumetric representation. Numerous examples can be found in medical data, fluid dynamic simulations, molecular models, or physics simulations. They all posses inherent spatial information as well other attributes (density, temperature, acceleration, molecule type,...) that can be visually represented with different colors for instance (or other visual variables). While all these example are data from applied and concrete, tangible experiments or measures, abstract data could also be considered to include three-dimensional networks/graphs.

While it is often said that a picture is worth a thousand words, it remains that a still image cannot possibly be the solution to all problems. Consequently, visualization is often used, today, to talk about interactive visualization and often encompasses data representations and interaction techniques. One can then distinguish between infographics (static content, often represented on papers), and visualization (dynamic or animated data depictions). Even though great advances in data representations have been achieved with Bertin (1983) or Tufte (1990)' work, to name a few, interaction remains essential in order to give users the possibility to look for different insights, or solve specific problems that are inherent with the visualized datasets. For instance, three-dimensional datasets, the focus of this thesis work, are severed by occlusion problems (Shneiderman, 1996). The possibilities to interact with the visualized datasets have been multiplied by the advent of dynamic displays. Hence, in the early 90, researchers in visualization have started focusing on providing interactive visualization systems. The early *Dynamic HomeFinder* (Figure 3) is a good example proposed by Williamson and Shneiderman (1992). With this application, Williamson and Shneiderman supported through interaction the Visual Information Seeking Mantra "Overview first, zoom and filter, then details on demand". However, as pointed out by Ben Shneiderman first (Shneiderman, 1996), interactive visualization systems must go further than that and provide relate (to highlight relationships), history (to support undo, replay...) and extract (to support exporting to a file).



The yellow dots above are homes in the DC area for sale.
You may get more information on a home by selecting it.

You may drag the 'A' and 'B' distance markers to your
office or any other location you want to live near.

Select distances, bedrooms, and cost ranges by
dragging the corresponding slider boxes on the right.

Select specific home types and services by pressing
the labeled buttons on the right.

Figure 3: The Dynamic HomeFinger (Williamson and Shneiderman, 1992).

The three dimensionality of the datasets we focus on is a specific and important notion for human beings. We are indeed used to interact with a

3D spatial world with all the possible problems that are linked to it (occlusion, selection, navigation...). Human beings possess a natural ability, in most cases, to grasp and manipulate physical and, in particular, three-dimentional objects (Ishii, 2008a). The loss of physicality of most visualization systems, however, makes these problems more complicated and confusing within a digital world. At the beginning, computer interaction was conducted through keyboard queries and later evolved to include a mouse. Most system, and thus, most visualization systems hence first used such mouse and keyboard interaction patterns to provide interactions. Surprisingly, this is still the case. Most of the visualization systems or 3D manipulations applications are desktop software supporting mostly mouse and keyboard (e. g.Katia, Blender, Paraview, ...). Yet the nature of these datasets and their representation clearly stimulates a support for more natural interaction paradigms to better leverage the sense-making power of visualizations. Nonetheless, interaction had still not garnered much attention fifteen years after Williamson and Shneiderman (1992)'s work. As a consequence, (Cook and Thomas, 2005) and later Yi et al. (2007) specifically placed their focus on that topic and called for more research on that topic. With their work, Yi et al. introduced an often debated user-intent-based categorization of interaction and drew attention to the importance and inherent complexity of interaction. This effort was then continued by Keefe and Isenberg (Keefe, 2010; Keefe and Isenberg, 2013) for the topic of scientific visualization arguing for the use of more natural interaction paradigms for this specific topic. As a consequence, a fair number of research work has been conducted to better understand the possible benefits of old and new interaction paradigms for visualization e. g. (Issartel et al., 2014a; Fu et al., 2010; Jackson et al., 2013; Malmberg et al., 2006; Mandalika et al., 2017; Sollich et al., 2016; Song et al., 2011; Sultanum et al., 2011; Ynnerman et al., 2016; Yu et al., 2012; Zhou et al., 2008).

Many different interaction paradigms and techniques have been considered to help visualization practitioners, but a few of them, including the traditional mouse-based interfaces, have raised a particular attention. The inherent benefits of mouse-based interfaces are probably best demonstrated by their omnipresence in most scientific domains (e. g.medical (Mandalika et al., 2017), flow (Besançon et al., 2017),...). Mouse and keyboard interface are omnipresent, and most of the 3D softwares available propose graphical user interfaces adapted for mouse interaction (e. g.Paraview, Katia, Blender, Cura, ...). But other interaction paradigms have also been investigated.

For instance, tactile interaction has been investigated a lot (Buxton, 2007) and has been popularized by the rise of mobile devices in the last decade. It can provide an improved performance for certain tasks (Kin et al., 2009) while being compatible to mouse-based input for others (Forlines et al., 2007; Sears and Shneiderman, 1991), it supports collaboration awareness (Hornecker et al., 2008), provides somesthetic feedback (Robles-De-La-Torre, 2006), and seems suitability for physically large displays (Tan et al., 2006). It also appears that it is a good communication channel when one is presenting visualizations to others (Sundén et al., 2014). As a consequence, several research work focusing on visualization have explored the possibility offered by tactile interaction. 3D data exploration has been widely covered, (Cohé et al., 2011; Fu et al., 2010; Reisman et al., 2009; Yu et al., 2010) and other visualization fundamental tasks such as 3D picking/3D subset selections have also been successfully investigated (Yu et al., 2012; Yu et al., 2016).

Tangible interaction have also been frequently studied. In general, tangible interaction has been shown to be more engaging (Tuddenham et al., 2010) than other forms of input and to provide rich feedback (Zuckerman and Gal-Oz, 2013). As a consequence their use for insight gathering on scientific data has been investigated too. Hinckley et al. (1994b) used them for medical datasets as early as the 1994. De Guzman et al. (2003) made use of them to help children navigate through a human body dataset in order to facilitate learning. Tangible interaction has also been used for molecular visualization (Schkolne et al., 2004) or fluid dynamic visualization (Issartel et al., 2014b).

Other forms of input have also been used—yet marginally. A complete review would be out of the scope of this thesis, but a few of them seem to be frequently mentioned (cubic mice or wands which are often used in immersive VR systems). VR systems have indeed been investigated a lot, but are rarely used in real-world scenarios. VR systems are often defined as "A synthetic, spatial (usually 3D) world seen from a first-person point of view"(Bowman et al., 2005). Roussou and Drettakis (2005) explain the issues with the deployment of such systems continue to "resolve around the familiar practical difficulties: setting up special and costly hardware within facilities that are not easily transportable, requiring special teams of developers and maintenance staff [...]". The high cost of these environments has been mentioned a lot in the literature (Margolis et al., 2011; Grimes, 2013) and is indeed probably hindering the deployment of such systems. As such, even though they can offer natural and interesting input and output environments, often investigated in research work (see Chapter 2), we decide not to include immersive VR systems in our work. We believe that Desktop VR systems, such as the Passprop (Hinckley et al., 1994b), or other form of tangible inputs used in a simpler environments (Jackson et al., 2013) are more likely to be used in real-world scenarios and thus more likely to be used for visualization tasks and purposes.

The cubic mouse (Fröhlich and Plate, 2000) is a good example of a specific device that has been built in order to provide the six degrees of freedom needed by 3D manipulations. However, it is seldom present in working environments and is not even considered a baseline for manipulation tasks in research papers anymore which would rather use tactile or tangible interaction (Antle et al., 2009; Lucchi et al., 2010; Jansen et al., 2012; Terrenghi et al., 2007).

Wands (or other 3D tracked devices) are often used in VR environments. Similar to hand-tracking systems, their use rely on precise 3D tracking that is made through the use of complex and expensive camera setups that are, for the reasons stated above for CAVEs and other immersive VR environments, not likely to spread to working environments.

Despite the large number of investigated techniques and paradigms, it remains that mouse and keyboard interaction re still predominantly used in most interaction scenarios, including those that deal with 3D data visualization and exploration. This is particularly surprising in case of three-dimensional datasets visualization, for which the paradigms and devices studied above provide interesting input and/or output strategies. It seems that researchers keep on incrementing the number of interaction devices or techniques that are most of time not adopted by domain experts who keep on relying on their readily available devices (mouse and keyboard and perhaps touch interfaces on mobile devices). It thus seems essential to be able to link new interaction paradigms, devices and techniques with already adopted ones. The work presented in this thesis aims at making a first step in this direction in order to pave the way towards an *interaction continuum* for the visualization of three dimensional datasets.

A continuum is usually defined as "A continuous sequence in which adjacent elements are not perceptibly different from each other, but the extremes are quite distinct" (Dictionnary, 2017). Such a continuum for interaction would thus aim at tearing down the barriers between interaction paradigms in order to allow researchers to *seamlessly* use them *sequentially* or in *parallel*. Several words are important in the previous sentence and can lead to specific requirements for the building of such an interaction continuum. These requirements will be heavily discussed in the thesis as they all represent different means and requirements that are needed to obtain a continuum of interaction. We will now discuss and define them.

First of all, the term "seamless" which can be understood in different ways.

A first interpretation is the possibility to easily switch from on interacting device to another, providing similar or different interaction paradigms. This is perhaps the first idea that comes to mind when thinking of a continuum of interaction, and it thus leads to our first requirements.

**R1**: Possibility to connect and sync several devices together.

A second interpretation is the possibility to easily switch from one interaction paradigm to the other that frames our second requirement:

**R2**: Possibility to use several interaction paradigms to solve a specific problem.

The use of "seamless" (i. e. without any particular interruption) can also be understood as a way to exclude all environments requiring specific maintenance or calibration. It thus excludes overly-complicated setups (such as immersive VR environments) and overly specific devices that almost never never made it past the research prototype phase (e. g. cubic mouse, globe mouse...). In this case, our third and final requirement is:

**R3**: Providing both first and second requirements in easy-to-maintain, easy-to-integrate , and affordable devices and setups.

By fullfilling these three requirements, domain experts relying on visualization will be able to (**R1**) transition and transfer findings from classical devices (i. e. workstations) to more specific devices (and vice-versa) and (**R2**) use specific interaction paradigms for what they do best. The third requirement (**R3**)ensures that the work is not one new research prototype that is not likely to make it past the research phase and that can without effort be integrated into the worklow and work environment of domain experts.

The words "sequentially" and "parallel" also refer to the possibilities that could be offered by such an interaction continuum and allow us to envision two different scenarios. One could imagine for a sequential use that a single researcher is able to use a specific interaction paradigm or device first to achieve the initial steps of a task and then switch to an other one. The parallel use on the other can refer to either co-located collaborative work or to the possibility of a single person to make use, with a single device, of several interaction paradigms.

With those requirements in mind, the creation of an interaction continuum includes several research axes.

The first research axis is to have more *hybrid working environment*, i. e., working environments that include and help connecting several traditional workstation on the one hand, and working environments that can help transitioning and including traditional devices into immersive environments. Research work conducted on this first aspect is covered in Section 2.1.1 whereas the second one is covered in Section 2.1.2. This work is particularly important because eventually, visualization practitioners often come back to traditional workstation to perform more in-depth analysis with scripts or specific softwares (see Chapter 4). Consequently, this first research axis is useful to help visualization practitioners transition from one device or environment to the other without losing findings or interesting views. Yet, these works do not explain why or how the several interaction paradigms offered by hybrid environments can be combined.

A second research axis consists of the creation of *hybrid interaction paradigms*: combining two (or more) interaction paradigms together to achieve specific tasks. Several hybrid interaction paradigms have been investigated in the literature and are reviewed in Section 2.2.

A third research axis is the support of such hybrid paradigm for *visualization tasks*. While the work conducted on both hybrid environments and hybrid interaction paradigms is tremendous, only sparsely is visualization mentioned in these works. This thesis hence aims at bridging this gap by covering how it is possible to leverage hybrid interaction techniques to help visualization practitioners. Furthermore, most of the work conducted on hybrid interaction paradigm include complicated and/or expensive setups (violating **R3**). We thus try to leverage the potential of hybrid interaction paradigms–thus fulfilling **R2**)–with only of-the-shelves devices that can easily be included in the daily workflow of researchers–hence fulfilling **R3**.

## 1.2 THESIS STATEMENT AND OVERVIEW.

This thesis thus focuses on readily and of-the-shelves technologies (that have proven to be useful in the context of three-dimensional dataset visualization) and how they can be combined to better support traditional tasks involved with three-dimensional dataset visualizations. focusing on this research axis, the work presented in this thesis thus paves the way towards an interaction continuum for visualization.

To pursue this goal, an initial review of the state of the art in interaction continuity is first conducted in Chapter 2. This chapter provides an overview of the efforts that have been conducted so far in order to create this idea of interaction continuum. With this overview, past research in both efforts to create working environments comprising of several input and output devices and prototype combining several interaction paradigms are reviewed and explained to better put the work presented in this thesis into context. All three interaction medium were found to be equally precise, though tangible interaction was faster than tactile interaction which was in turn faster than mouse interaction. Qualitative feedback highlighted the lack of feeling of precision for tangible manipulation as well as the overall preference for this interaction paradigm.

For several interaction paradigms to be combined using of-the-shelves devices and strategies, their inherent advantages and limitations within such a setup for 3D manipulations should be clearly understood. Chapter 3 thus provides an initial investigation of mouse-based, tactile-based and tangible-based for 3D manipulations with commercially-and-public available and affordable screens and tablets. All three interaction paradigms were found to be equally precise but with different completion time (tangible interaction being the fastest). Fatigue and workload measure as well as qualitative feedback are also heavily discussed. In this chapter, we also describe and easy and affordable setup that can include these three interaction paradigms.

Based on these findings, Chapter 4 proposes a first hybrid interaction paradigm combining tactile and tangible inputs on a single position-aware and tactile-enabled tablet in order to help the exploration of fluid dynamic data by domain experts. A first description of the design space for such a hybrid interaction paradigm is given. Then, based on the needs of domain experts that were observed during a field study, a prototype implementing a hybrid tactile/tangible interaction is described and validated with an experiment with 7 domain experts.

After the focus placed on 3D picking and 3D data manipulations, Chapter 5 focuses on an other crucial task in visualization: 3D spatial selection. Usually, 3D selection techniques rely on an initial 2D input by the user that is then extended into 3D by the computer. Using the hybrid tactile/tangible interaction, it is possible to offer a fully manual selection technique. The taxonomy of 3D selection technique if first refined before the hybrid tactile/tangible 3D selection technique and its implementation are detailed. A final evaluation with a partially-automated approach concludes that a fully manual approach benefits the accuracy of the selection but impacts the completion time. The qualitative feedback highlights the respective qualities and possible applications of each technique and further validate the usefulness of hybrid interaction paradigms.

Building on the findings from Chapter 3 and Chapter 4 that tangible interaction does not provide the same feeling of precision than the other two (mouse and touch), in Chapter 6, a new hybrid tactile/tangible interaction is created to improve the precision that can be acquired with tangible manipulations of a tablet. Tactile input represents more than coordinates information and can also inform on pressure levels. This input is then used to control the gain factor of 3D tangible manipulations on a tablet. Possible mappings and prototypes are described and evaluated through two studies, highlighting the large preference for pressure-based control of the gain factor and its better performances.

In a final chapter (Chapter 7) we reflect on the work presented in this thesis and our ultimate goal of paving the way for a continuum of interaction for 3D data visualization. We also reflect on the possible follow-up work that would further extend and develop this concept.

Since all the results and their discussions presented in this thesis rely on–still rarely used–estimation techniques, Appendix A aims at explaining why such techniques were used and how to interpret them. It quickly summarizes the issues with p-values and NHST and presents the advantages of estimation techniques and how to interpret results presented with confidence intervals.

# 2

# BACKGROUND

This chapter provides an overview of the current state of interaction continuity. While very few research works have focused on the continuity of interaction for visualization, this thesis is not the first piece of work focusing on an interaction continuum. However, such a continuum of interaction covers several different research aspects that are analysed in this chapter.

On the one hand, having an interaction continuum implies being able to transition between similar or different devices in order to visualize and interact in different environments. As a consequence, many research papers have investigated the possibility to bring different interactive environments and devices closer. On the other hand, providing an interaction continuum implies being able to transition from one interaction paradigm to an other, that is, being able to combine two, or more, interaction paradigms on a single device or within a specific environment.

These two aspects are being discussed in the two sections of this chapters.

## 2.1 TOWARD HYBRID WORKING ENVIRONMENTS

Before sensor-enriched smartphones and tablets invaded our lives, most computing environments were dedicated to a single interaction paradigm (usually for a single user). With the increasing need for co-located collaborative work in several domains, whole branches of research have thus focused on the creation of systems dedicated to collaboration and thus on the possible merges of homogeneous or heterogeneous computing environments. In order to analyze and synthesize this effort, the work presented here will be divided into two subparts. A first section focuses on the effort to bridge the gap between devices by providing middlewares that can link and help communication between several devices. A second section focuses on the research conducted to add more traditional devices into immersive environments.

### 2.1.1 *Connecting Devices*

Many early systems focusing on new ways to use devices together were based on manual configuration or calibration. For instance, Myers (2001)'s system necessitated a manual entry of network addresses while the systems developed by both Streitz et al. (1999) and Johanson et al. (2002) required manual entry of the geometry of displays.

However, other more automated approaches were also developed early on. Holmquist et al. (2001) developed Smart-Its Friends . This technique can create a connection between two devices when they are held together and shaken. Such a system is still used for some text communication between smartphones today, in order to add friends directly on one's contact list in the application. No other feature was supported by this system. Hinckley

(2003) developed the bumping technique that consisted in sensing when and how two devices were bumped together in order to create a shared display that spans several devices . An apparently simpler concept was developed by Rekimoto et al. (2003) with SyncTap which allowed users to simultaneously press Sync buttons on two separate devices in order to connect them. However, any action on the connection between the devices itself required multiple additional steps (such as indicating the edge of the screen that had to be linked to the additional device).

With multiple possibilities to synchronize devices together, researchers then started to focus on proper interaction techniques that could be used across the span of several displays or devices. Inspired by this initial work on device synchronization, Hinckley et al. (2004) developed a set of pen-based gestures that facilitate the combination of, and interaction with multiple, wirelessly linked mobile devices. As stitching displays together is usually the cause of interaction issues, Nacenta et al. (2006) created the Perspective Cursor technique. They base their technique on a more natural way for human beings to compose display space which is perspective. With the Perspective Cursor, the mapping of the cursor to the display space appears natural from where the user is located. The user study they conducted proved to be faster than a traditional beam-based technique with stitched displays. This effort was then extended to interaction between mobile hand-held devices and large displays. Dachselt and Buchholz (2009) investigated an intuitive basic set of tilt gestures. They introduce this set for a stepwise or continuous interaction with both mobile applications and distant user interfaces by utilizing the hand-held device as a remote control. With this work Dachselt and Buchholz demonstrate that a natural flow of interaction can be obtained in such environments.

Based on these ideas, multiple middleware application for multi-surface applications were then developed. Gjerlufsen et al. (2011) present, in 2011, both Substance, a data-oriented framework that decouples functionality from data, and Shared Substance. Shared Substance is a middleware providing sharing abstractions, necessary for the multi-device interaction. Focusing on the information transfer between personal and shared devices Marquardt et al. (2012) inspire their work from proxemic interactions. In their setup, the distance between devices is used to measure the engagement with other devices. With fine-grained measures of proximity, users get aware of devices surrounding them and progressive reveal of content and interaction help transferring information. With HuddleLamp, Rädle et al. (2014) proposed a device that track all the displays and surfaces layed out on a table. HuddleLap is a desk lamp with an integrated RGB-D camera that precisely tracks the movements and positions of mobile displays and hands on a table. With this hardware, around-the-table collaboration without an interactive tabletop is promoted. Devices can ba added or removed at any time, and the detection of hand movement provided by the lamp facilitates cross-device interaction. An other sensing technique was presented by Goel et al. (2014). Their SurfaceLink is a system where users can make gestures to control association and information transfer among several devices placed on a shared surface.

Based on the finding that users usually have a hard time understanding multi-display environments, Houben et al. (2014) presented ActivitySpace. ActivitySpace enables users to integrate and work across the devices in the shared space by making use of the space between each devices. Their study not only allowed them to state that ActivitySpace could help users to manage devices and their resources but it also highlighted a certain number of usage patterns. In 2015, Simeone et al. (2015) decided to focus on the factors influencing cross-device interaction. They conducted two user studies. The first aimed at gathering insights on how people currently perform cross device operations and how they would ideally like to perform them. The second specifically targeted the factors that influence multi-device interaction with focus groups. Building on the finding that cross device communication and specifically interaction between different devices is primordial yet still nowadays difficult, Paay et al. (2017) investigated possible strategies for moving objects from one device or display to another. They did so by conducting a study involving a mobile device and a large display, with the mobile device being the interaction proxy. They concluded that an important factor of performance of a technique is the ability for users to stabilize the pointer on the large display while interacting.

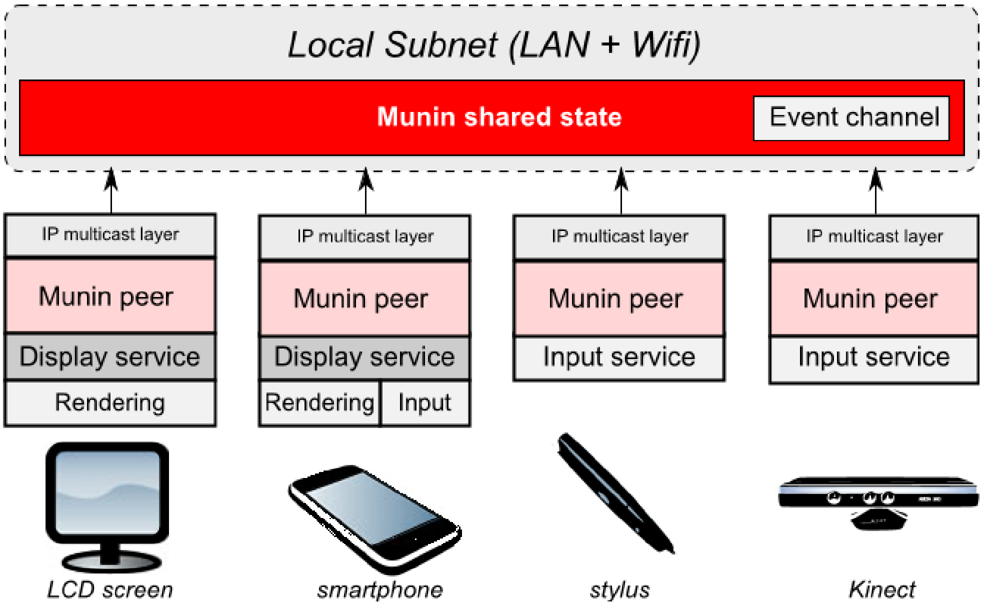


Figure 4: An example of the Munin architecture allowing several input channels and paradigms and several output displays (Badam et al., 2015).

For the particular field of visualization, it is now clear that visualization no longer solely relies on mouse and keyboard interaction but rather uses an expanded device spectrum including tablets, tabletops (Isenberg and Carpendale, 2007) and wall-sized displays (Isenberg et al., 2011). While collaborative visualization can show parallels with CSCW research, it is clear that visualization is less document-oriented and more data-driven in its sensemaking process. Collaborative visualization as such poses specific problems for such collaborative environments. Hence, some researchers have focused on creating ubiquitous analytics environments. A more visualization applied application was thus presented by Seyed et al. (2013) with SkyHunter. SkyHunter is an application specifically built for oil and gas exploration that involves several displays (tabletop and tablet) and combine several interaction paradigms in order to answer the specific needs of this kind of exploration. A more high-level discussion on multi-surface environments is also proposed by the authors. Closely related to visualization, Kammerer et al. (2015) focused on collaborative process modeling with touch-enabled devices. They present a set of multi-touch gestures designed to help this complicated task on multiple devices and present the results of a controlled experiment, stating that multi-touch application have a high potential for process modeling. Noteworthy, a less applied work has been conducted by Badam et al. (2015). They proposed Munin, designed to help building environments comprising of several homogeneous or heterogeneous input and output surfaces. The authors present the case study of a Munin environment for multidimensional visualization (see Figure 4).

In summary, many research work has focused on the creation of a middleware that can connect and ease the communication between several homogeneous or heterogeneous devices. While this is an important aspect of the seamless transition that should be offered by an interaction continuum (**R1**), only a small amount of them focused on visualization. Furthermore, none of these really explained what were the benefits offered by each device, when they should be used or for what specific tasks. The benefits offered by the several interaction paradigms and their combination (**R2**) are also rarely explored. In this thesis however, the focused is placed on the advantages that are provided by combining different interaction strategies.

### 2.1.2 *Hybrid Virtual Environments*

Early-on in the literature, many advantages had been found for the use of immersive three-dimensional displays. Such virtual reality environments can give users a better understanding of the virtual space and can improve performance for specific tasks. For example, an early study by Pausch et al. (1993), demonstrated that, for a generic search task, completion time was lower on a Head-Mounted-Display (HMD) when compared to a stationary display. Yet, such immersive environments have several limitations that researchers have mostly addressed by creating *Hybrid Virtual Environments*. A Hybrid Virtual Environment (HVE) is a system in which the same virtual world is rendered in multiple and heterogeneous display contexts.

One of the first HVE system was developed by Stoakley et al. (1995) who noticed, in 1995, that most implementations of virtual environments only give users a single point of view, thus prohibiting them from having a larger context and putting most of the virtual world out of their reach. To compensate for this limitation, they explored a interface called World in Miniature which consists in having users hold in their hands a three dimensional and virtual miniature copy of the life-size virtual environment. By doing so, they thus give users an other point of view from which they can observe the virtual world and that they can change by simply manipulating the hand-size

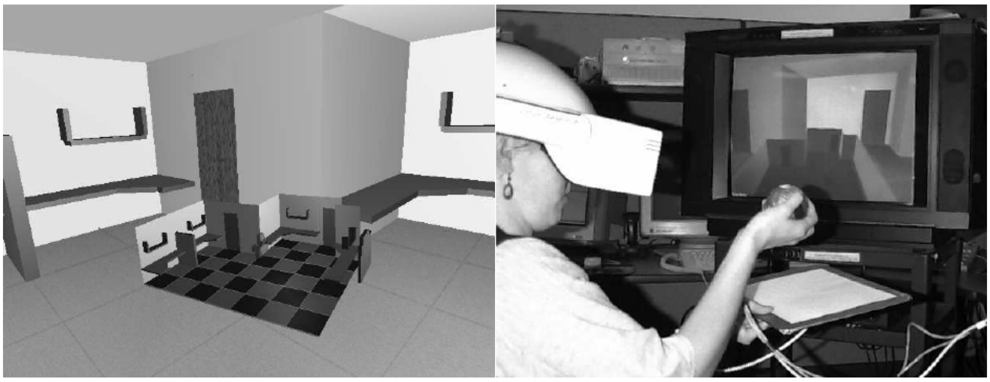


Figure 5: The World In Miniature technique: Figure 5a a user manipulating the WIM using the physical clipboard and the ball prop, and Figure 5b the WIM as viewed against the background of the life-size virtual environment.

physical prop (see Figure 5). Later, in 1999, Schmalstieg and Schaufler (1999) introduced SEAM: a 3D user-interface metaphor to connect virtual worlds that manages scalability in distributed virtual environments. Kiyokawa et al. (2000) worked on a possible transition between fully immersive and individual virtual environment on a HMD and a possibly collaborative augmented reality view for the prototyping of 3D objects. This was made possible thanks to the optical see-through head-mounted displays.

Brown and Hua (2006) proposed, with SCAPE, to use a see-through workbench in the middle of a room with projection walls . The walls form a CAVE environment that provides the immervise interaction and the workbench is used to show a world in miniature view of the exact same virtual environment but allows navigation with lenses. Bornik et al. (2006) built a specific setup combining a tablet PC and a stereo wall for liver visualization. They dealt with the specific 2D and 3D interaction mean by creating a specific device that was tracked in 3D and that allowed them to interact on the tablet PC.

Models and guidelines for multiple interaction context work have also been conducted. On the one hand, Grasset et al. (2006) started to investigate the effect of transitioning between multiple environments on the mixed reality continuum. They formulated an initial concept that they later improved by reporting on an evaluation study (Grasset et al., 2008). On the other hand, Wang Baldonado et al. (2000) proposed, based on their experience, design guidelines for the use multiple views in information visualization. Highlights of their design guidelines include the need to synchronize interaction tasks between immersive environments and other views so as to reduce the cognitive overload often induced by the context switching.

In 2012, Carvalho et al. (2012) reflected on the fact that a complex task is usually divided into subtasks requiring different demands. Consequently, conducting them in a single homogeneous environment could be seen as a challenge for users who would rather have multiple interactive environments. With their work, they focused on transactions between environments in HVEs and highlighted the importance of the interaction continuity. They proposed HybridDesk, a system featuring a traditional desktop station integrated in the space of a CAVE. In contrast to (Grasset et al., 2008)'s work, (Carvalho et al., 2012) propose to use several interaction paradigm in order to avoid disorientation and confusion for users.

In a very recent work, Wang and Lindeman (2015) proposed a new interaction technique for HVEs that consists in impersonating a virtual object to perform and enhance some 3D interaction tasks.

The tremendous work put into HVEs is clearly a good step towards an interaction continuum in the sense that work focusing on HVEs usually try to include traditional displays or devices within complex, yet useful, environments. As such, HVEs allow for an easier transition between tasks that are usually conducted on traditional workstations and devices and other tasks that can be better conducted in immersive setups. While immersive interactive environments are certainly helpful, it remains that they involve high maintenance, calibration or financial costs (violating (**R3**). Furthermore, in most of these work, little thought is actually given to the capabilities offered by the possible combinations of the input strategies (**R2**). This aspect is the focus, on the contrary, the focus of this thesis work, with particular thoughts given to the advantages that can be obtained by creating hybrid interaction paradigms for 3D data visualization.

## 2.2 COMBINING INTERACTION PARADIGMS

A large body of work has also focused on the realization of an interaction continuum via the combination of several interaction paradigms. Interestingly, most of these efforts have been done with tactile interaction. This abundance can probably be explained by the dominant position tactile interaction has in people's lives as well as the rich sensory capacities and the dexterity offered by human fingers (Robles-De-La-Torre, 2006).

The first "touch" screen is often said to be Sutherland (1964)'s Sketchpad which, as early as the 1960s made use of a pen-like device to interact on a screen. Work on touch screens quickly followed with different sensing strategies: some relied on capacitive sensing (Johnson, 1965; Johnson, 1967), optical tracking (Ebeling et al., 1973), or resistive sensing (Colwell Jr William C, 1975). The first multi-touch screen followed in 1976 and is likely to be the keyboard with variable graphics proposed by the MIT (Kaplow and Molnar, 1976). Since then, multiple sensing systems and configuration (table, tablet) have been explored. With the explosion of mobile touch-enabled smartphones, horizontal projection surfaces integrated into a tabletop soon also became touch-enabled. Short, after, tabletops became possible desktop surrogates.

The benefits of tactile interaction over other forms of interaction have been deeply studied for a whole variety of tasks and parameters. Studies have compared mouse and tactile interaction for speed (Forlines et al., 2007; Glesser et al., 2013; Sears and Shneiderman, 1991), error rate (Forlines et al., 2007; Sears and Shneiderman, 1991), minimum target size (Albinsson and Zhai, 2003), etc. In a very similar way, studies have compared tactile with tangible interaction for tasks as various as puzzle solving (Terrenghi et al., 2007;

Wang, 2010), layout-creation (Lucchi et al., 2010), photo-sorting (Terrenghi et al., 2007), selecting/pointing (Raynal et al., 2010), and tracking (Jansen et al., 2012). To summarize, tactile interaction appears to be a good compromise between fast and precise input. More importantly though, tactile interaction is often considered as direct: the fingers interacts, most of the time, directly on the displayed data (albeit on a 2D projection of the data). This directness of tactile interaction has been studied in previous work (Knoedel and Hachet, 2011; Levesque et al., 2011; Meyer et al., 1994; Poupyrev and Maruyama, 2003; Schmidt et al., 2009; Sears and Shneiderman, 1991; Simeone and Gellerseny, 2015). It gives users a feeling of directly manipulation the data they are visualization which can make it more engaging and encourage further manipulations.

Despite these interesting advantages, tactile interaction is often limited and limiting. It is limited because it is often but a discrete interaction mechanism while human being's interaction mechanisms are continuous (Freitag et al., 2012). It is limiting in the sense that many complex tasks (in particular for 3D manipulations) require more than three degrees of freedom. Providing them usually requires to use multiple fingers, thus leading to occlusion issues.

Tactile interaction is still, however, omnipresent: on mobile devices, touch-enabled laptop (such as Microsoft's Surface products), and on wall-size displays as well as other collaborative settings. This strong presence of tactile interaction makes it an interesting paradigm to combine with others. A lot of research projects have tried to augment tactile interaction, either to cirvumvent its inherent weaknesses or to further take advantage of the richness offered by humans' fingers and hand. This section addresses these efforts by first analyzing how tactile interaction has been combined with tangible interaction and then reviewing how it has been combined with mid-air gestures.

It is possible to distinguish two main type of devices offering tactile interaction. On the one hand, tabletop (or similar horizontal tactile-enabled displays) which are fixed and usually facilitate the viewing of large data with a possibility to carry co-located cooperative work. With such large display, it is possible to use physical object as tangible user interfaces or to include additional sensing system to broaden the range of possible gesture on and above the tabletop. On the other hand, mobile devices all offer today a multi-touch interface. They also come with many different built-in sensors (accelerometers, cameras, ...) that make them gesture-sensing ready and spatially aware. Both tabletop environments and mobile devices are discussed in the two subsections below.

### 2.2.1 *Combining Tactile and Tangible Interaction*

First prototypes and platforms of tangible interaction came into view as early as 1976 with Perlman and Tech. (1976)'s Slot Machine (see Figure 6) to help children discover programming languages. Later, both Aish (1979) and Frazer Frazer et al. (1980) tried to simplify the use of computer-aided design systems with physical systems. They adopted physical blocks to create assemblies, and used computers to recognize the topology that would lead to digital 3D models. These would ultimately lead to the generation of plans and drawings.

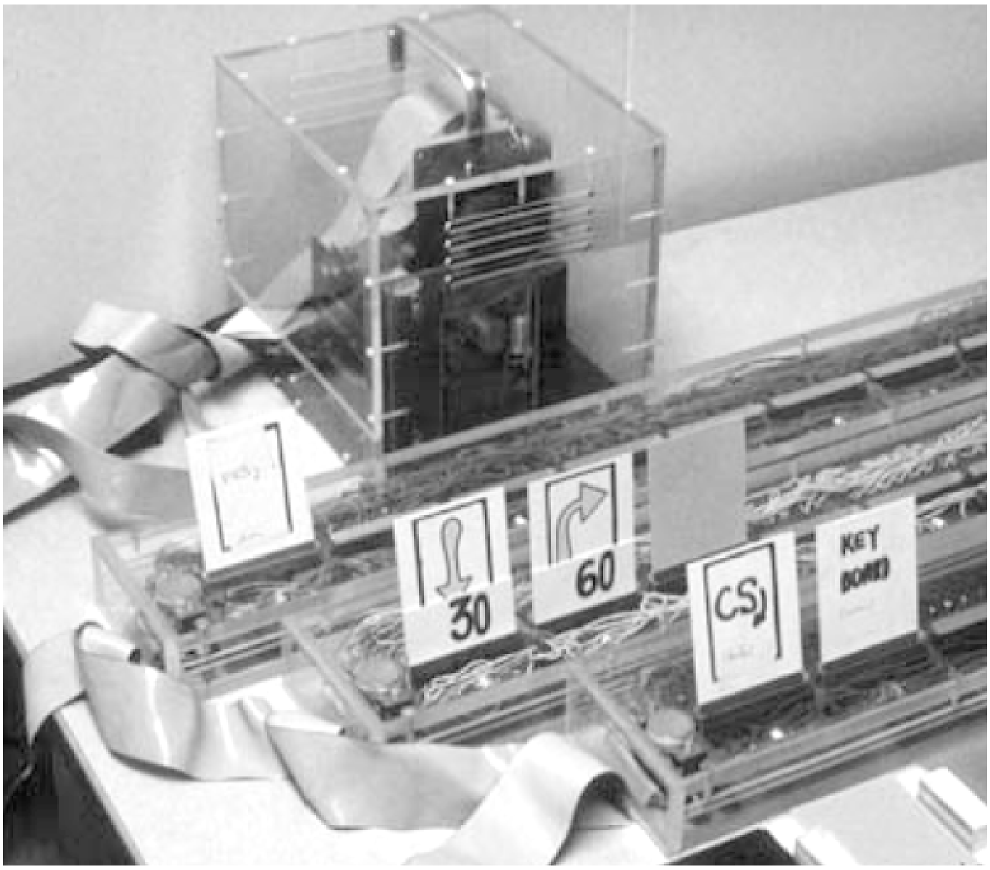


Figure 6: Perlman's Slot Machine (Perlman and Tech., 1976).

A decade later, Fitzmaurice (1996) introduced the concept of graspable user interfaces . It was the first interaction paradigm that used physical objects to synchronously manipulate digital counterpats. In his work, the grapsables were associated with specific functions and allowed users to interact with both hand simultaneously.

The concept of graspable user interfaces was then then cornered into tangible user interfaces by Ishii and Ullmer (1997). Tangible User Interfaces can be seen as an evolution of graspable user interfaces since they do not only provide input but also rely on tangible representation of digital information.

Tangible User Interfaces (TUI) and especially the class of TUIs called Graspable User Interfaces aim at taking advantage of people's natural skills for manipulating their physical environment (Fitzmaurice, 1996; Ishii and Ullmer, 1997; Ishii, 2008a). Tangible input inherently offers 6 integrated DOF per prop. Several studies have tried to investigate the possible benefits of TUIs when compared to other interaction paradigms for different tasks. However, the focus of these studies will be out of the scope of this background section. A better overview of these studies will be given in Chapter 3. It remains that tangible interaction have been proven to be useful for 3D rotations

(Chen et al., 1988; Hinckley et al., 1997), good for collaboration (Marshall et al., 2009; Olson et al., 2011) and entertaining (Xie et al., 2008).

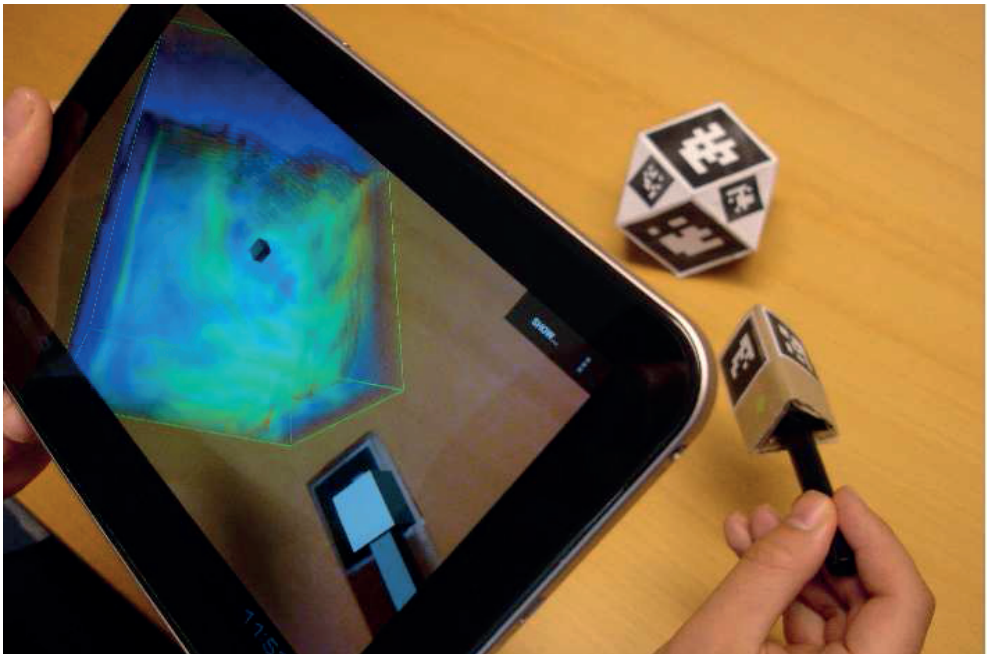


Figure 7: The particle tracing allows to explore vector datasets by visualizing the trajectory of particles in vector fields. The origin of the particles is determined by the stylus (Issartel et al., 2014a).

While recent research on Tangible User Interfaces consider tangible props as both physical representation and means of interaction, several works have focused more on the input aspect. Restricting ourselves to interaction designed for visualization, Hinckley et al. (1994b)'s props for neurosurgeons Issartel et al.'s tangible interfaces (Figure 7) for fluid dynamic visualizations (Issartel et al., 2014a; Issartel et al., 2014b), or Jackson et al. (2013) prototype which focused on fiber structures are examples of TUIs that are specifically used for their input properties. In this case, the tangible props are considered more like handles.

Other researchers have sought to include them in several environments in order to benefit from their natural advantages. Most of the literature thus focused on their use in tabletop environments or on the inherent manipulations offered by mobile devices. These two different interactive environment are reviewed separately in the following subsections.

#### 2.2.1.1 *Tabletop environments*

A very large body of work has focused on the possible addition that could be made to tabletop environments. Tabletops natively offer tactile input sensing. Tactile interaction is often considered limited for some aspects of the work conducted on tabletop. As a consequence, several researchers proposed to add tangible props in tabletop settings.

The pioneer project that combined physical object on a digital surface probably goes back to 1993 with the DigitalDesk (Wellner, 1993): it consisted

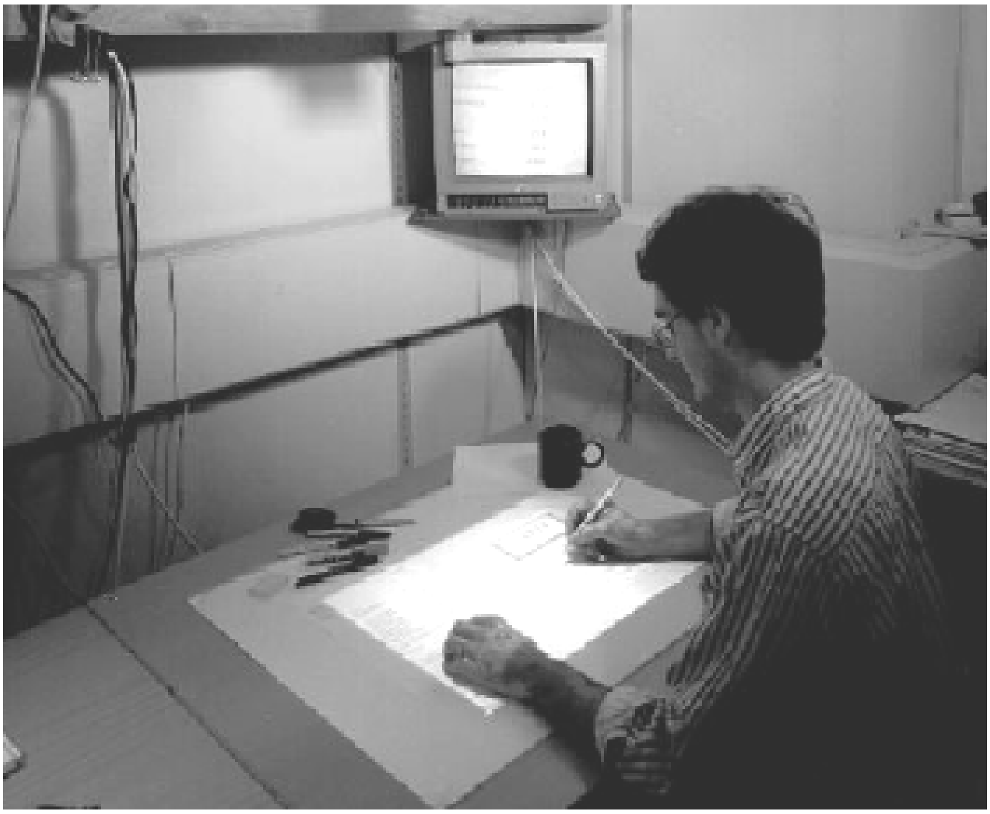


Figure 8: The Digital Desk (Wellner, 1993).

in augmenting a digital surface by adding paper-based interaction. With this idea, Wellner, in his PhD dissertation, suggested that the visionary approach following Xerox PARC's desktop metaphor in the 1970's to make paperless desktop was too simple. He instead suggested to keep the paper but to make it more powerful with computers. The project relied on a simple desk that was augmented by a projector–to project digital information onto the desk or the papers–and a camera to read papers and facilitate pointing gestures with fingers (see Figure 8). Though the physical objects that interact on the Digital Desk were only 2D papers, they still represented some kind of early tangibles. Similarly, the prototype supported pointing gesture which can be assimilated to tactile interaction. Thus, this visionary work on tabletop systems already offered a hybrid tactile/tangible interaction paradigm.

With their work on Tangible User Interfaces, Ishii and Ullmer (1997) pushed further Wellner's DigitalDesk by proposing the metaDesk which makes use of physical objects onto a LCD screen. With URP, Underkoffler and Ishii (1999) applied this concept of adding tangibles onto a digital surface for the specific application of urban planning.

A large body of work have then focused on the simple addition of tangibles onto tabletop/flat surface.

Wilson's work on depth sensing cameras included into a tabletop system (Wilson, 2007), suggest that users are eager to interact with in-air gestures in such contexts, even though Wilson's initial purpose was to study the use of tangible objects in a tabletop environment.

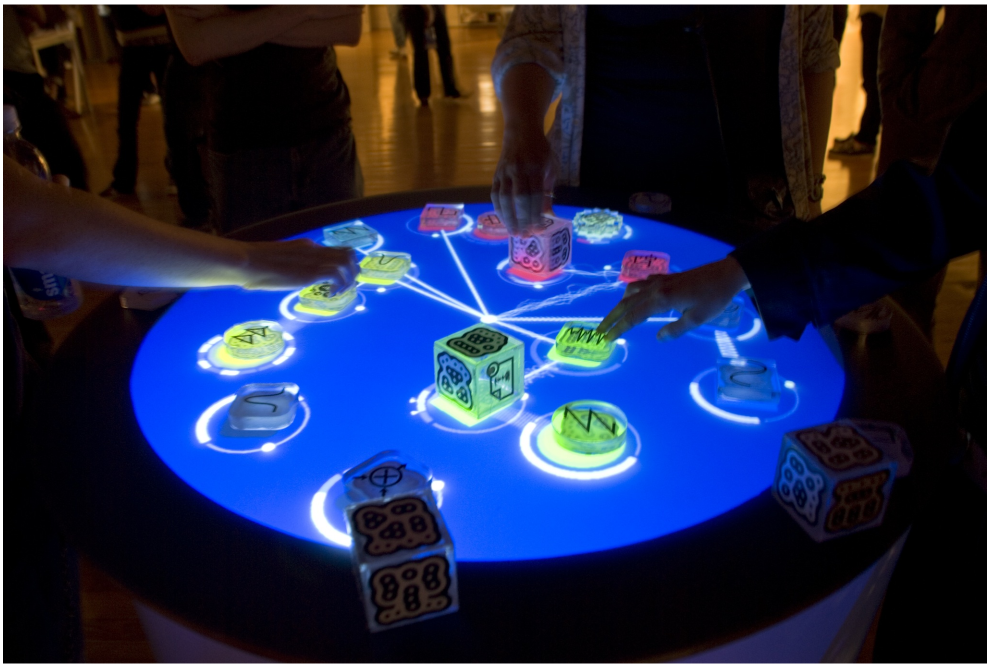


Figure 9: The reacTable (Jordà et al., 2007), from Daniel Williams Creative Commons.

A major step towards an interaction continuum between tactile and tangible interaction on a tabletop was probably Jordà et al. (2007)'s work with the reacTable (see Figure 9). The reacTable makes use of computer vision in order to detect tangibles on the tabletop. The reacTable thus allowed the creation of live music with tangible tokens placed and combined onto the tabletop and tactile interaction in order to modify the values of parameters. This work was of particular importance for hybrid interaction paragidms in tabletop development for it was one of the first to propose and defend the use of computer vision for tangible manipulation. Indeed, before the reacTable (or the earlier PlayAnywhere (Wilson, 2005a)), the use of computer vision was discouraged in tabletop environments as it was slow, instable, and would cause occlusion. Therefore, tangibles had to be enhanced with RFID tags (Patten et al., 2001) or ultrasound tracking systems (Mazalek, 2005) for instance. The ReacTable clearly showed that the tracking of fiducial markers was robust, fast, and occlusion-free, and thus allowed more researchers to easily include them in their tabletop environments.

Olwal and Feiner (2009) took the concept of bridging the gap between tactile and tangible manipulation even further. They used the spatially aware and tactile-enable devices onto a tabletop to allow for high-precision interaction on large display. The tactile interaction was possible on both the mobile device and the tabletop and the motions of the mobile device were used as a way to interact in a tangible manner. They also conducted a user study to determine if such a combination was useful the specific task of precise selection. Their study revealed no performance difference with a tactile-only baseline, but user preference seemed to be higher for the hybrid interaction approach.

Spindler and Dachselt (2009) proposed to use a tracked sheet of paper as a way to navigate 3D spaces on a tabletop. They used the sheet of paper as a magic lens. With this magic lens, users were able to navigate through time-data, volumetric data, and zoomable or layered data. The study they conducted mainly informed them on better design options for their magic lenses. Baudisch et al. (2010) presented a building block system with each block containing a marker and a glass fiber bundle that allowed users to put blocks on top of each other. The tangible blocks they presented have the advantage that they are not powered and maintenance-free, thus allowing the easy use of large numbers. Baudisch et al. present in this work three demo applications including a construction kit.

Very recently, Al-Megren and Ruddle (2016) presented a tabletop TUI that combines tangible objects with a multi-touch interaction for the specific needs of data visualization tasks. They first highlighted the requirement for a data visualization interface and then presented the interface they built accordingly. They also conducted a study in order to compare multi-touch and tangible input on the tabletop in their data visualization context and found that due to more effective strategy that users picked, they were able to find patterns faster with the tangibles. Plimmer et al. (2016) recent work showed that a hybrid tactile and tangible interaction could provide benefits for 3D object manipulation on tabletops. They also found out that, contrary to most other studies, users tended to prefer tactile interaction due to its familiarity but that the tangibles were still favored for some specific tasks.

Figure 10: A user manipulation the CAT (Hachet et al., 2004).

Noteworthy, an interesting vision of the tabletop has also been developed by Hachet et al. (2004) with the CAT. The CAT can be seen as a circular tabletop with the particularity that it can be oriented in space on three nested rotation axes (see Figure 10). The angular sensors enable the recovery of the orientation of the tabletop and a potentiometer facilitates the sensing of the forces applied on the tabletop in any 3D direction. Hachet et al. also argue that most interaction tasks are usually better performed by 2D interaction, with annotating as an example, and thus provide tactile interaction (with a pen) on the tabletop. Their device is meant to be used in virtual environments. This work is particularly interesting as it tried to remove the limitations of traditional tabletops in order to provide integrated tangible interaction with the tabletop itself. Though, to the best of my knowledge, this idea has not been pushed further on tabletop systems, it has widely been used on mobile devices.

This idea to use the tactile-enabled device's motions to provide tangible interaction has been explored a lot with mobile devices which are the focus of the next section.

#### 2.2.1.2 *Mobile devices*

Mobile devices are omnipresent in our lives now. With their relatively small size, using them as a surface onto which tangible objects could be placed seems unreasonable. However, their embedded sensors often allow to sense their own motions (at the very least rotations) thus making them possible tangible user interfaces.

Even though nowadays, most, if not all, mobile devices offer tactile interaction, this was not initially the case. Therefore, in the early nineties, before the definition of tangible user interfaces was even made, Fitzmaurice (1993) proposed to use a spatially-aware palmtop computer combined with touch sensitve LCD strips in the environment . He imagined the used of combined interaction in several scenarios such as a computer-augmented library or office. Even though the two interaction paradigms were not combined onto the same device, the scenari still relied on tangible manipulations of a mobile device that were augmented or refined by tactile interactions. One could conjecture that, if at that time smartphones had existed, George Fitzmaurice would have probably replaced the touch-sensitive LCD strips with a simple GUI on the smarpthone.

Later, in 2002, Tsang et al. (2002) decided to combine a spatially-aware display, allowing tangible manipulations, and a tactile-enabled screen. Their prototype, the Boom Chameleon was a novel input/output device, capable of sensing the tangible manipulations of the device, the tactile and the vocal interaction. The display acted as a physical window into the 3D virtual environment (with a direct one-to-one mapping). The addition of tactile and vocal input was made to facilitate note-taking tasks onto 3D objects. Their study showed that such a combination of inputs was used even simultaneously and was easy to learn.

This idea to use a spatially-tracked and tactile enabled device has also vastly been investigated in immersive environments (such as CAVEs). First

Figure 11: The Virtual Notepad: Figure 11a the pysical setup of the Virtual Notepad comprises a spatially-tracked tablet and a pen (Poupyrev et al., 1998a), and Figure 11b users can annotate and draw on selected images on the notepad.

of all, in 1995, Angus and Sowizral (1995) first thought of using a mobile device in a VR environment in order to take advantage of already developed softwares for desktop stations. In their setup they simply migrate applications developed for the flat screen on a personal digital assistant that they built which is used as an extension of the hand in 3D but also as a touch input device (with pen-based interaction in fact). Three years later, based on this idea, for note-taking in virtual environments, Poupyrev et al. (1998a) proposed to use a spatially-tracked graphics tablet with tactile input (through pen interaction, as seen in Figure 11) . As for Schmalstieg et al. (1999), they used transparent props and a pen that were tracked to augment the interaction space of a virtual table. These were furthered explored by Darken and Durost (2005). They evaluated the possibility of combining 2D interaction (with pen sensing on a tablet) and 3D interaction (with the tracked pen) in a cave environment for several tasks (selection, reading, positioning, writing text). They concluded that an appropriate combination of 2D and 3D interaction techniques was preferred over exclusive use of either 2D or 3D interaction techniques. Indeed, for tasks such as reading and writing participants clearly favored 2D input while tasks such as selection and 3D positioning obviously call for 3D interaction techniques. Later, Miguel et al. (2007) used a tracked PDA to facilitate interaction in CAVEs: users moved the PDA in 3D to get a suitable "captured" view and then selected a 3D object with a tactile input. Similarly, Yee (2003)'s peephole displays combined position-aware displays with pen input and applied them to three different applications scenarios. Marzo et al. (2014) studied the possibility to combine a spatially aware mobile device and multi-touch interaction in a mobile augmented reality (MAR) context. They compared tangible manipulation of the device only on the one hand, and tactile interaction only on the other hand, to a hybrid tactile and tangible interaction technique. Their study suggest that overall hybrid interaction leads to better performances. Tangible interaction was judged to be the most intuitive interaction technique while tactile interaction lead to more accurate results. Wang and Lindeman (2014) investigated the use of hybrid visualization environment with a wand for tangible manipulation and a multi-touch screen. Recently, Sollich et al. (2016) proposed to explore time-dependent scientific datasets using a similar configuration to López et al. (2016)'s approach . They use a spatially-aware mobile device in addition to a large-touch sensitive display. They conducted a study with developmental biologists in order to test their prototype who confirmed the potential of such a system for their specific needs. This work thus clearly showed the potential of hybrid interaction paradigms for visualization purposes.

While using spatially-aware (or rather spatially-tracked) devices has been extensively studied, this option could be seen as limited since the visual tracking of a device in the 3D space often requires heavy computation, tremendous maintenance efforts and high financial investments. However, with the wide adoption of mobile devices in people's everyday lives, new sensors have started to be included by default in smartphones and tablets. These sensors can, very often, provide information that help precisely recording the way the devices are rotated and help partially computing their own motions. This lead to researchers trying to use these built-in sensors instead of tracking mobile devices. Several projects have exploited these possibilities. For instance, Hassan et al. (2009)'s Chucking technique relied on the natural gesture that human beings tend to do when throwing or passing objects. Chucking was designed as a document sharing technique that made use of both the tactile input and the motions of a mobile device. The direction of the motion was used for placing the document on a distant (larger) screen after an initial touch interaction had selected the document that had to be shared. Similarly, Rahman et al. (2009) focused on the embedded sensors of a mobile devices and more specifically on rotation sensors. They also contributed to the combination of device motion with tactile in their study demonstrating that a wide range of wrist deflection angles could be obtained. They thus showed the potential of a simple tilt-based interaction combined to the normal use of a tactile-enabled device. Later, Hinckley and Song (2011) completed that approach. While they investigated the potential of augmenting the inherent tactile interaction of mobile device with its motions they also envisioned the possibility to augment motion-sensing with tactile interaction. By doing motion-enhanced tactile interaction they enable more expressive tactile interaction.

A similar idea was detailed in López et al. (2016)'s work in which they investigated the use of tactile input on a mobile device for 3D manipulations and visualization. A stereoscopic view of the data was obtained from the large vertical display while the mobile device presented a monoscopic view (see Figure 12). They augmented the tactile interaction by using the integrated sensor of the tablet in order to allow for tangible rotations of the visualized data. With the study they conducted with domain experts in fluid mechanics and structural biology, they show that this setup and hybrid interaction paradigm supports interactive data exploration.

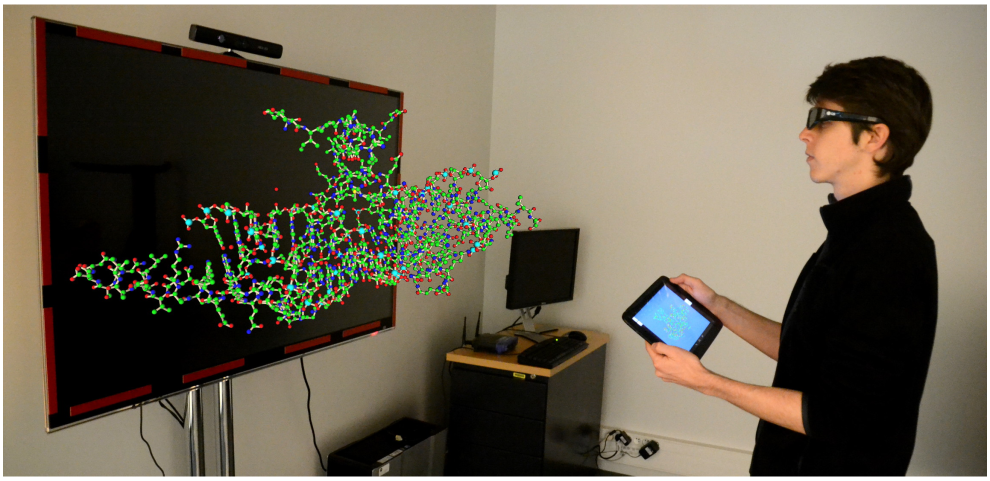


Figure 12: Tablet-based navigation of stereoscopically displayed 3D data (López et al., 2016).

#### 2.2.1.3 *Summary*

It thus seems that the combination of both tactile and tangible interaction is promising in tabletop environments (Section 2.2.1.1) or on mobile devices (Section 2.2.1.2). Even if tabletops are more and more widespread, above-table tangible interaction requires specific and expensive sensing systems (violating **R3**), so that mobile solutions seems to be the most promising systems for such a hybrid interaction paradigm. Yet, their possible contributions to visualization purposes have been rarely explored. The work presented in this thesis on the hand focuses on these possible contributions.

### 2.2.2 *Mid-air gestures, augmenting the interaction space*

In addition to hybrid tactile/tangible interaction systems, past work has also focused on the combination of mid-air gestures with tactile input.

Mid-air gestures have very early on been studied for 3D manipulations tasks (Kiyokawa et al., 1997; Hilliges et al., 2009; Song et al., 2012; Wang et al., 2011). In a way, like tangible interaction, mid-air gestures mimic the physical actions we make in the real world (Frees et al., 2007) and is thus interesting for 3D manipulation tasks. For instance, a large number of research papers have focused on mid-air gestures to increase their accuracy (Frees et al., 2007; Osawa, 2008).

Gestures in mid-air (or in-air gestures) are often seen as a way to enrich the tactile interaction that can happen in several environments. The early work by Buxton (1995) who created a model of background and foreground interaction is probably the motivation for the development of many gesture-recognition systems in several environments. Buxton distinguishes between foreground interaction which is captured with traditional graphical user interfaces and background interaction which happens out of reach of the user interface. In his work, he mentions that such background interaction could be useful in system with passively sensed gestures for instance and advocate for the potentials of such systems.

Gestures are usually tracked with optical systems (cameras, depth-sensing cameras, stereo cameras...) but can also be tracked thanks to the use of wired-gloves. When the detection system is not worn by the user (which is the case for the gloves for instance), these systems offer the advantages that users do not need to rely on external and/or intrusive devices.

Similar to Section 2.2.1, the combination of mid-air gestures with tactile interaction is reviewed in the two following subsections. The first focuses on tabletop environments while the second reviews in-air gestures around mobile devices.

#### 2.2.2.1 *Tabletop*

Most of the early in-air gesture recognition has solely focused on the on-surface interaction that hand gestures can provide.

Even before Buxton's work on background/foreground interaction, pioneer work in the domain of combining gestural and tactile interaction probably has to be attributed to Krueger (1990)'s VideoPlace . It is one of the early examples of multi-hand and multi-finger interaction that also recognizes gestured through 2D video silhouettes. In 2002, Rekimoto (2002) used a capacitive screen to recognize several hand gestures on a tabletop. With this system, capacitive-augmented object could even be recognized on the tabletop. He designed interesting interacton gestures such as a shape-based object manipulation which allowed users to make use of both hands or even of entire arms to manipulate digital objects.

Later, Wu and Balakrishnan (2003) integrated this idea into a proper tabletop environment to support more expressive input from users . Their system is based on DViT (which was not initially designed for tabletop interaction) which is a computer vision technique to sense touches and hovering interactions. However, their interaction design did not include any-mid air interaction design. They only mention this sensing to determine finger orientation if one wanted to use a specific rotation metaphor. Still, they supported a good variety of hand gestures and also investigated for issues in shared spaces such as awareness and privacy. Building on these previous works, other researchers thus later tried to push the gestural interaction even further by recognizing mid-air gestures. In their work, Benko and Ishak (2005) proposed to use hybrid interaction mechanisms in a hybrid augmented reality environment (following the work on HVE explained in Section 2.1.2) combining a tactile-enabled projection surface with head-worn display. They proposed to merge 2D interaction on the flat surface on the one hand and 3D gestures with the 3D AR visualization on the other hand.

With TouchLight, Wilson (2005b) proposed to make use of two infrared cameras in order to track interaction on and in front of a transparent projection surface, thus allowing the use of tactile interaction and mid-air gestures (Figure 13). With this work, he also pushed further the pioneer idea from Wellner (1993) to make the desktop a combination between virtual and physical places by also enabling tangible interaction on the transparent surface (with paper documents for instance). The potential of such interaction was reinforced by Wilson (2007)'s work on depth sensing cameras included into tabletop systems. His work suggested that users were eager to interact with mid-air gestures in tabletop contexts. Understanding the potential of adding a third dimension to tabletop interaction, Grossman and Wigdor (2007) surveyed past work in this domain and classified them within their taxonomy. Hilliges et al. (2009) also proposed to use computer vision techniques in order to track hands above the tabletop. They thus tried to augment tactile interaction on a tabletop with above mid-air gestures in order to alleviate the inherent planar (2D) interaction on tabletops for 3D manipulation purposes.

The potential of extending the tabletop to third dimension has then been extended for a variety of tasks. Banerjee et al. (2011)proposed with Pointable to use in-air bi-manual perspective based interaction in order to facilitate remote target selection (with the dominant hand) and manipulation (with the non-dominant hand). Yet, Marquardt et al. (2011) state that tabletop environments usually ignore the continuous interaction space between the two discrete interaction paradigms that are multi-touch and mid-air gestures. With their work, they further explored the design space of hybrid interaction mappings combining tactile and in-air gestures and implement examples of the continuum. Freitag et al. (2012) also further investigate a more theoretical approach of this combination. They proposed to use feed-forward (as opposed to feedback which happens during or after the interaction) on tactile enabled mobile devices to make the tactile interaction a more continuous one. To enable this feed-forward, they make tactile-enabled devices aware of the user's presence and thus augment the tactile interaction space to 3D gesture sensing.

A similar amount of effort to augment tactile interaction with mid-air gestures has been placed on mobile devices, which are the focus of the next section.

#### 2.2.2.2 *Mobiles*

The possibility to passively sense background interaction can also be done with small additions to mobile devices. A first attempt at doing so was conducted by Harrison et al. (1998). They added pressure sensors on a mobile device in order to detect which hand was holding it. Still, Hinckley et al. (2000) were among the firsts to advocate for hybrid interaction approaches on mobile devices. They investigated the potential of adding sensing capabilities to portable devices. With their work they suggested that simple and

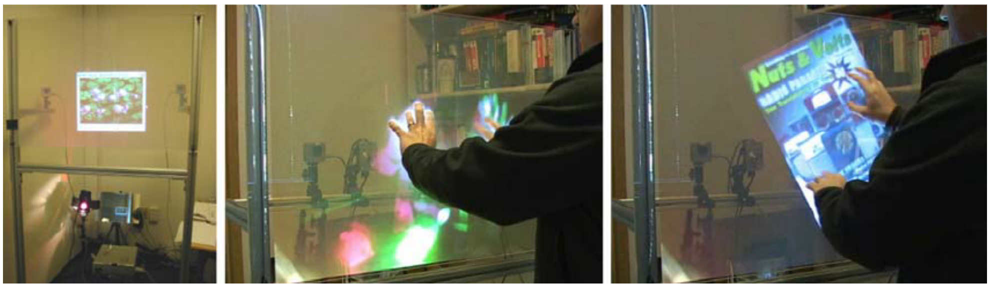


Figure 13: The TouchLight system

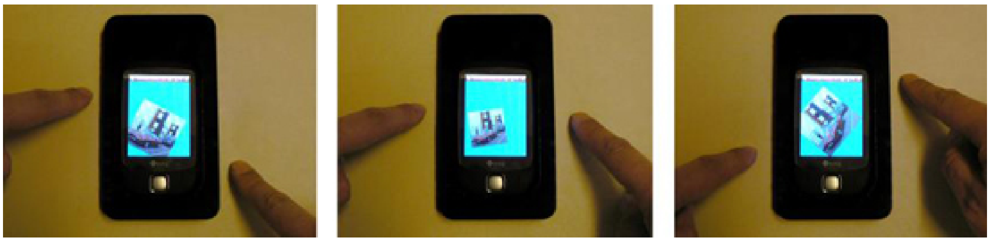


Figure 14: Sidesight, (Butler et al., 2008)

cheap sensor addition could be used and play an important role in mobile interaction and concluded that hybrid approaches "may prove to be the most practical approach".

In 2007, Baumgärtner et al. (2007) proposed to use a different approach to combine mid-air interaction mechanisms with a pen-interaction on a tablet PC for document searches. The tablet is used in addition to a stereoscopic display and the hand gesture are not detected by the tablet device but rather with a tracking device that is put onto the hand of the users. A quick evaluation of their system showed encouraging results in the acceptance of such a hybrid environment and interaction.

Small mobile devices particularly suffer from the occlusion issue. This is all the more true when they are used for tasks requiring more than two degrees of freedom and thus more than one finger on the screen. Consequently, Butler et al. (2008) proposed to create a so-called multitouch input on portable devices by adding infrared proximity sensors on the sides of mobile devices. This way, additional interaction can be performed on the side of the portable devices without occluding the screen (Figure 14). With this technology, finger gestures can be performed on the side of the mobile device as a primary input technique to replace or be combined with tactile interaction.

Further exploring the possibility to integrate gesture sensing into mobile sensing, Kratz and Rohs (2009) first explored the design space of around-device interaction on wearable and mobile devices. They then present HoverFlow a prototype tracking hand gestures above a device's screen. Their prototype is based on infrared proximity sensors and allowed users to select colors from a flowing palette. With their system they claimed to conceptually demonstrate how extending a mobile device's interaction area beyond its physical boundaries can enhance mobile interaction in general.

Later, Kratz et al. (2012) worked on rotation of 3D objects and proposed to augment the number of degrees of freedom of the classical tactile interaction with mid-air gestures in proximity of the mobile device. They conducted a study comparing two possible hardware implementation of their idea to a virtual trackball. Their study showed that their idea led to a lower tast completion time when compared to the virtual trackball technique with tactile only input thus proving again the potential of extending the interaction area to the whole volume surrounding the mobile device.

Chen et al. (2014) proposed to interweave touch events with in-air gestures in order to augment the tactile modality. They based their work on the observation that most supported air gestures are fundamentally compartmentalized from touch interaction. They thus provided a first prototype of what could be blend into single and fluid interaction mechanisms combining both interaction modalities. With their observational study, they devised a possible taxonomy of in-air gesture combined with tactile interaction and provided an implementation of some possible hybrid interactions (Figure 15). In their prototype, air gestures were not only made before or after touches, but also in between them. This work clearly paved the way towards a *fluid* interaction continuum between air gesture and tactile interaction.

Also seeing the potential of providing a greater input expressiveness for mobile devices, Withana et al. (2015) proposed zSense, a shallow depth gesture recognition system. They aimed at enhancing the interaction on small wearable systems including smartwatches. While their work clearly focuses on the recognition system itself, which proved to be efficient in several configurations, zSense could easily be used to make hybrid mid-air and tactile interactions easier on small tactile-eanabled wearables.

In 2016, Hinckley et al. (2016) proposed to use pre-touch sensing for mobile interaction, i. e., sensing mid-air gestures above the phone to augment tactile interaction. With this work, they proposed to use the gestures in an anticipatory fashion, a retroactive fashion or even a hybrid touch and hover gesture. While their focus is clearly on everyday interaction with mobile devices, their ideas could potentially be adapted to more complex interaction tasks.

### 2.2.2.3 *Summary*

Similar to hybrid tactile/tangible interaction (Section 2.2.1), hybrid tactile and mid-air gesture interaction has been studied a lot and can be useful in both tabletop environments (Section 2.2.2.1) and on mobile devices (Section 2.2.2.2). However, contrary to tangible interaction which can be obtained with readily available mobile devices, mid-air-gesture sensing requires on both tabletops and mobile devices specific sensing equipment that is thus not very likely to be adopted into visualization practitioners' workflow (violating **R3**). In this thesis, however, we focus on readily available and easy to maintain and install devices and setups that can offer hybrid interaction strategies and their possible benefits to 3D data visualization.

Figure 15: Air+Touch possible hybrid interactions, (Chen et al., 2014).

## 2.3 DISCUSSION

The review of literature provided in this chapter is by no means exhaustive. Other work combining other interaction paradigms have also been studied with for instance hybrid mid-air and tangible interaction combination (Starner et al., 2003). However, this chapter provides the necessary background to illustrate the point that a lot of research effort has been made to connect devices together (**R1**), and to investigate hybrid interaction paradigms (**R2**). Still, most of the systems combining two (or more) interaction paradigm narrowly focus on hardware feasibilities and do not focus on the possibilities that these systems could offer, in particular for visualization, which is the research axis that we want to investigate with this thesis work. Furthermore, this review of the related work highlighted that most systems combining interaction strategies usually rely on specific and expensive setups (violating **R3**). This is the case for all but spatially-aware mobile devices that can offer native tactile and tangible inputs. As a consequence, most of the work presented in this thesis makes use of this hybrid interaction paradigm to help domain experts with specific visualization tasks. We pay particular attention to the fact that the developed interaction techniques can be easily integrated within the workflow of domain experts. Some recent research work has also placed the focus on bringing easy to integrate hybrid interaction to specific scientific domains. For instance Mandalika et al. (2017) designed a hybrid interface with hybrid interaction mappings to facilitate radiological diagnosis which comprises a regular 2D display and a zSpace display to facilitate both usual mouse and keyboard and zSpace stylus interaction. This work is in line with our initiative to use devices or setups that can easily be included into domain experts' worklow and working environments.

Overall, this thesis thus focuses on hybrid interaction paradigms (**R2**) and their benefits for 3D visualization and manipulations. Specific attention is given to providing affordable, easy-to-maintain, and easy-to-integrate prototype (**R3**). To achieve these goals, an intial understanding of the inherent benefits and limitations of commonly used interaction paradigms is conducted in Chapter 3.

# 3

# USABILITY COMPARISON OF MOUSE, TACTILE, AND TANGIBLE INTERACTION

This chapter studies and compares three main interaction paradigms: mouse interaction, tactile interaction and tangible interaction. The first one, mouse interaction, is a common interaction paradigm with computers and is used a lot for desktop visualization purposes. The second one is used to an increasing degree in our everyday lives with the avent of smartphones and is also more and more used for visualization purposes in specific context like tabletop environments, wall-size displays, or tablet devices. Finally, tangible interaction has also been used more recently for scientific visualization in augmented reality or virtual reality environments. Our goal in this chapter is to identify the inherent benefits of these three interaction techniques for generic 3D manipulations. Such 3D manipulations are the quintessence of all manipulations required in 3D tasks and in particular in visualization tasks involving volumetric datasets. We thus evaluate the usability (Nielsen, 1993) of the three interaction paradigms. This includes the efficiency (task completion time), the learnability, the effectiveness (performance), and the satisfaction (subjective preferences). However, we go beyong this usability evaluation by adding fatigue and workload measurement.

The findings presented in this chapter thus serve as grounding work for the rest of the work presented in the thesis.

Main portions of this chapter were previously published at ACM CHI 2017 (Besançon et al., 2017). Thus, any use of “we” in this chapter refers to myself, Paul Issartel, Mehdi Ammi, and Tobias Isenberg.

## 3.1 INTRODUCTION

Many application domains rely on effective, efficient, and intuitive means of interacting with 3D data (Keefe, 2010; Munzner et al., 2006). Traditionally, this interaction has often relied on mouse and keyboard inputs. Recent developments of interaction technology, however, have led to new input modalities becoming available, in particular tactile input (Isenberg, 2016; Shneiderman, 1991a; Wigdor and Wixon, 2011)[1] and tangible interaction (Ishii, 2008b; Shaer and Hornecker, 2010).[2] Several researchers have thus started to explore their use for interaction with 3D data. Nevertheless, the three input modalities—mouse, touch, and tangibles—are not identical in characteristics such as their capabilities or usability: their advantages and disadvantages depend on the the interaction goal and the given application domain. For example, while one may use a tangible input device intuitively in a game, scientific visualization applications may require a level of accuracy that one could expect to better be provided by touch-based or in particular mouse-based input.

Tangibles are often regarded as the best way to interact with 3D data. We question this assumption here with our study that measured several usability factors: participants' accuracy (i. e., rotational difference and Euclidean distance), their perceived fatigue levels, and their perceived workload. We also took into account participants' preferences and their general feedback for each technique. The study consisted of 15 abstract 3D docking tasks—bringing an abstract virtual object to a given target orientation and position—for each of the three modalities. Our study confirmed that mouse, tactile, and tangible input are all valid means to control 3D manipulations. Much to our surprise, however, we found that all three input modalities allow users to achieve the same level of accuracy. Differences only arose with respect to task completion times and preferences. Qualitative observations of the participants during the study provided additional insights on what users tend to do when facing a docking task with these three input techniques which we discuss in detail below.

In summary, we contribute (1) an in-depth analysis of people's understanding and use of mouse-based, tactile, and tangible input for 3D interaction, (2) a study design that compares the three modalities, and (3) in-depth qualitative observations and people's preferences in the context of 3D data analysis environments. We thus shed light on the advantages and disadvantages of the techniques and serves as a basis for their further development and evaluation, in particular for 3D visualization.

## 3.2 RELATED WORK

Much of past work has focused on the comparison of interaction techniques or devices—many academic studies compare novel technique(s) or device(s) to established ones. For instance, many studies were conducted to compare the advantages and limitations of mouse interaction compared to touch interactions for tasks as various as selection, pointing, exploration etc. (e. g.,

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[1] I. e., interfaces based on finger or pen input on display surfaces.

[2] I. e., interfaces that follow Ullmer and Ishii (2000)'s four characteristics.

(Forlines et al., 2007; Kin et al., 2009; Sasangohar et al., 2009)). Our review of the literature, however, revealed a lack of studies that would analyze these modalities for 3D manipulation tasks—only few researchers actually conducted such analyses (Chen et al., 1988; Hinckley et al., 1997; Tuddenham et al., 2010; Yu et al., 2010).

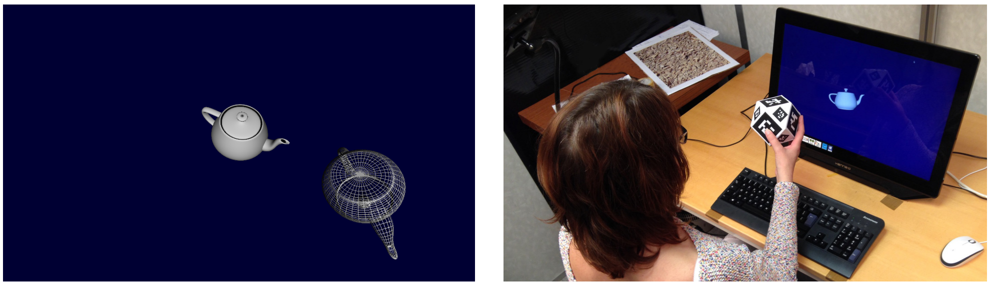
Among them, Chen et al. (1988) and later Hinckley et al. (1997) compared input techniques for 3D manipulation. Both studies, however, narrowly focused on rotation and did not take into account other parameters such as Euclidean distance to the target or usability. Tuddenham et al. (2010) compared mouse, tactile, and tangible interaction for a matching task on a tabletop, thus constraining the interaction to two dimensions. They measured the task completion time, the ease of use, and people's preference. Yu et al. (2010), finally, compared mouse and touch interaction to validate their FI3D widget for 7DOF data navigation. In contrast, we aim to get a holistic and general view of how the three input methods affect the interaction in 3D environments, ultimately to understand how we can better support the analysis of complex 3D datasets.

Moreover, most comparative studies focus on comparing either mouse and tactile interaction or tangible and tactile (and many concentrate on 2D tasks). The literature indeed contains many comparisons of touch and mouse input for a whole variety of tasks and a whole variety of parameters: speed (Forlines et al., 2007; Glesser et al., 2013; Sears and Shneiderman, 1991), error rate (Forlines et al., 2007; Sears and Shneiderman, 1991), minimum target size (Albinsson and Zhai, 2003), etc. Similarly, much research has compared tactile with tangible interaction for tasks as various as puzzle solving (Terrenghi et al., 2007; Wang, 2010), layout-creation (Lucchi et al., 2010), photo-sorting (Terrenghi et al., 2007), selecting/pointing (Raynal et al., 2010), and tracking (Jansen et al., 2012). Most of the work comparing tangible to other interfaces builds on the assumption that physical interfaces are necessarily better because they mimic the real world. However, this assumption was rightfully questioned by Terrenghi et al. (2007). A 2DOF input device (e. g., a mouse) may, in fact, perform well in a 3D manipulation task due to its inherent accuracy or people's familiarity with it. To better understand advantages and challenges of the three input modalities we thus compare them with each other in a single study.

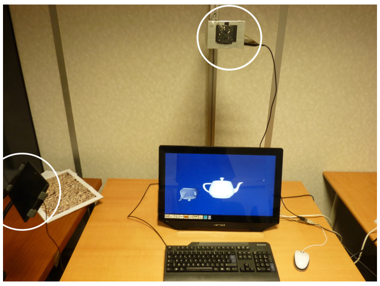
Esteves and Oakley (2011) also emphasize the fact that most studies comparing tangible interaction to other interaction paradigms are hard to generalize due to the highly simplistic tasks assigned to participants. Studies can thus only support very general claims on tangible interaction and its possible benefits. The lack of generalizability of such studies may also be explained by the overly focused participant groups in such studies. Very young participants often seem to be chosen to evaluate tangible interaction: school-aged children, for instance, were asked to evaluate the entertainment of Tangible User Interfaces (TUIs) (Xie et al., 2008), to solve puzzles (Antle et al., 2009), or asked to collaborate to understand which paradigm can be used to reduce conflicts in collaboration tasks (Marshall et al., 2009; Olson et al., 2011). Similarly, Lucchi et al. (2010) asked college students to recreate layouts using tactile and tangible interfaces. The learning effects of tangible interaction was also tested on non-adult participants in a study conducted by Price et al. (2003). We try to avoid this lack of generalizability by having a variety of participants and by using a task that is highly generalizable to 3D manipulation—3D docking. Such tasks have often been used in the literature to evaluate new 6DOF devices (Froehlich et al., 2006; Zhai and Milgram, 1998), new interaction techniques (Hancock et al., 2007), and for paradigm comparison studies (Tuddenham et al., 2010) (for the latter, the docking was only conducted in two dimensions). We argue that using a low-level 3D docking task is the key to be able to generalize results from comparative studies.

Related to our work are also remote 3D manipulations through tactile input that benefit from the increasing availability of large displays and the pervasive nature of mobile, tactile-enabled devices. For instance, Liang et al. (2013) investigated the use of two back-to-back mobile devices—to facilitate tactile input above and under the mobile device—with a combination of tactile gestures and sensors to support rotation, translation, stretching, slicing,. . . They also conducted an experiment to examine the use of dedicated regions on the mobile device to control objects or the 3D environment. Similarly, Du et al. (2011) investigated the use of a smartphone to navigate within a virtual environment on screen, while Katzakis et al. (2013) examined the combination of mobile sensors and tactile input for 3D translation and rotation through a docking task. Coffey et al. (2012), however, used 'indirect' tactile manipulation to navigate and examine a volumetric dataset to overcome the inherent issues of tactile interaction with stereoscopic rendering (Valkov et al., 2010). We are interested, in contrast, in a more 'direct' interaction[3] which also displays the 3D information (e. g., (Besançon et al., 2017))—we do not focus on remote manipulation using separate displays.

Our study mainly builds on the work by Hinckley et al. (1997) and Tuddenham et al. (2010). Hinckley et al. (1997) conducted comparative 3D docking studies focused on rotation with four different techniques including a 3D ball (our equivalent is a tangible interface) and a mouse. We go beyond their approach in that we consider a full 6 DOF manipulation and evaluate more than time and accuracy. We go beyond Tuddenham et al. (2010)'s approach in that we, while also comparing mouse, tactile input, and tangible interfaces, use 3D manipulation tasks—including for the tangible input device.



(a) Screenshot of the task. (b) Person interacting in the tangible condition.



(c) Tracking using cameras.

Figure 16: Study setup. Participants were asked to move and orient the shaded object such that it matches the target.

## 3.3 EXPERIMENT

As we aim to understand the use of mouse, tactile input, and tangibles for the manipulation of 3D scenes or datasets, our study investigates a task representative of 3D manipulation, in a realistic scenario, using a wide range of participants. Beyond time and error metrics, we observed people's actions, learnt about their realistic preferences, and their subjective ratings of the techniques. We aimed to understand four of Nielsen's five factors of usability (Nielsen, 1993): effectiveness, efficiency, subjective satisfaction, error tolerance, and ease of learning. Error tolerance, was not within the scope of our study. The effectiveness is reflected by an accuracy score (in both angular and Euclidean distance), the efficiency by means of the time to complete the task, the subjective satisfaction by looking at participants' answers to our questions, and the ease of learning by looking at the evolution of task completion times.

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[3] The terms 'direct' and 'indirect' interaction have to be used carefully. While mouse input is arguably indirect, tangible and tactile input have both direct and indirect properties. Tactile input, in our case, occurs directly on the displayed data (albeit on a projection of the 3D shape) and is thus typically considered to be a direct interaction (Knoedel and Hachet, 2011; Levesque et al., 2011; Meyer et al., 1994; Poupyrev and Maruyama, 2003; Schmidt et al., 2009; Sears and Shneiderman, 1991; Simeone and Gellerseny, 2015). Tangible input directly manipulates a 3D shape (tangible) where the virtual shape is thought to be, but our visuals are projected onto the separate display. We thus argue that tactile and tangible interaction are more direct than mouse interaction.

### 3.3.1 *Task.*

The docking task we employ comprises translation in 3 DOF, re-orientation in 3 DOF, and precise final positioning of 3D shapes—actions representative of interactive 3D data exploration. A docking task[4] consists of bringing a virtual object to a target position and orientation. The docking target is shown on the screen as a wire-frame version of the object, without the users having any control over the target's position or orientation. We argue that high-level or low-level 3D manipulations can be decomposed into or simply are in the end, even just mentally, docking tasks. For instance, cutting plane manipulations to understand the internal structure of the data is in fact positioning and orientating the plane into 3D.

In practice, we used the Utah teapot as the 3D object to manipulate. It is a generic shape most people understand and does not present any orientation ambiguity. Other objects could have been used (Hinckley et al. (1997) and Chen et al. (1988) used a house with difference colors on each side, Zhai and Milgram (1998) used a tetrahedra with colored edges). Our pilot studies confirmed that there was no ambiguity in the orientation of the teapot. We randomly generated and validated the target positions beforehand (to ensure that all targets are reachable by all input modalities), yielding a pool of 15 valid target positions (see example in Figure 16a). Our pilot studies confirmed that the use of perspective and relative size were enough to allow depth perception on a void background. Per input modality, we asked our participants to carry out 15 repetitions. For each of them we randomly selected the positions from the remaining positions in the pool. We used the same pool of positions for all modalities. We counter-balanced the order of input modalities each participant saw to reduce the bias from learning effects. Our within-participants design thus comprised of 3 input modalities × 1 task × 15 trials = 45 trials in total for each participant.

Each trial was started and validated on a key press by the participant (similar to Chen et al. (1988) or Hinckley et al. (1997)). We considered using a pedal for validation (e. g., (Hinckley et al., 1997)) but our pilots showed its triggering precision to be inferior to a key press. We asked participants to balance accuracy and speed, and intentionally did not reveal their achieved accuracy after each trial (as done by others (Chen et al., 1988; Hinckley et al., 1997)) to avoid a bias toward accuracy (Hinckley et al., 1997). In addition, to avoid participant response bias (Dell et al., 2012), we explicitly told them before the experiments that none of the techniques was developed by us.

### 3.3.2 *Apparatus.*

For all three input modalities we used the same touch-enabled 21″ LCD screen with a resolution of 1920 × 1080 pixels and a 60 Hz refresh-rate. Participants were seated in front of the screen which was slightly tilted (approx. 15°) to provide a comfortable tactile input setting (see Figure 16). We decided against using a stereoscopic display as this causes a parallax issue (Goodman and Teicher, 1988; Valkov et al., 2011a), as well as 'touch-through'

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[4] Other examples of docking task studies: (Chen et al., 1988; Froehlich et al., 2006; Glesser et al., 2013; Hancock et al., 2007; Hinckley et al., 1997; Vuibert et al., 2015; Zhai and Milgram, 1998).

issues(Chan et al., 2010)—users touch through the 3D objects to reach the touch-enabled screen. The mouse condition used a classical computer mouse: a Logitech m100 at 1000 dpi with a 125 Hz polling rate. The tangible condition was based on an optically tracked hand-held cardboard-based cuboctahedron (see Figure 16b), each edge measuring 65 mm. The lack of embedded electronic parts make the tangible prop weigh only 26g. Markers on each face facilitated its 3D tracking with 6 DOF. Each marker was as big as the cuboctahedron face it was placed on to ensure an optimal tracking. The optical tracking system comprised two Project Tango tablets.[5] Since camera refresh rates depends on lighting conditions (the darker the room, the lower the refresh rate), we set up a room with only artificial lighting.[6] The lighting was then improved by using two 220W lightbulbs—each one producing 3300 lumen—reflected by photography umbrellas to avoid a direct over-lighting of the tangible prop which would hinder the optical tracking. Ultimately, our setup yielded camera framerates of 30 fps at a resolution of 800 × 600. We adjusted the tablet positions according to a previous pilot study. In the final setup, the two cameras were located as shown in Figure 16c: one above to see both the screen and the tangible probe from above, and one on the participants' left side (at approx. head level) so that the space in front of the screen was visible. Together, they allowed us to avoid dead angles: participants could comfortably hold the cuboctahedron without blocking the camera's view. Programmatically, the optical tracking was realized thanks to a combination of the Vuforia[7] and ARToolKit[8] frameworks and stabilized by using the 1 euro filter (Casiez et al., 2012).[9] The tactile input, finally, was captured using capacitive touch sensing built into the screen. This touch sensor provided up to 10 points—captured via TUIO (Kaltenbrunner et al., 2005).[10] The overall setup (distance to screen, camera placement) also allowed users to rest their arms/wrists (mouse+keyboard condition) as well as to rest their arms, elbows, and shoulders (tactile/tangible conditions) on the table.

### 3.3.3 *Interaction Mappings.*

As much as possible, we chose established mappings for the evaluated input modalities as follows.

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[5] See https://www.google.com/atap/project-tango/ .

[6] In practice, the setting of refresh rates for cameras is not fully reliable on Android systems—even with our precautions. Nevertheless, our setup reduced the refresh rate variability as much as possible.

[7] See https://www.vuforia.com/ .

[8] See https://www.hitl.washington.edu/artoolkit/ .

[9] See http://www.lifl.fr/ casiez/1euro/ .

[10] See http://www.tuio.org/ .

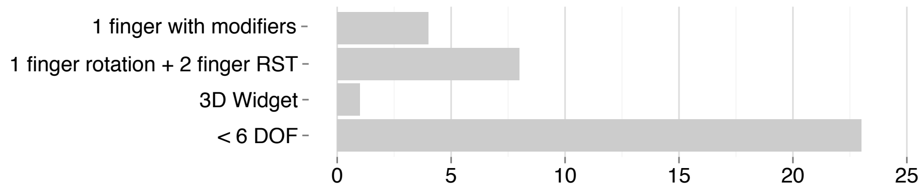

Figure 17: Tactile mappings for mobile 3D interaction.

#### 3.3.3.1 *Mouse+Keyboard mapping*

Inspired by the mappings used by Blender,[11] Autodesk MDT,[12] or Catia and software tools based on VTK such as Paraview,[13] we used the following mappings:

- right button: translation along the $x$-/$y$-axes,
- left button: Virtual Trackball rotation for the $x$-/$y$-axes,
- keyboard modifier + right button: $z$-axis translation,
- keyboard modifier + left button: rotation around the $z$-axis (leftward mouse motion = clockwise rotation), and
- the use of the scroll wheel was disabled since zooming needed to be inaccessible for the docking task.

While several rotation techniques have been implemented ( see the surveys by Chen et al. (1988) and Bade et al. (2005)), Bell (1988)'s Virtual Trackball (VT) and Shoemake (1992)'s Arcball seem to be the ones most frequently used in available softwares. Yet, they are often seen as frustrating by users because they violate a number of principles for intuitive interaction (Bade et al., 2005). Based on our pilot studies we decided to use an improved version of Bell's VT; one that respects the third principle mentioned by Bade et al. (2005) and provides a transitive 3D rotation.

#### 3.3.3.2 *Tactile Input Mapping*

In contrast to mouse+keyboard and tangible input, no single established standard or quasi-standard for touch-based interaction with 3D data exists. Based on our survey of 36 commercial and academic mobile applications on Android and iOS (see Figure 17), we found that most interaction mappings do not provide the 6 DOF we need. From those which do, most used the mapping that relies on either one or two fingers, with the latter providing rotation round the $z$-axis, uniform scaling, and translation along the $x$-/$y$-axes using pinching (RST—Rotation, Scale, Translation). Some systems provide a RST technique with a system-controlled moding: once the user's intention is captured by the system the control mode is locked. However, we decided not to use system-control moding because this could hinder the way

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[11] See https://www.blender.org/ .
[12] See http://www.autodesk.fr/products/autocad-mechanical/overview.
[13] See http://www.vtk.org/ and http://www.paraview.org/ .

users understand the interaction mapping. While studies have shown that it is possible to outperform the classical RST technique by separating the degrees of freedom (Martinet et al., 2010), we believe that the intuitiveness of the pinching mapping can be of advantage in our case, so we decided to use the following mappings:

- 1 finger motion: virtual trackball rotation for the $x$-/$y$-axes,
- 2 fingers—RST:
  - translation: translation along the $x$-/$y$-axes,
  - rotation: rotation around the $z$-axis, and
  - pinching: $z$-axis translation (cf. Hancock et al. (2009a)).

#### 3.3.3.3 *Tangible Input Mapping*

Tangible input is not yet widely established outside academic research so we could not draw from established mappings in software tools. We thus decided to use the intuitive isomorphic position control: a one-to-one mapping that moves and rotates the virtual object similar to the motions of the tangible object in real life. While such an interaction could be classified as a minimal TUI, it fulfills the four characteristics of TUIs as defined by Ullmer and Ishii (2000)—similar to other comparable tangible input devices in the literature (Hinckley et al., 1994b; Song et al., 2011)—and is thus well suited for our study.

*(d) Input Range.* The input range of each modality was adjusted so that translations would not exceed the cameras' Field of View (FoV) in the tangible condition. In other words, it was possible to achieve all 3D docking tasks without clutching for translations. Rotations, however, were not constrained by the cameras' FoV and ranged from 19° to 228°. Clutching could be used for each modality by releasing the finger-pressure on mouse button, removing fingers from the tactile screen, or briefly using a second-hand grasp with the tangible object.

### 3.3.4 *Participants.*

36 unpaid participants (10 females) took part in our comparative study. Their ages ranged from 19 to 52 years (mean = 30.2, SD = 8.7; median = 26). Three were left-handed, the remaining 33 right-handed. With respect to their expertise with 3D manipulation on a computer, 12 participants ranked themselves as skilled due to frequent use of video-games or 3D softwares, while 24 participants stated they had no significant prior experience. Furthermore, 22 of the participants had a university degree, while 14 had a high school degree. They all had either normal or corrected-to-normal vision.

### 3.3.5 *Procedure.*

Participants were guided through the study by means of a study controller software that presented the different task blocks in turn. Before starting the trials of a new input modality, participants were introduced to the interaction technique. They were intentionally given minimal instruction on using each device, they were only informed that they could

- use the mouse's left and right buttons and the keyboard's shift key in the mouse+keyboard condition,
- use multiple fingers on the tactile screen in front of them for the tactile condition, and
- use the tangible object for the tangible condition.

Further, the space in which the tangible object could be used was pointed out because participants had to keep within the field of vision of the cameras. An evaluator was present to answer potential questions during the experiment as well as take notes about the usage of each of the three input modalities.

Throughout the study, we asked participants to fill in several questionnaires. A first questionnaire captured their demographics and their level of fatigue before the experiment. After each condition, participants filled a questionnaire to assess their workload and fatigue level. For the former we used NASA's Task Load Index,[14] the latter was based on Shaw (1998)'s approach . A final questionnaire assessed the subjective ratings for the different techniques. We go beyond the usual Likert-scale or ranking approach suggested by Nielsen (1993) undergone in most studies: to confirm this last self-assessment, we informed participants that they would have to do a final set of 15 docking tasks, for which they could pick their favorite technique. Only after they had voiced their choice, we informed them that, in fact, the study was over and that the last question was only used to understand their true preferences. We used this procedure to better understand their preferences and to avoid a bias toward the technological advantages of tangible input. Because the experiment already took approx. more than an hour, we conjectured that, if asked to perform an additional set of trials, participants would have a strong incentive to pick the solution they really preferred to use. We finally asked whether, if given the free choice, they would have carried the additional batch of 15 tasks—to better understand people's eagerness to interact with the chosen technique. Indeed, in his book, Nielsen (1993) explains that "data showing voluntary usage is really the ultimate subjective satisfaction rating," which is what we assessed by this last question. *Variables.* In our comparative study we thus analyze one independent variable—the interaction modality—and five dependent variables—completion time, accuracy, fatigue, workload, and preferences. We took two different types of accuracy into account: the Euclidean distance to the target in 3D space as well as the rotational difference (in degrees) to the target.

### 3.3.6 *Hypotheses.*

Based on our previous experience with the three input modalities, we hypothesized that:

H1 The time spent on trials would be shorter in the tangible condition than in the tactile condition due to the inherent and fully integrated (Jacob

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[14] See http://humansystems.arc.nasa.gov/groups/tlx/downloads/TLXScale.pdf

et al., 1994) structure. Tactile-based interaction would also be faster than mouse-based input due to its higher directness and partially integrated structure.

H2 The accuracy for both the rotation and the Euclidean distance to the target would be better for the mouse than the tactile condition due to the better support of the hand when using a mouse. The accuracy of the tactile input, in turn, would be better than the tangible condition due to the lack of support for the hand when using tangibles.

H3 The workload for the tangible condition would be low overall due to its intuitive mapping and fast interaction times—yet the need to have to hold the object and fine-position it would have a negative impact. The higher mental demand necessary to understand the mapping of tactile and mouse interaction balanced by the reduced physical demand of these techniques would produce a slightly higher workload than for the tangible.

H4 The resulting fatigue would be highest for tangible input due to having to hold the physical object, lower for tactile input due to the added rest on the surface, and minimal for mouse input due to the arm resting on the table.

H5 People prefer both tangible and tactile inputs over mouse input: tactile for its "intuitive" mappings and reasonable accuracy, tangible because it benefits from the similarity to real-world interaction (but lacks a bit of accuracy). Mouse-based input is not preferred because it forces the separation of input DOF, while the others provide means of controlling several DOF in an integrated fashion.

## 3.4 RESULTS

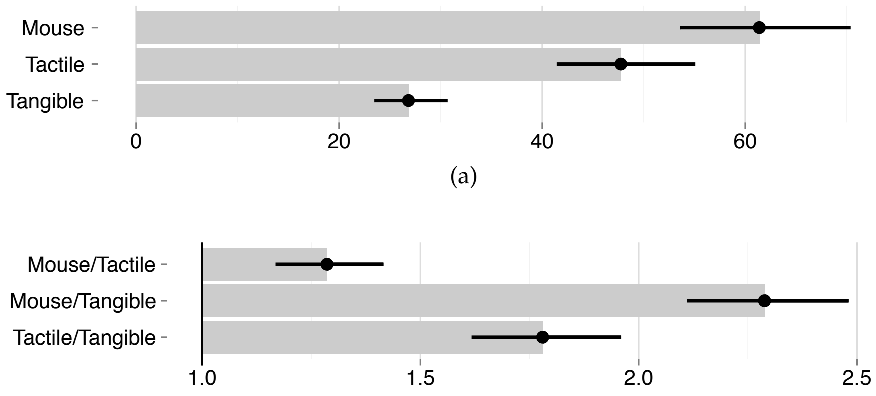
We collected a total of 1620 docking trials from 36 participants, i. e., 540 trials for each input modality. To compare the three conditions, we measured the task completion times as well as an accuracy score for each condition and each participant based on their results in each of the trials for a given condition.

We analyse the collected results using estimation techniques. A complete justification and explantion of how the results are analysed and presented is given in Appendix A.

### 3.4.1 *Task Completion Time*

We analyze log-transformed time measurements to correct for positive skewness and present our results anti-logged, as it is standard in such cases (Sauro and Lewis, 2010). Consequently, we arrive at geometric means which dampen the effect of potential extreme trial completion times which could otherwise have biased an arithmetic mean.

We present the completion time results in Figure 18a. It shows that it took participants 61 s to complete the task in the mouse condition, 47 s in the touch condition, and 26 s in the tangible condition. While the confidence intervals reveal a difference in favor of the tangible condition over the mouse



(a)

(b)

Figure 18: Task completion times: (a) absolute values in seconds and (b) pairwise comparison ratios (left-side technique divided by right one, 1 means similar performances). Error bars: 95% confidence intervals.

and touch conditions, they do not allow us to say anything more with confidence. We thus computed a pairwise comparison between the different conditions, see Figure 18b. The differences in these pairwise comparisons were also anti-logged and thus present ratios between each of the geometric means. These ratios all being clearly $\neq 1$ allows us to interpret the time differences of completing the task. Figure 18b shows that there is strong evidence for the tangible condition to clearly outperform the mouse condition: it is more than twice as fast as the mouse condition. The difference between the tangible condition and the touch condition is also quite strong: the tangible condition is almost twice as fast as the touch condition. The difference between mouse and touch is not as strong; yet, the touch condition can still be considered faster than the mouse condition.

We also checked for learning effects by dividing the 15 trials of each condition into three subsets of 5. We thus analysed the completion times for the three thirds of trials in Figure 19. As shown in Figure 19a, the completion time in the mouse condition drops from 75 seconds in the first set of 5 trials to approximately 55 seconds in the second and third subsets of trials. In the tactile condition, we can observe a strong evidence of a reduction of the completion time between the first subset of trials and second subset and less evidence for a decrease from the second to the last subset. In the tangible condition, however, we did not find any evidence of a difference in completion time

### 3.4.2 *Accuracy*

An inspection of Q-Q plots on the Euclidean and angular distance showed that the data did not follow a normal distribution but instead approximately followed a log-normal distribution. Thus, we also log-transformed both measurements for the analysis and we present the results anti-logged.

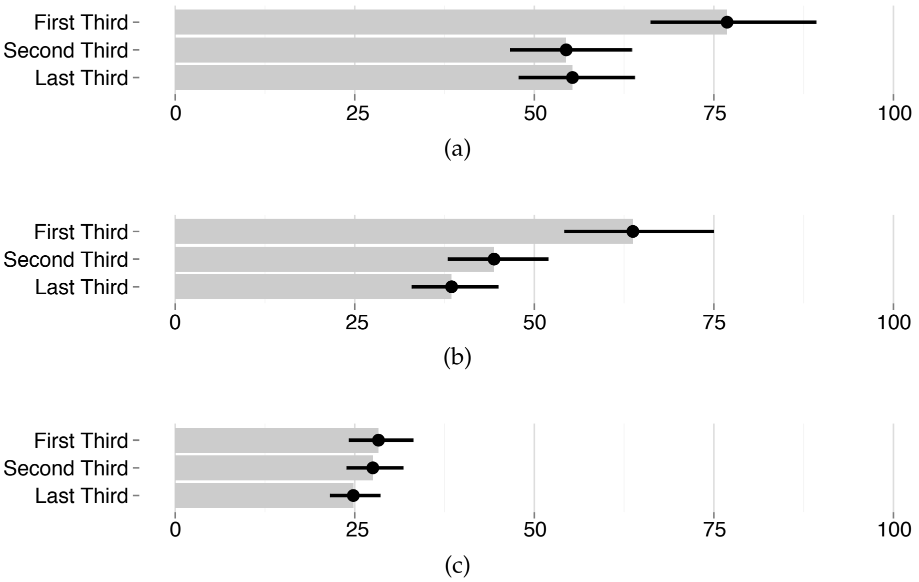


Figure 19: Task completion times in seconds: (a) mouse condition, (b) tactile condition, and and (c) tangible condition. Error bars: 95% CIs.

#### 3.4.2.1 *Euclidean Distances*

We report the Euclidean distance to the target in Figure 20a. It is computed as the distance between the target's 3D center to the movable teapot's 3D center. Figure 20a shows that all three techniques lead to similar accuracies, with means of 5 mm for the mouse condition and the tangible condition, and 6 mm for tactile input. Pairwise comparison between the conditions (Figure 20b) suggest that the tangible and the mouse input may have a slight advantage over tactile interaction, while both mouse and tangible inputs are very similar in accuracy to each other for our chosen task.

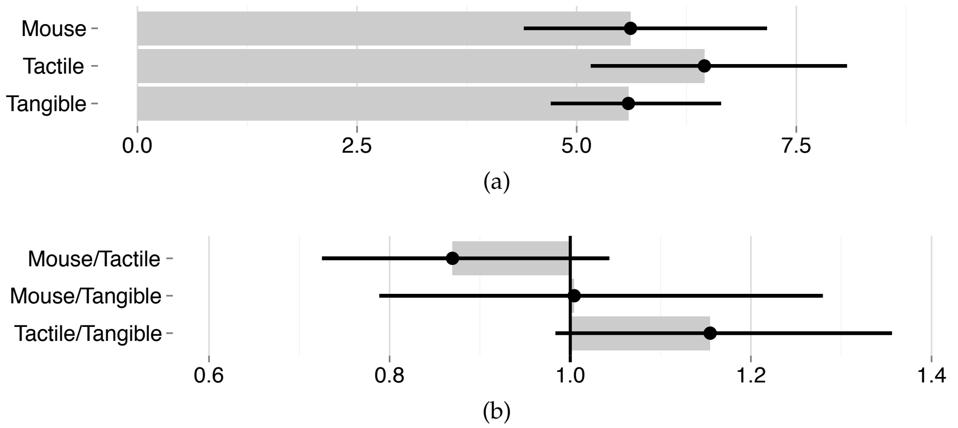


Figure 20: Euclidean distances: (a) absolute values in space units and (b) pairwise comparison ratios. Error bars: 95% CIs.

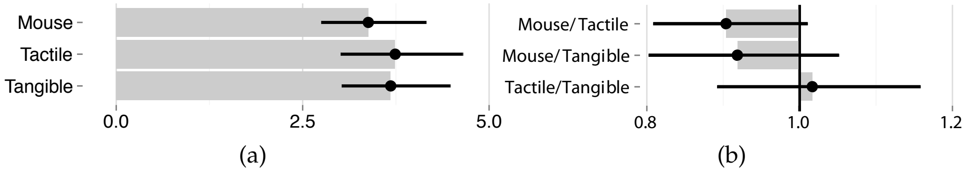


Figure 21: Rotational distances: (a) absolute values in ° and (b) pairwise comparison ratios. Error bars: 95% CIs.

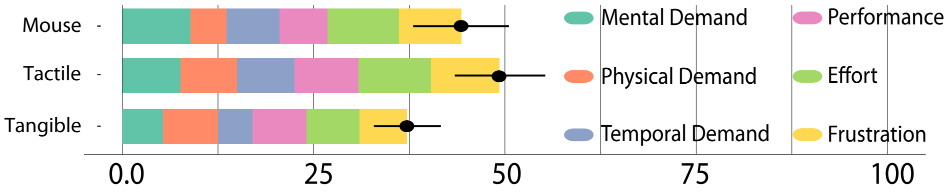


Figure 22: Total workload in overall NASA TLX units (∈ [0, 100]). Error bars are 95% CIs for the total workloads.

### 3.4.2.2 *Angular Distances*

Figure 21a reports the rotational distance to the target. The results are 3.4° for mouse input and 3.7° for both tactile and tangible input. Figure 21b shows the pairwise comparison between the conditions. Similar to the Euclidean distance, these comparisons indicate that all techniques are similar. There is weak evidence that the mouse may yield slightly more rotationally-precise results than tactile or tangible. However we did not find evidence for a performance difference between tactile and tangible for the rotation.

Our analysis of both types of accuracy did not yield evidence for a large difference in accuracy between the different input modalities. This result did not change if we—to account for learning effects—only analyzed the latter 2/3 or even the last 1/3 of the trials of each participant in the different conditions.

### 3.4.3 *Workload*

When collecting workload measurements using NASA's TLX we noticed that the pilot-study participants were often confused by its second part—weighing each of the different sub-aspects (i. e., mental, physical, and temporal demand, performance evaluation, effort, and frustration) for a given task. To avoid the seemingly random choices which would lead to inconclusive or even incorrect results we decided not to consider this second part of the TLX. We were thus left with what is called a *Raw TLX* (RTLX). According to Hart (2006)'s survey, the RTLX may be equally well suited as the regular TLX. We thus compute the workload for each task as the average of the RTLX ratings by participants.

The results of this analysis are shown in Figure 22. Here, we show the total workload for each condition as well as the specific sub-aspects rated by participants. The non-overlapping confidence intervals between the tactile and the tangible condition show that there the tangible condition requires

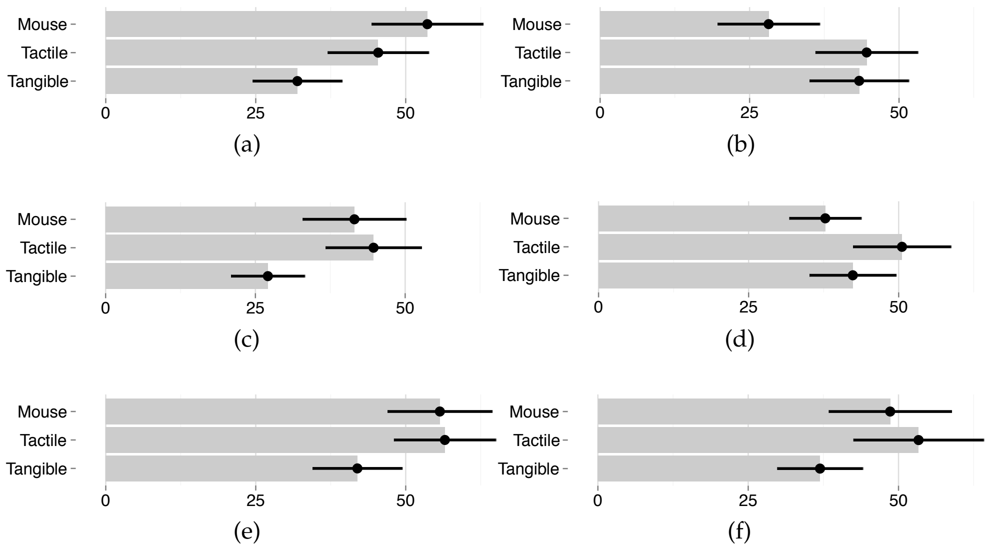


Figure 23: Workload sub-aspects of Figure 22's data in individual TLX units ($\in [0, 100]$): (a) mental, (b) physical, and (c) temporal demand, (d) performance (0 is best), (e) effort, and (f) frustration. Error bars: 95% CIs.

a lower workload than the tactile condition, yet for differences between the tangible and the mouse condition and even more so between the mouse and the tactile condition there is much less evidence.

The individual sub-aspects of the workload differs somewhat between the different conditions, but we did not observe many striking differences between the three input modalities. Figure 23 shows a detailed analysis of the differences of the sub-aspects. We can observe that there are only clear differences in the rating of mental demand between the mouse and tangible condition (Figure 23a), for the physical demand between the mouse and the other two (Figure 23b), as well as for the temporal demand between tactile and tangible condition (Figure 23c). The other comparisons between conditions for the sub-aspects only show gradual differences (also evident in the respective lengths of the colored patches in Figure 22). Yet, we can observe a slight advantage of mouse over tactile for performance evaluation (Figure 23d), a small advantage of tangible over the other two for effort (Figure 23e), as well as a lower frustration in the tangible condition (Figure 23f). The difference in temporal demand between mouse and tangible (Figure 23c) matches the differences observed in overall interaction times between them (Figure 18). In contrast, there was no difference between the mouse and tactile condition even though we observed a clear difference in the completion time between them.

### 3.4.4 *Fatigue*

We present the analysis of the fatigue measurement in Figure 24. Interestingly, none of the conditions exhibits a particularly high level of fatigue with the means all being lower than 4 on the scale of 0 to 10. While the mean of our measurements is highest for the tactile condition, based on the

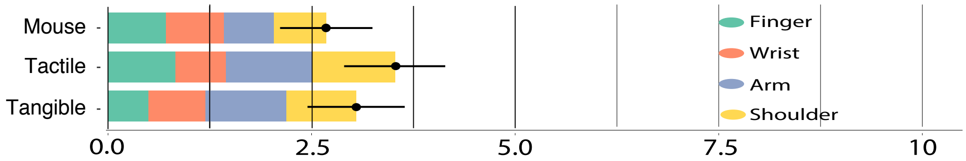


Figure 24: Total fatigue on a scale from 0 to 10. Error bars are 95% CIs for the total fatigue ratings.

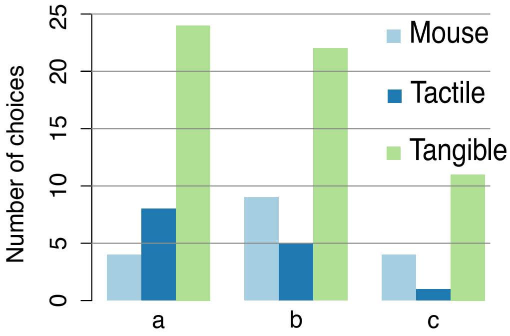


Figure 25: Participant preferences: (a) self-reported preferred technique, (b) technique chosen for the additional (but hypothetical) set of 15 trials, and (c) technique chosen by those participants who would have voluntarily stayed to complete the additional set of 15 trials.

confidence intervals there is no evidence that there would be an important difference between any of the conditions.

### 3.4.5 *Preferences*

In addition to the measured values we asked for participants' preferences. As described above, we asked for both a normal preference rating and the technique they would choose if faced with another set of 15 trials, as well as if they would want to actually stay for these additional 15 trials. Figure 25 reports these self-ratings.

Interestingly, the tangible condition was chosen most often for the stated preference (24 ×). Among those, however, 5 participants hesitated between touch and tangible, all ultimately picking the tangible as their favorite. The remaining 12 participants stated that they preferred tactile over mouse (tactile: 8 ×; mouse: 4 ×). When faced with an additional set of trials, a majority still preferred the tangible condition (22 ×). The tactile vs. mouse preference, however, changed with the mouse now being rated higher than the tactile (tactile: 5 ×; mouse: 9 ×). Of the 16 participants who freely decided to do the tasks again ((c) in Figure 25), 11 preferred the tangible condition, 4 favored the mouse, and 1 picked tactile.

### 3.4.6 *The Impact of Experience*

Based on the demographics of the participants as well as their experience in 3D manipulation we also analyzed the difference between experienced and non-experienced participants. Figure 26 shows the Euclidean and rotational distances as well as the completion times for each condition, for different

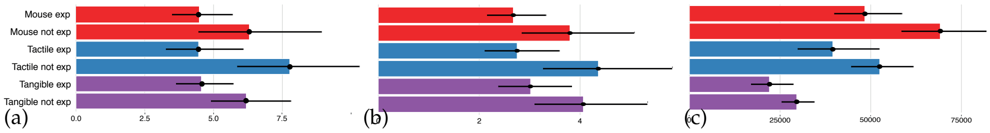


Figure 26: Impact of experience on (a) Euclidean distance (in mm), (b) rotational distance (in °), and (c) completion time (in ms). Error bars: 95% CIs.

levels of experience. The confidence intervals seem to always suggest a more accurate task completion of experienced participants for each input modality. For tactile input we can even observe strong evidence for this difference, both for Euclidean and angular distances. For task completion times there is strong evidence of a better performance of experienced user only for the mouse condition.

## 3.5 DISCUSSION

With our ultimate goal of better understanding the different input modalities that are available for spatial manipulation in the context of the exploration of 3D scientific data, we now discuss those aspects of our results that are most surprising and/or most relevant for our target application domain.

### 3.5.1 *Efficiency*

In line with our hypothesis H1, we found that the tangible interaction was faster than the tactile input which, in turn, was faster than mouse control. The reason for this difference in completion times is likely the inherent and straightforward integration of DOF control in the tangible condition, whereas the tactile and mouse condition need to switch interaction modes—with all the negative implications arising from user- or even system-controlled interaction modes (e. g., (Buxton, 1986; Sellen et al., 1992)). While tactile input still facilitates some degree of direct manipulation and DOF integration (4 DOF in the RST mode), the mouse only controls 2 DOF at any given time and is also the most indirect input device.

We conjecture that, despite the established benefits of the RST mapping, participants encountered difficulties with it that may have impacted their performance, in particular the completion time. We also hypothesize that the tangible condition's fast completion time may be a reason for its high accuracy: an approximate docking is achieved much faster than in the other conditions, giving participants time to fine-tune their docking.

### 3.5.2 *Learnability*

According to Nielsen (1993), learnability is one of the most important factors of usability. We noticed during the experiment that not a single user decided to give up on reaching the level of accuracy he/she wanted to achieve in a given trial with a given technique. In other words, they were all able to complete the tasks successfully. Looking at Figure 19 we can clearly see that learning happens in the mouse and tactile conditions. In the mouse condition, a third of trials (i. e., 5 trials) were enough to achieve significantly better results and master the mouse interaction. In the tactile condition, after a first subset of trials, the completion time required for a trial was also visibly decreased. From the evolution of the completion time in the tactile condition, we could however wonder if results would have gotten any better if participants were given an additional set of trials. In the tangible condition, we cannot find any evidence of a learning in Figure 19. Even when comparing the completion time of the first trial to the others, we could not detect signs of an improvement. These results thus support previous statements concerning the affordances of TUIs: they do not require learning as people are used to performing physical manipulation in the real world.

### 3.5.3 *Effectiveness*

The effectiveness was measured in form of an accuracy score of each modality. We initially thought that the different input modalities provided different degrees of accuracy. A mouse has a high-dpi sensor and a well-rested grasp configuration, while tactile relies on the finger as a rather blunt instrument with less support. The tangible condition, finally, needs optical tracking with the arm operating in empty space. Yet, surprisingly, our data does not provide evidence for any of the three techniques being more efficient (not providing evidence for H2). These results are even more surprising since they contradict as well the results obtained in the 2D docking task studied by Tuddenham et al. (2010) who found that the tangible condition exhibits an easier and more accurate manipulation than the tactile condition. Similarly, they contradict results by Vuibert et al. (2015) who found that a constrained desktop device—such as the PHANTOM—leads to a better accuracy than unconstrained interaction. The results extend previous finding from Hinckley et al. (1997) who found no difference of rotational accuracy between a tangible-like interface (3D ball and 3D tracker) and the mouse condition. However, many participants still reported that they *perceived* that they had precise control over their actions in the mouse (22 ×) and tactile conditions (8 ×). In the tangible condition, however, they felt that they had uncontrollable and involuntary hand movements and 20 of them reported the lack of accuracy they experienced. We believe that this *perceived* level of accuracy should not be disregarded in a decision of which interaction device to use or to offer for tasks that require a high accuracy. A possible explanation is that, overall, tangible and tactile interaction are less accurate than mouse and keyboard interaction but all inputs allow users to achieve a similar final accuracy. We believe that this *perceived* level of accuracy should not be disregarded in a decision of which interaction device to use or to offer for tasks that require a high accuracy. A possible explanation is that, overall, tangible and tactile interaction are less accurate than mouse and keyboard interaction but all inputs allow users to achieve a similar final accuracy.

### 3.5.4 *Workload*

With our data we cannot confirm hypothesis H3, but the overall measurements show—for our task and participant group—the same tendency as argued in H3: The perceived workload for the tangible interaction is lower than for the tactile condition as well as slightly lower than for the mouse condition. We believe, however, that the tactile input (as well as mouse input) can be improved. We saw that many participants kept their arms in the air while interacting in the tactile condition which contributed to the workload. This issue could be improved upon using a better (tactile-only) setup and a better interaction mapping. For the latter we noticed that many participants had problems with the sensitivity of the $z$-translation—caused by them starting the interaction with their fingers very close together as they are used to interact that way on smart phones and tablets. Tactile interaction—even or in particular if it uses the same interaction mappings—may require people to re-learn some of their familiar interaction techniques as they transition from small to larger screens.

Similarly, we also observed some frustration with tangible input. Some participants who felt at ease with tangible input tried to manipulate it fast with one or two hands. Our optical tracking system, however, was only good enough for slow to medium movements but could not follow relatively fast manipulations, leading to participant frustration. Similarly, participants occasionally occluded both cameras of our tracking system, leading them to report frustration due to the interruped tracking—maybe even focusing on such issues when rating the frustration and not concentrating on other interaction issues.

### 3.5.5 *Fatigue*

Based on fatigue measurements we cannot confirm our hypothesis H4. The study setup was created such that—to facilitate a fair comparison—there was both enough space for mouse-based and tangible input as well as an equivalent view on the screen for all conditions. This arrangement, however had an implication on the self-assessed fatigue values. Indeed, many participants did not rest their elbows in the tactile condition, potentially resulting in shoulder and arm fatigue that would probably not have been perceived on a setup created specifically for tactile interaction. Such a setup would have also reduced the physical demand of the workload for tactile interaction. This arrangement would only reduce the arm and shoulder fatigue but would not impact the finger fatigue that we observe in Figure 24. Nevertheless, the fatigue ratings for all techniques are quite similar, so that at least the fatigue measurement seems to have little impact on the choice of interaction modality. Because our tangible prop was comparatively light (26 g) it probably had no influence on the overall fatigue of the users, and we thus cannot generalize these results to other types of props relying on self-tracking which are heavier.

We would also like to emphasize that tangible interaction lacks the possibility to easily maintain the virtual object in a given position and orientation as people release it. This was reported by four participants when asked what they liked about each condition. We can thus conjecture that an extended use of the tangible could drastically impact fatigue if it is impossible to release the tangible object without causing exit errors.

### 3.5.6 *Subjective Preferences*

Our data shows an overwhelming preference for tangible input, thus contradicting our hypothesis H5. We believe, however, that this result should be taken with a grain of salt. Our participants' preference for tangible interaction is likely biased by them being used to mouse-based and tactile interfaces, while tangible input is new to most of them. Indeed, some of the participants who selected tangible input as their favorite explained that they would use this technique for the forced and free choice (i. e., (b) and (c) in Figure 25) because they do not have the opportunity to "play" with such technology at home, while they have easy access to tactile screens and mice. The novelty effect thus clearly made a difference at least for 5 out of the 11 participants who picked the tangible option for the last preference choice (i. e., (c) in Figure 25). We also believe the use of the word "play" by the participants is noteworthy. While usually subjective satisfaction measures focus on aspects such as simplicity, safety, completeness, and irritation/frustration, TUIs introduce the concept of fun. This may further bias subjective preference studies. We can thus conclude that, thanks to its entertaining dimension and the novelty effect, the tangible interaction is the preferred mean of interaction. While the novelty effect may fade, the entertaining property of tangible interaction will probably remain, making tangibles perfectly suitable, for instance, for children—as studied, e. g., by Horn et al. (2012).

### 3.5.7 *Experience*

The faster completion times in the mouse condition for experts is not surprising: most of tools available for 3D manipulation use the classical mouse and keyboard interface and these results were predictable. It is interesting to notice, however, that experience had less influence in the mouse condition over the accuracy achieved by the two groups of participants. Similarly, since tangible interaction is still largely a focus of research activities as of today, experience had likely not a big influence on the results we obtained. All participants were equally prepared for this type of interaction due to their general experience manipulating objects directly in 3D space. We have no clear explanation, however, for our observation of a small improvement in accuracy for experienced participants for tactile input. While some of them may have tried one of the few 3D exploration or modification applications on mobile environments, the lack of a standard way of interacting with 3D data in mobile apps (Figure 17) leads us to believe that is probably not the reason for the observed difference.

### 3.5.8 *Realistic Application Scenarios*

While our study scenario and tasks were chosen to be representative of generic 3D interaction as needed for visual data exploration, for realistic scenarios we likely face different requirements. We envision, for example, that longer interaction periods will be needed with different types of tasks and more complex interaction techniques. The longer interaction periods will have an effect on fatigue and workload, in particular for tangible and tactile input. Realistic tasks, moreover, require more than 6 DOF interaction: uniform or non-uniform scaling are needed as well as interactions constrained to specific DOF should at least be included. In addition, many other interaction modalities are needed for practical applications such as cutting plane interaction, parameter specification, view or data selection, etc. (e. g., (Coffey et al., 2012; Keefe and Isenberg, 2013; Yu et al., 2010)). All these are likely to favor mouse-based and tactile input, as tangible interaction will likely be more difficult to use for generic interaction—unless multiple tangible input devices are used. Tangible input, however, may have some benefits for specialized input (e. g., (Jackson et al., 2013; Sultanum et al., 2011)), while tactile input may be better for integrated approaches (e. g., (Coffey et al., 2012; Klein et al., 2012; Sultanum et al., 2011)). A final aspect to consider for realistic application scenarios is that, unlike the participant population we tested, we would be faced with experts in 3D interaction as they carry out such tasks on an everyday basis. Even though the learning effects we saw did not affect the results of our study overall, we may see other preference ratings among domain experts after longer periods of use than the ones voiced by our participants.

### 3.5.9 *Summary of Limitations*

The discussion so far has, in fact, mentioned many of the limitations of this work already, so we only provide a brief summary here. We strove to conduct a study that would avoid the numerous pitfalls of such a comparison study by having a population of users that was more representative than in other HCI studies, facilitating a fair comparison of each technique, and limiting the impact of biases. Yet, our study was limited by the need for a setup that would accommodate all three input modalities, while in practice dedicated setups better suited to a given modality would lead to better individual results. Moreover, practical applications will require more complex interaction scenarios, for which mouse and tactile-based input are likely better suited than tangible interaction. In addition, the chosen participant population for a quantitative experiment such as ours is different for the ultimate target audience, and the novelty factor of tangible interaction also introduced a bias—in particular for the self-reported preferences. Another influence of the chosen participants is that we faced learning effects, that would disappear if the techniques would be used in practice for a longer time. Finally, the chosen mapping for, in particular, tactile interaction may be successful in one type of application, but other applications and combinations with additional interface elements may require other mappings that may better be suited for visual exploration of 3D data. We believe that this mapping question should be the focus of future research.

## 3.6 CONCLUSION

We have compared mouse, tactile and tangible interaction in the context of 3D manipulation with a 3D docking task. We have provided a study design that limited the biases involved in this kind of study—participant response bias (Dell et al., 2012), or learning effect. We set reliable and comparable methods in a setup that was not in the advantage of any of the techniques.

| | advantages | disadvantages |
|---|---|---|
| mouse | • availability, familiarity<br>• perceived accuracy<br>• DOF separation<br>• low physical fatigue<br>• moding for complex tasks | • difficult mapping<br>• slowest interaction<br>• moding required |
| tactile | • availability, familiarity<br>• perceived precision<br>• increased directness<br>• faster than mouse<br>• easier mapping<br>• multiple mapping options | • unclear suitability of given mappings<br>• slower than tangible<br>• physical fatigue, exit error |
| tangible | • fastest interaction<br>• intuitive mapping<br>• impression of control<br>• novelty factor | • complex tasks unsupported<br>• relies on 3D tracking<br>• physical fatigue, exit error<br>• separate object needed<br>• rigid interaction mapping<br>• always on, extra moding needed to stop interacting |

Table 1: Advantages/limitations of each input modality.

We also imagined a technique to better assess the subjective preference of participants by tricking them in thinking that they had an additional set of trials to perform.

Despite the limitations mentioned, our study has provided valuable insights on the potential of the three input modalities—mouse, tactile, and tangible—for the use in 3D interaction in general and, specifically, for the visual exploration of 3D data. In particular, we found that they are all equally well suited for precise 3D positioning tasks—contrary to what is generally assumed about tactile and tangible as input modalities. Our analysis of task completion time showed that tangible interaction was fastest, tactile slower, and mouse slowest. However, we did observe learning effects that may play out for longer-term usage, even though our data still showed the same advantage for tangible interaction if only the last third of trials was examined. Moreover, we discussed several additional considerations that need to be taken into account when designing practical interaction scenarios that put the observed advantages of tangible interaction into perspective. Researchers can now build on our findings by knowing that there is not a single input modality that would be a clear favorite for controlling 3D data during visual exploration, but that all three have their respective advantages and disadvantages that which be considered and which are summarized in Table 1.

Our findings also facilitates further studies that can now focus on other aspects of the different input modalities. In particular, the interaction mapping for tactile input will remain a focus of future research. In addition, the issue of the exit error will have to be addressed for both tactile and tangible inputs. The presence or the lack of spatial multiplexing of DOF control for tactile (which some participants did not use despite this being possible) is another aspect that should be investigated. A closer investigation of people's use of dominant and non-dominant hands during interaction for both the tangible and the tactile conditions also would be an interesting path to follow.

Ultimately, however, the work conducted and the study results has helped us to continue our examination of how to best create an interaction continuum that allows one to fluidly switch between different interaction scenarios and interaction environments—picking the *best* one for a given task or situation. For such an interaction continuum, the definition of the *best* interaction technique could rely on several of the factors studied here that we take into account for the design of several hybrid interaction paradigms explored in the remainding of this thesis.

Finally, in this chapter, we have also implemented a robust and cheap setup that can support three different interaction modalities (mouse, tactile, and tangible interaction), hence making transitions from one to the other easy and affordable. This is particularly important because the interaction continuum that we envision cannot be achieved with overly complex or expensive setups (**R3**).

# 4

# HYBRID TACTILE/TANGIBLE FOR SCIENTIFIC VISUALIZATION

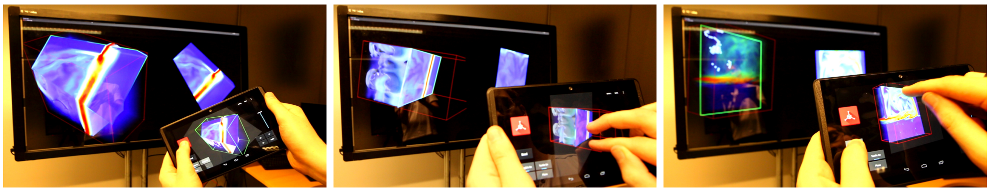

(a) Isosurface view.
(b) Isosurface view.
(c) Volumetric view.

Figure 27: Tangible and tactile interaction for 3D visualization: (a) tangible manipulation of a cutting plane in the visualization; (c) seed placement for particle tracing; and (b) tactile manipulation of a cutting plane in the visualization.

Based on the results presented in Chapter 3, we present the design and evaluation of an interface that combines tactile and tangible paradigms for 3D visualization. On the one hand, we have seen in Section 3.5.3 that tactile interaction and tangible interaction are equally well suited for precise manipulations, although tangible interaction was much faster as seen in Section 3.5.1. On the other hand, tactile (and mouse) interaction was perceived as more accurate by participants. We thus conjectured that combining these two interaction paradigm to create a hybrid interaction paradigm on a single device could be of use for experts researchers in other research fields. This chapter thus reflects on the possibility to combine these two complementary interaction techniques.

We conducted an initial field study with follow-up interviews in order to assess the needs of experts in fluid dynamic research and then to present a conceptual framework of the use of these different interaction modalities for visualization both separately and combined—focusing on free exploration as well as precise control. We present our prototypical implementation of a subset of these combined mappings for fluid dynamics data visualization. It relies on a portable, position-aware device which offers both tactile input and tangible sensing. We finally evaluate, the combination of tactile and tangible input with domain experts, by reporting on quantitative data and qualitative feedback.

Main portions of this chapter were previously published at IEEE VIS 2016 (Besançon et al., 2017). Consequently, any use of “we” in this chapter refers to myself, Paul Issartel, Mehdi Ammi, and Tobias Isenberg.

## 4.1 INTRODUCTION

Interactive data exploration has long been an essential aspect of the visualization of 3D datasets. Traditionally, researchers have been investigating both dedicated interactive visualization platforms such as immersive VR settings (Cutler et al., 1997; Dam et al., 2000; Krüger and Fröhlich, 1994) and traditional workstations. While the former rely on dedicated 3D input devices such as wands, gloves, or 3D tracking, the latter make use of either desktop-based 3D input devices such as 3D mice or the traditional mouse+keyboard setup. Both of these interaction settings (VR and workstation) have a long tradition and continue to be important. Yet people have increasingly easy access to novel display and computation environments such as tablet computers and large displays. In addition to traditional ones, these offer new interaction paradigms such as tactile and tangible input.

Research has shown that these tactile and tangible input paradigms have many benefits for effective and efficient interaction, in particular for 3D data exploration (e. g., (Fu et al., 2010; Hinckley et al., 1994b; Issartel et al., 2014b; Yu et al., 2010)). Yet, they are quite different from each other: tactile input benefits from its directness and a resulting perception of control and precision of interaction (Watson et al., 2013; Yu et al., 2010), while tangible input offers an integrated, multi-sensory, and intuitive 6 DOF control due to its similarity to day-to-day interaction with real objects (Ishii and Ullmer, 1997; Fitzmaurice, 1996; López et al., 2016). The development of portable position-aware devices offers opportunities to use a tablet for tangible input in addition to the usual tactile input. Indeed, a device capable of tracking its own position in 3D space and interacting with a digital environment fulfils the four requirements for tangible interfaces as defined by Ullmer and Ishii (2000), while at the same time providing a display with tactile sensing.

One of the main benefits of both input paradigms is that the input sensing and the data display can be integrated into a single device—Google's Tango tablet even supports both input modalities. This sensor integration not only allows the devices to be used for data exploration by themselves, but also allows them be integrated into traditional data exploration environments such as immersive settings (e. g., (Cutler et al., 1997; Klein et al., 2012; Dam et al., 2000)). These devices allow us to take a large step toward an interaction continuum (Isenberg, 2014) in which different input and output modalities can be used for data exploration, depending on the setting and user needs.

Yet, it is still unclear how this transition between the different input modalities could and should be realized in practice, in particular due to the different characteristics of tactile and tangible inputs. While several mappings for the two paradigms have been explored in the past (Olwal and Feiner, 2009; Sultanum et al., 2011), their respective benefits and challenges with respect to 3D data exploration remain uncertain. We thus investigate their integration in one device and the resulting possibilities and potential interaction mappings for common 3D data exploration tasks. Based on the analysis of a field-study and on follow-up interviews of five fluid dynamic researchers, we focus on a subset of the potential interaction mappings to provide interaction for common fluid-dynamic analysis tasks based on the Google's Tango tablet as the interaction device.

Our contributions of this paper are thus threefold. First, we contribute an understanding of how the two interaction paradigms can be combined to benefit from their inherent characteristics in the context of 3D data exploration by discussing the design space for possible interaction mappings. Second, based on this understanding we propose a design of hybrid mappings to achieve common 3D visualization tasks. In particular, we focus on mappings that make tactile and tangible inputs complementary as well as investigate the resulting interaction accuracy and constrained control. Third, we evaluate a subset of these hybrid mappings and compare them to touch-only or tangible-only approaches in a qualitative evaluation with fluid dynamic experts. Our results inform the creation of hybrid and complementary mappings between tactile and tangible input and paves the way towards a more complete interaction continuum for scientific visualization.

## 4.2 RELATED WORK

Within the field of 3D interaction (Bowman et al., 2005; Hand, 1997; Jankowski and Hachet, 2013), our work relates to tactile, tangible, and mixed input techniques to explore 3D scenes. We review relevant work next with a focus on interactive 3D visualization.

### 4.2.1 *Tactile Input and Its Use for 3D Data Exploration*

Tactile input for interactive systems has been investigated for a long time (Buxton, 2007) and has been popularized by the rise of mobile devices in the last decade. It has multiple advantages over other forms of input including an improved performance for certain tasks (Kin et al., 2009) while being compatible to mouse-based input for others (Forlines et al., 2007; Sears and Shneiderman, 1991), its support of interaction collaboration awareness (Hornecker et al., 2008), its somesthetic feedback (Robles-De-La-Torre, 2006), its suitability for physically large displays (Tan et al., 2006), and its use as a communication channel when one is presenting visualizations to others (Sundén et al., 2014).

The use of tactile input to control 3D scenes such as visualizations, however, requires a mapping from the 2D input surface to the 3D data space (Isenberg, 2011; Isenberg, 2016). Several basic interaction techniques have been proposed, including those for the exploration of 3D visualizations. For example, Coffey et al. (2012) designed a set of tactile interaction mappings for virtual reality (VR) contexts, combining a large stereoscopic screen with a touch-enabled tabletop display using a world-in-miniature metaphor. Their widget-based interaction techniques let users navigate the 3D visualization (rotation, translation, scaling), position slicing planes, place annotations, select data subsets, and plan camera paths. Klein et al. (2012) presented a similar design study, but this time for monoscopic-only projections of fluid dynamics data. They also provide navigation and cutting plane interaction techniques, using only a single surface. In addition, they investigate particle seeding in 3D vector fields and the support of collaboration. A third example of a design study for the exploration of scientific data is (Lundström et al., 2011)'s virtual surgery table, also intended for collaborative setups. It supports 6 DOF navigation as well as additional exploration techniques such as the exploration of slices from medical imaging datasets.

In addition to these systems and design studies, a number of additional tactile interacttion techniques have been proposed. For example, Cohé et al. (2011)'s tBox , Reisman et al. (2009)'s 3D-RST , and Yu et al. (2010)'s FI3D provide dataset navigation facilities, Fu et al. (2010)'s powers-of-10 ladder provides scale navigation at different levels, and Yu et al. (2012) and Yu et al. (2016) suggest context-aware spatial selection techniques.

Although these tactile interaction techniques offer the benefits described above, tactile input also has some issues compared to traditional input devices that have been confirmed by study presented in the previous chapter. In particular, finger fatigue (Besançon et al., 2017), fat finger, and a higher sensitivity to noise in the input data (Besançon et al., 2017; Tuddenham et al., 2010) are issues that one has to account for when selecting or designing a tactile interaction technique. It is also worth noticing that, although pinching is used and perceived as a natural gesture for zooming, the gesture cannot at the same time provide $z$-translations (Hancock et al., 2009b; Hancock et al., 2010). In our work, we thus base the implementation on some of these methods, but also learn from the insights reported by their respective authors and propose slightly adjusted designs.

### 4.2.2 *Tangible Input and Its Use for 3D Data Exploration*

Tangible User Interfaces (TUI) and especially the class of TUIs called Graspable User Interfaces aim at taking advantage of people's natural skills for manipulating their physical environment (Fitzmaurice, 1996; Ishii and Ullmer, 1997; Ishii, 2008a). While many TUIs use tangible props as both physical representation and means of interaction, several TUIs focus more on the input aspect (Hinckley et al., 1994b; Issartel et al., 2014a; Issartel et al., 2016b; Issartel et al., 2014b; Jackson et al., 2013; Song et al., 2011) by considering the tangible props as *handles*. Tangible input inherently offers 6 integrated DOF per prop. In our case, we are thus restricted to a single set of 6 DOF as we work with a single device.

The benefits of Tangible interaction have already been explained in the previous chapter. To summarize, tangible interaction has been shown to be more engaging(Tuddenham et al., 2010) than other forms of input and to provide rich feedback (Zuckerman and Gal-Oz, 2013). There is also evidence that it requires very little mental effort to use(Besançon et al., 2017). It has been reported to be preferred by users when compared with other interaction means (Besançon et al., 2017; Zuckerman and Gal-Oz, 2013), even though it is still unclear whether this reported preference was obtained because of a novelty effect (Besançon et al., 2017). Tangible interaction can be a source of fatigue and exit-errors (Besançon et al., 2017) and users have reported feeling that it was less reliable than mouse or touch inputs (Besançon et al., 2017; Zuckerman and Gal-Oz, 2013). Furthermore, 3D data space navigation requires zooming which is something that a tangible handle does not naturally provide.

Two general approaches have been proposed for tangible interaction in a visualization context: either a tangible object serves as an input device while the result of interaction is displayed on an external screen, or the result is displayed on the tangible object itself. In the first category, Hinckley et al. (1994b) use a rectangular acrylic surface as a slicing tool for neuro-surgical datasets and display the sliced dataset on an classical external display. They combine this approach with a head prop to manipulate the dataset as well as clutching through a foot pedal (for the head-prop) and a button directly located on the plane (for the cutting plane). Similarly, De Guzman et al. (2003) use a fork as a metaphor for the slicing plane to help children navigate through a 3D virtual model of the human body. The fork can be attached to a mechanical arm (thus providing a form of clutching) or can be freely manipulated by hand. They represent the dataset by either a 2D or 3D physical body model but its orientation in physical space is not linked to that of the virtual dataset. In contrast, Qi and Martens (2005) provide a generic shape (a cube) to represent their dataset and propose cutting plane with either a tracked pen (that defines the plane's normal) or a tracked square frame similar to De Guzman et al. (2003)'s solution. Like Guzman et al., Mulder and Van Liere (2002)'s approach relies on a fixed tracking system and a fixed display setup and maps the orientation of a tracked pen to that of a virtual slicing plane, while Schkolne et al. (2004) use tracked props to position elements in 3D space for molecular visualization. A more lightweight tracking approach is used by Jackson et al. (2013) whose tangible interface consists of a printed 2D barcode that can be rolled into a pen-like object whose location and orientation can be easily captured using a camera—to be used, for example, for fibertract exploration. While Issartel et al. (2014b)'s data exploration system also relies on simple fiducial tracking to control the cutting plane with a tangible pen, they integrate this approach in a portable and affordable augmented reality setup that uses a tablet computer to view the dataset and track the interaction props. As an alternative to pen-based control, they also investigate the use of a cutting plane that is sightly offset from the tablet toward the data. The last two approaches have the benefit that a dedicated 3D tracking system is no longer necessary and thus avoid the calibration and maintenance issues that otherwise affect such setups. We use a similar approach in form of a spatially-aware tablet computer which can track its location and orientation in space.

The second approach for tangible interaction with 3D visualizations is to display (at least a part of) the data on the tangible device itself. For example, Spindler and Dachselt (2009) track the location of a small tangible surface (the PaperLens) over a tabletop display and project visual information on this surface as it is used to slice through the data. Song et al. (2011) use a tablet computer instead as a tangible cutting plane and show the resulting data slice both on the tablet and on a large vertical display. On the other hand, Bertelsen et al. (2012) use a full monitor mounted on a mechanical arm both for tracking and support, and show the respective data slice on the display depending on its location and orientation. In a way, all of these are variations of an earlier approach by Konieczny et al. (2005) that also allowed users to bend the tangible cutting plane and show the appropriate intersection with the data.

While we believe that all these techniques are indeed useful, they fail to provide other means of input in addition to the tangible 6 DOF control without the use of additional devices. We thus base our design on displaying a view on the tangible, but go beyond tangible interaction by using a position-aware table to also provide tactile input possibilities.

### 4.2.3 *Combinations of Tactile and Tangible Interaction*

The work reviewed here has been previously reviewed in Section 2.2.1. Yet, in order to give a better explanation of what our hybrid interaction system is based on, we still present here a short sum-up of relevant work in this area.

From the respective challenges and benefits of both input modalities and results from a previous study (Besançon et al., 2017), it appears that the touch and tangible modalities are complementary paradigms and can be combined. Past work that combines tactile and tangible input in a single system is largely found in tangible additions to tabletop displays where props are tracked using fiducial markers. Good examples of this approach are Jordà et al. (2007)'s prototype for live music performance as well as Al-Megren and Ruddle's Al-Megren and Ruddle (2016) setup for abstract data analysis. An example of such a combination for spatial 3D visualization is Sultanum et al. (2011)'s table-based system for exploring geologic reservoir data. They use tangible props for detailed data read-out and parameterizing a focus+context view, while tactile input is used for regular data navigation as well as for dedicated exploration techniques such as dataset splitting and layer peeling. However, most existing applications (mainly based on TUIO (Kaltenbrunner et al., 2005)), do not take full advantage of the physicality of tangible interaction as the tangible props remain on the tabletop—only their 2D position and orientation are used. We investigate, in contrast, the combination of tactile with full 6 DOF tangible input.

A previous step in this direction was Olwal and Feiner (2009)'s use of a spatially-aware small display device on a large tabletop surface. The small device was tracked in 2D and could thus show a section of the data displayed on the tabletop, but at much higher resolution. Tactile input was possible both on the tabletop display and the small device to explore the data. Taking this concept into 3D space, López et al. (2016) investigated the use of tactile input on a mobile device for 3D visualization, with both a stereoscopic view of the data and the mobile device's monoscopic view. In their study, they included a tangible interaction mode in which the tablet's orientation controlled the data view, yet restricted to 3D orientations. We extend such interaction to use the tangible device's full physicality, including full 6 DOF interaction.

Our approach also builds on earlier work by Watsen et al. (1999) questioning whether 2D or 3D interaction is best to integrate tactile PDA interaction in CAVE environments. Similarly, as early as 1993, Fitzmaurice (1993) and later Rekimoto and Nagao (1995) proposed to use position-aware PDAs as a magic lens to interact with the physical world. Schmalstieg et al. (1999) used transparent props and a pen that were tracked to augment the interaction space of a virtual table. Later, Miguel et al. (2007) used a tracked PDA to facilitate interaction in CAVEs: users moved the PDA in 3D to get a suitable "captured" view and then selected a 3D object with a tactile input. Similarly, Yee (2003)'s peephole displays combined position-aware displays with pen input and applied them to three different applications scenarios. We mainly based our approach on the last three but, instead of using pen interaction we explore tactile interaction in the context of 3D manipulations—as previously done by Tsang et al. (2002). Recently, Bergé et al. (2014) compared tactile and tangible interaction with a smartphone to explore 3D public displays.

## 4.3 TACTILE AND TANGIBLE DATA EXPLORATION

To better understand a potential integration of touch and tangible inputs we start by discussing the interaction tasks needed for spatial 3D data visualization, then analyze the resulting design space for the two input modalities, and finally motivate our prototypical implementation.

### 4.3.1 *Interaction Tasks in Spatial 3D Data Visualization*

Interaction tasks for the exploration of data visualizations have been analyzed in detail in the past (e. g., (Shneiderman, 1996; Yi et al., 2007; Brehmer and Munzner, 2013; Ren et al., 2013)). Shneiderman (1996), for instance, describes abstract tasks such as getting an overview, zooming, filtering, finding and selecting details or data subsets, discovering relationships, and interacting with the data exploration history. While others (Brehmer and Munzner, 2013; Ren et al., 2013) discuss the multiple levels of granularity in tasks concepts for visualization, Yi et al. (2007) provide a synthesis of abstract tasks based on a literature analysis. They include exploration, selection, reconfiguration, encoding, abstraction/elaboration, filtering, and discovery of relationships as well as an "other" category.

Applied to visual representations of 3D spatial data (rather than abstract data), the first four of these abstract tasks can be loosely mapped to 3D navigation (translation, rotation, zoom), data selection, and parameterization of the visualization mapping. Aspects of reconfiguration and encoding that change the spatial mapping of visual representation are rare due to the spatial data's inherent mapping to 3D space. Abstraction/elaboration, filtering, and relationship discovery also exist as well as "other" interaction tasks. For example, the use of a cutting plane, a drilling probe, or isosurface rendering could be seen as a form of data abstraction, while seed point placement adds a visual encoding of vector field's dynamic aspects. Overall, we thus need the following fundamental interaction techniques in most visualization systems of 3D spatial data (Keefe and Isenberg, 2013):

- 3D data space/view navigation: 3 DOF translation, 3 DOF rotation, 1 DOF uniform zooming; potentially with the possibility of constraining the interaction to specific DOF and/or align them to specific data dimensions,

- visualization styles/types adjustment and parameterization: selection of volumetric, iso-surface, or vector-based representations and their parameters,
- positioning/manipulating data exploration objects such as cutting planes (3 DOF) or probes such as drilling cores (2 DOF),
- 3D picking or selection of data subsets for further analysis,
- specifying/manipulating 3D points and other primitives for particle seeding, picking, or path planning,
- generating data read-outs or measurements, and
- temporal navigation.

Beyond these fundamental tasks, a smaller or larger set of other techniques may be needed depending on the data and application domain. However, the described set can be seen as a common set that is needed in most applications including our fluid dynamics application domain.

Several mappings for such data exploration tasks have been proposed for both input modalities (see Section 4.2). We can now analyze how the different tasks can be mapped to the two modalities, thus creating a design space for tactile and tangible control of 3D spatial visualizations.

### 4.3.2 *The Design Space for Tactile and Tangible Control*

Table 2 shows the design space and gives examples for specific types of control based on the related work. For navigation tasks we assume that the tangible interaction device is able to display a visualization of the data on its own touch-enabled screen, such a tablet computer, in order to investigate combinations of both input paradigms. However, we also include cases where dedicated tangible props are used for additional interactions as these could be combined with the tablet device. For tactile input we specifically point out the minimum number of hands necessary for a particular technique. For example, even though Coffey et al. (2012)'s Slice WIM widgets were demonstrated in their video in a bimanual fashion, the widget could also be used with several fingers of the same hand and we thus classify it as unimanual interaction. In contrast, while Yu et al. (2010)'s FI3D can be used in a unimanual fashion, their constrained interaction modes necessarily require bimanual input due to the widget's design.

As Table 2 shows, tangible interaction based on physically moving a mobile device in 3D space facilitates a direct mapping of up to 6 input DOF to the respective output DOF. Scaling would need to be supported separately, but mode switches facilitate the control of data space navigation, cutting plane manipulation, seed point placement, spatial selection, and data readout. Tactile interaction, in contrast, uses a variety of mappings and widgets that are either controlled uni-manually or bimanually. This essential distinction affects our hybrid interaction design because the need to hold the device during interaction severely restricts potential input from the non-dominant (carrying) hand (Wagner et al., 2012).

In all manipulation interactions, precision can be controlled by setting specific control-display gains either explicitly (e. g., through physical or vir-

Table 2: Design space for tangible and tactile control of 3D visualizations. For the uni- and bimanual usage we specify the lowest mode that a technique can be used in, not how it was demonstrated in publication videos.

| task | DOF | tangible | tactile |
|---|---|---|---|
| 3D data space navigation | 7 | 6 input DOF mapped directly to 6 output DOF; absolute or relative motion, rate control (Issartel et al., 2016b) (uniform scale cannot be provided by tangible interaction) | widget-based mapping: unimanual (Coffey et al., 2012; Cohé et al., 2011; Yu et al., 2010; Fu et al., 2010) or bimanual (Fu et al., 2010; Yu et al., 2010); purely posture-based mapping (Reisman et al., 2009) (uni- or bimanual) |
| cutting plane manipulation | 3 | same as 3D data space navigation | same as 3D data space navigation + posture/ widget combinations (Klein et al., 2012) |
| integrated data space + cutting plane manipulation | 7+3 | same as 3D data space navigation; through either explicit mode switches on the tangible device or multiplexed TUI interaction with more than one device | same as 3D data space or cutting plane navigation, using widget- or posture-based mode selection (e. g., (Coffey et al., 2012; Klein et al., 2012)) |
| style setting / parameterization | n/a | dedicated tangibles (e. g., (Moore et al., 1999; Ullmer et al., 2008; Oh and Woo, 2004)) | typically via separate widgets (e. g., (Klein et al., 2012; Sultanum et al., 2011); typically uni-manually) |
| picking / seed point placement | 3 | same as 3D data space navigation (direct 3 DOF pointing) + physical or virtual button to activate | tactile 3D positioning such as balloon positioning (Benko and Feiner, 2007) (e. g., (Coffey et al., 2012)) or 2 DOF pointing by casting a ray on a cutting plane (Klein et al., 2012) (both uni-manually) |
| spatial selection | n/a | "tangible brush" with button-based moding and additional size controls | context-aware selection techniques based on 2D projected view (e. g., (Yu et al., 2012; Yu et al., 2016), bi-manually) |
| data read-out | 3 | same as 3D data space navigation (direct 3 DOF pointing) + physical or virtual button to activate | 2 DOF pointing based on 2D projection, ray-casting on a cutting plane, or view-aware picking (Wiebel et al., 2012) (uni-manually) |
| temporal navigation | 1 | tangible sliders (Jansen et al., 2012; Ullmer et al., 2003) | slider-based widget (uni-manually) |

tual widgets) or implicitly (e. g., velocity of the tangible device/finger or distance to the starting point). In addition, precise interaction is supported when specific interaction constraints are observed. Such constraints can also be specified though the use of specific widgets (physical (Jansen et al., 2012) or virtual (Cohé et al., 2011; Yu et al., 2010; Fu et al., 2010)), or, in the tangible case, by using the device's own orientation (e. g., constraining the manipulation along the nearest data axis) or its position (e. g., translating along the axis with the longest distance from the starting point of the interaction).

After having discussed the individual mappings, we can now discuss how a combination of tactile and tangible input can be achieved. We concentrate on the spatial direct manipulation tasks because tasks such as style setting and temporal navigation, on a tablet-based interface, are most flexibly realized using a tactile widget. Table 3 summarizes some of the possible combinations. In contrast to the interactions in Table 2, we place here particular emphasis on ensuring that combinations do not conflict with each other. Table 3 shows that hybrid techniques exclusive to 3D data space navigation or cutting plane manipulation are possible, but do not make much sense. However, with situations requiring the two tasks it becomes meaningful to assign the two input modalities to one of the two mapping alternatives.

Additional challenges arise when an additional 3D point needs to be specified—either for picking/seed point placement or for data read-out—because both input modalities are already mapped to either view or cutting plane manipulation. If this point is specified using the tactile input, positioning a cutting plane is necessary in order to perform a ray-casting so that the finger's position can be interpolated to a 3D position. In this case, the positioning of the cutting plane and dataset are assigned to touch or tangible input. In the alternative case of tangible specification, the cutting plane is not necessary to provide a 3D location, so the tactile input can control the data view.

Similar difficulties arise when considering spatial selection, as this interaction also has to be mapped either to the tangible or to the tactile modality. Here, no additional cutting plane is necessary. In the first of these cases, the tactile modality can thus be used to specify the data view while the tangible is used as a "tangible brush." Physical or virtual buttons can be used to activate the brush mode and control its size. In the latter case, the view on the data can be adjusted with the tangible input, while the tactile input is used to specify context-aware selections.

### 4.3.3 *Field Study and Prototypical Implementation*

This design space can now inform the creation of actual hybrid interaction mappings for a specific domain. In this paper we focus on supporting data exploration for fluid dynamics researchers. In order to better understand their needs, and following Shneiderman (2010)'s recommodentations, we carried out a field study with five experts (3 males; 2 females; ages 22–44; mean of 13.6 years of professional experience). For this purpose we visited them in their lab and individually observed their normal working procedures as they analyzed new datasets. Each observation session was video-recorded

Table 3: Design space for hybrid tactile and tangible interaction.

| task | hybrid tangible + tactile control |
|---|---|
| 3D data space navigation | tangible and tactile input mapped separately to location and orientation; mapping of subsets (e. g., only $x$-/$y$-rotation to tactile) also possible |
| cutting planes | either tangible or tactile control, not both simultaneously |
| integr. data space + cutting plane | tangible and tactile input mapped separately to data space navigation and cutting plane manipulation |
| picking / seed point placement | as with integrated data space + cutting plane interaction, specifying the 3D point can be done with either tangible or tactile input: use of either an explicit user-controlled mode switch for tangible input or of the intersection of the finger's position with the cutting plane's position (ray-casting) for tactile input |
| spatial selection | e. g., tangible input to set data view and tactile input for context-aware selection; or tactile input to set the view and tangible input for selection using a "tangible brush" metaphor |
| data read-out | same as picking/seed point placement |

for further analysis and was followed up with a semi-structured interview in which we asked about the steps involved in dataset analysis and the interaction features that participants thought were lacking in current software. One result from this field study was the realization that an essential part of understanding new datasets relies on being able to manipulate cutting views of the data. Fluid dynamics researchers do not perform much translations on the data itself, but frequently rotate it in order to get better views and then use several cutting planes to get an understanding of its internal structure. When analyzing new datasets, experts first want to obtain a general understanding of the dataset—particularly through cutting planes—and then focus on understanding how the flows evolve spatially and temporally. The latter can be evaluated thanks to particle seeding.[1]

Based on this analysis, we decided to place our focus on several tasks in 3D space as the most fundamental building blocks for 3D data exploration. In line with the described design space, we decided to support the following tasks: 3D data space navigation, cutting plane manipulation, and seed point placement. Our work particularly focused on three points: (a) supporting these tasks in a way that the interaction mappings do not conflict with each other, (b) providing not only hybrid but also both purely tactile and purely tangible mappings so that they can be compared to each other, and (c) adding support for control-display gain control and DOF constraints in our mappings to provide a fine-grained control of manipulation.

Based on Table 2, we used a simple 1:1 mapping for the tangible-only case in which translations and rotations are captured by the Tango tablet and directly mapped to respective manipulations of the dataset. Zooming was

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[1] We contrast the traditional interaction software currently used by experts in the discussion section of this paper.

not possible in the tangible-only setting. For the tactile-only case we used a simple posture-based mapping that assigns motions of one finger to arcball rotations (e. g., (Fu et al., 2010; Klein et al., 2012)), motions of two fingers to 2D rotations, scaling, and translations (2D-RST, e. g., (Yu et al., 2010)). These mappings were chosen in part because unimanual input is easily supported and because they relate to common 2D tactile interaction mappings. Since many people are also used to translating items only using two fingers placed and kept next to each other, our 2D-RST mapping only becomes active if the distance between two simultaneous touches grows beyond a threshold (i. e., 300 pixels, equivalent to 29 mm). Due to the scaling gesture, translation along the $z$-axis was not possible with this mapping but could be achieved through combinations of $x$-/$y$-translations and arcball rotations.

For hybrid mappings we implemented four combinations. In the first two, we explore how a combination of tangible and tactile input can be used for either view navigation or cutting plane manipulation alone (Figure 27a, (c)). For this study, instead of mapping dataset orientation to one modality and location to another, as suggested in the first row of Table 3, we mapped both *both* location and orientation to a single modality. In the first mapping both modalities controlled the data volume, and in the second mapping both controlled the cutting plane. This way a temporal multiplexing made it possible to switch between the two input modalities for a given interaction, allowing us to investigate which mappings would be preferred by participants. In the other two combinations we explored the mappings mentioned in row 3 of Table 3: either tactile input mapped to view manipulation and tangible input mapped to the cutting plane manipulation, or the other way around.

We also wanted to investigate at least one mapping that requires the specification of a 3D point. We thus decided to explore 3D seed point placement (Figure 27b, row 4 in Table 3). From the different alternatives we implemented tactile input for specifying a seeding point because the act of touching is a good metaphor for the placement of objects. Consequently, we realized the two alternative mappings for integrated view specification and cutting plane arrangement with tactile and tangible input—using the considerations discussed in Section 4.3.2—and based the seeding on the specified cutting plane.

To facilitate the necessary mode switching, we implemented the interface shown in Figure 28. Menus on the top allow users to load datasets and change general settings. The buttons on the lower right constrain the interaction to a particular coordinate axis of the dataset. The slider on the right manipulates the control display gain factor associated with both tactile and tangible input to provide experts with an explicit control over the accuracy of their interactions. The buttons on the lower left control the mapping, allowing people to enable or disable the two input modalities and to map them to data or cutting plane manipulation. These are system-controlled states as user-controlled moding is already used for seeding and to activate tangible input through clutching. Tangible clutching is achieved by pressing and releasing the red button on the upper left (i. e., located beneath the left thumb of the user when holding a tablet 'normally'). Similarly, seeding point place-

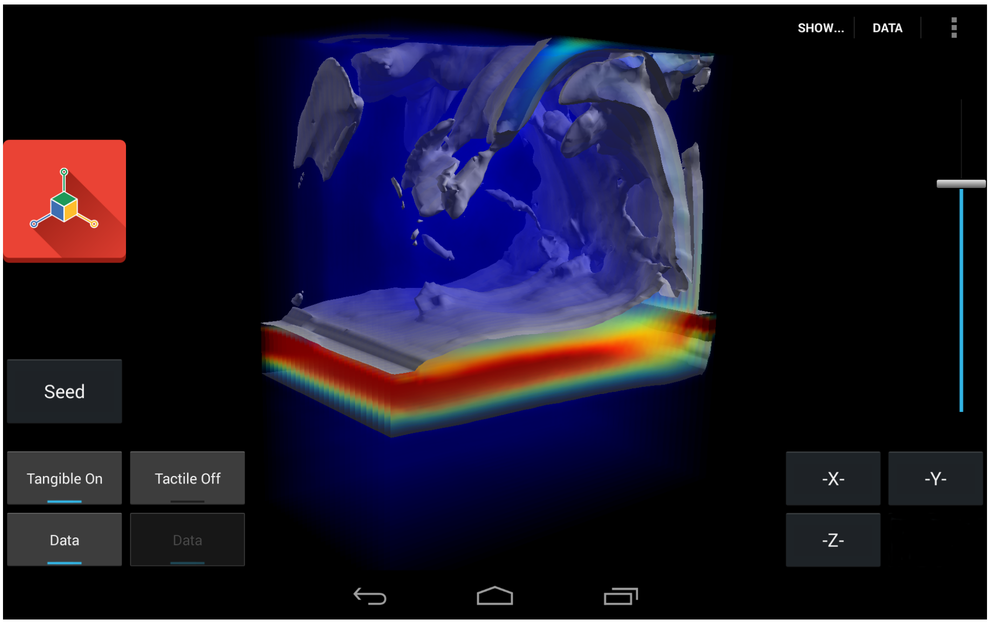

Figure 28: Our interface controlling the tactile input and the mode switching for the tangible control.

ment is achieved by placing the finger on the screen when the seed button is pressed.

## 4.4 OBSERVATIONAL STUDY WITH EXPERT USERS

To better understand the combined touch-tangible interaction and the use of the different possible mappings in practice, we conducted a second observational study with domain experts, this time with our actual prototype implementation. We were interested in their general opinion about such a hybrid interaction style, their understanding of the mappings, the way they transition between different modalities, how well the chosen mappings support their data exploration goals, and how they made use of those interaction capabilities in practice. We used an observational strategy like several visualization researchers before us (e. g., (Klein et al., 2012; López et al., 2016; Lundström et al., 2011; Sultanum et al., 2011; Fu et al., 2010)). We specifically decided against a classical usability study for several reasons. First, interaction mappings such as the ones we study are highly complex and are not easily studied by means of completion times and error metrics. Second, our pool of experts confirmed they do not consider data exploration and understanding as a task to be completed as fast as possible—in fact, a slower technique may be equally good or better when trying to understand unknown data. Moreover, as emphasized by Carpendale (2008) and Greenberg and Buxton (2008), classical quantitative studies can prevent the desired insights from users on the suitability of the different interaction techniques, e. g., by muting creative ideas or meaningful critique. Based on Lam et al.'s (Lam et al., 2012; Isenberg et al., 2013) categorization of evaluation strategies, we thus conduced a combination of a User Experience and VDAR evaluation: We asked our experts about how our techniques support their data exploration needs to understand how they can be improved and/or integrated in their work practice. Both of these evaluations have previously been conducted by means of observations and questionnaires/interviews (e. g., (Dwyer and Gallagher, 2004; Grammel et al., 2010; Song et al., 2004)).

### 4.4.1 *Participants*

We recruited 7 researchers (all male; ages 23–61 years, mean: 35.7, median: 32, and SD: 13.1) from a fluid dynamics lab whose work focuses on volumetric flow data. Our unpaid volunteers had 1–38 years (mean: 12.9, median: 9, and SD: 12.9) of post-Master's professional experience. All participants were used to interacting with 3D datasets in the course of their work using typical mouse+keyboard interaction. All were familiar with tactile interaction on their smartphones, and two had previously participated in tactile interaction experiments for 3D visualization. Only one reported to be familiar with the term tangible interaction and had been using such techniques before in experiments for classical 3D manipulations and 3D scientific visualization.

### 4.4.2 *Apparatus*

Our setup included the 7 inch Google Tango tablet[2] (370 g, 1920 × 1200 pixel resolution) and a 55 inch (139.7 cm diagonal) vertical screen with a 3840 × 2160 pixel resolution. Users were asked to stand in front of the large display throughout the experiment. The external screen showed larger views of the data as well as additional visualization elements in order to address the occlusion issue of tactile interaction (Hancock and Booth, 2004; Shneiderman, 1991b). As dataset, we used a domain-specific Finite Time Lyapunov Exponent (FTLE) scalar field (Figure 29) with its associated vector field. Our implementation uses the VTK library[3] to load and process the datasets. The dataset was rendered using OpenGL ES 2.0 on the tablet and OpenGL 3.0 on the vertical display. Communication between the devices used the UDP protocol and we sent absolute transformation matrices to ensure that packet loss would not be critical for the display/tablet synchronization. Elaborate computations and visualizations were restricted to the vertical display. For instance, the input information for particle tracing/seeding was captured by the tablet but processed and rendered by the vertical display's computer, and the external display also showed a 2D view of the slicing plane to ease the understanding of the sliced data. Our prototype is modular: the vertical display is handled by a PC running Ubuntu, while the tablet code can be adjusted to be fully functional with any position-aware device. Others can thus build on our work to create other hybrid interaction mappings with other devices.

### 4.4.3 *Study Design and Tasks*

We started by telling participants the purpose of the study, the setup, and the handling of the tablet. The study was divided into a training stage, two

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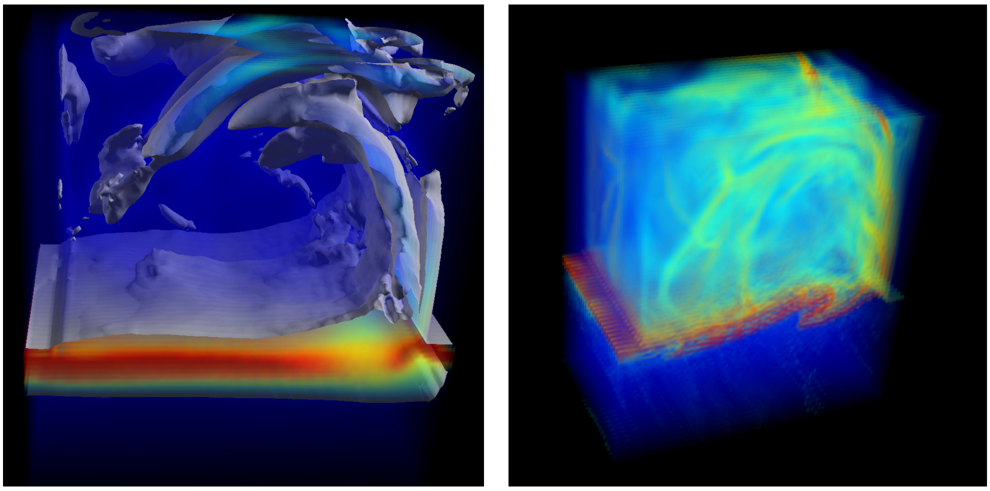
[2] https://www.google.com/atap/project-tango/

[3] http://www.vtk.org/



(a) Isosurface view. (b) Volumetric view.

Figure 29: Two views of the FTLE dataset used in the study.

main tasks, and a final session consisting of a questionnaire and an interview. Overall, each study session took between 18 and 50 minutes, not counting the questionnaire and interview parts.

**Training.** Using a simple 3D shape as a training dataset, we introduced the participants to all interaction techniques and gave details on the user interface in the form of a tutorial. Participants were also encouraged at this point to ask questions to the experimenter. This training session is not taken into account in our analysis of the results. Because we wanted to understand the entire interaction spectrum between tactile-only and tangible-only input, we encouraged the participants to explore all possible mapping combinations and ensured that this happened at least during the training stage.

**First Task: Exploration.** Once the participants declared that they were ready for the actual study, we switched to the FTLE dataset. We asked them to navigate the data and to try to understand it—as they would normally do in their work—by using any interaction technique provided by our interface. While interacting with the data, the participants were encouraged to ask questions and especially to think-aloud: explain what they liked, what they disliked, what they did not understand, or when they felt that unexpected things happened. We took notes about the oral insights given by participants. These notes were completed after each session based on video recordings and log data.

**Second Task: Particle Tracing.** After a thorough exploration of the data using the different mappings, the experimenter enabled the interaction mode for particle tracing[4] and explained how it could be performed. Participants were then asked to use it to gain additional insights on the datasets. Similar to the previous section, they were encouraged to explore all the different interaction mappings and to use the think-aloud protocol to allow us to

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[4] Particle tracing/seeding is a technique to explore vector fields datasets by generating a number of particles at a given 3D location. Each of them then follows the vector fields for this starting point.

capture their reasoning and preferences. In both the 3D navigation and the particle-based exploration parts, participants were free to explore the dataset until they had gathered enough knowledge.

**Questionnaires.** In the final part of each session we asked participants to fill out a questionnaire that asked about the effectiveness, usability, and intuitiveness of each interaction mapping. Participants were asked to provide their opinions using 5-point Likert scales. In addition, we asked about their overall preference for any of the different interaction mappings and the rationale for their choice. Finally, we conducted a semi-structured interview to discuss their experience in order to understand the pros and cons of each technique, why and how they would like to use them, and possible improvements. We based the interview on Lam et al. (2012)'s main questions for User Experience (UE) evaluation. An experimenter took notes which were augmented from the captured video of the session.

## 4.5 QUANTITATIVE RESULTS

Next we report the quantitative data we captured during the study. Due to variations in the overall study duration we report time ratios as suggested by Dragicevic (Dragicevic, 2012). Even though our participant pool was small, it was composed of domain experts and observational studies of interactive systems with experts can yield important insights (e. g., (Lundström et al., 2011)). Nevertheless, we report our results using estimation techniques (see Appendix A).

### 4.5.1 *Relative Interaction Times*

Figure 30 shows the fraction of time the participants spent using tangible, tactile, and hybrid input mappings. There is strong evidence that, after the training, participants predominantly used the hybrid mapping (86% of the time on average). In addition to this overall usage, we also examined the distribution of tactile and tangible inputs in the hybrid interaction mappings (Figure 31). The results show that our participants, on average, spent approx. 74% of their time interaction with the tangible and only 26% with the tactile input. We hypothesize that the flexible manipulations of tangible interaction is the reason why it is mostly used, which was confirmed by our interviews. Finally, we were interested in the use of the four different hybrid mappings described in Section 4.3.3 for view and/or cutting plane manipulation. Figure 32 reports the relative times spent in each of the four mappings. The ratios of time spent with each combination of data and plane manipulation (Figure 32) do not provide evidence for a dominant mapping. It appears, however, that mapping tactile input to the cutting plane and tangible input to the dataset was not used much by participants. We conjecture that this result was caused by the tablet being—due to its shape—an easier metaphor for the cutting plane than the data volume, leading participants to more directly associate it with the cutting plane rather than with the dataset when selecting the mappings. This was confirmed by participants.

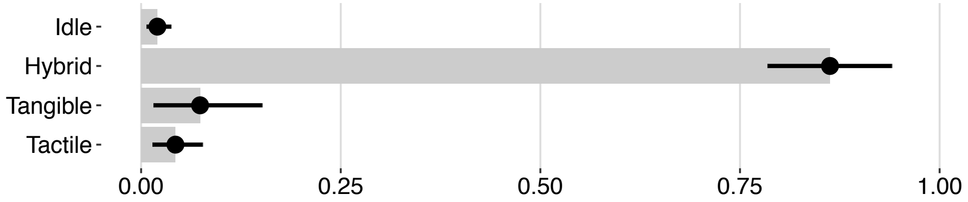

Figure 30: Ratio of time spent interacting in the different conditions. Error bars are 95% confidence intervals.

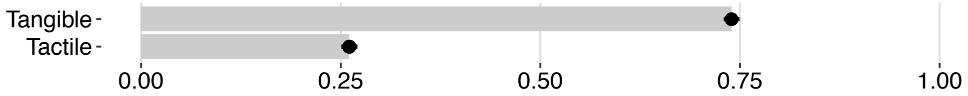

Figure 31: Ratio of time spent using the tactile and tangible conditions while using the hybrid interaction. Error bars: 95% CIs.

### 4.5.2 *User Preferences and Assessments*

We asked experts to rate the tactile-only, tangible-only, and hybrid interaction modes using 5-point Likert scales according to several usability criteria. In addition, we asked them to rank the three different techniques by preference. The results, collected using a questionnaire, are shown in Table 4. Overall, our participants agreed that they were able to accomplish what they wanted, quickly achieve their goals, and that the three techniques were intuitive enough. It appears, however, that they needed some mental effort to use the techniques, an effect that could be attributed to the mappings being new to them.

## 4.6 QUALITATIVE OBSERVATIONS AND DISCUSSION

Our main goal is to understand the role of hybrid interaction in the context of 3D visualization. We thus not only need to evaluate the tested interaction techniques by themselves but also have to discuss how they compare to and can be integrated with the usual PC/workstation-based environment that experts typically use. Most rely on tools such as Paraview[5] or MATLAB.[6] Based on our initial field study as well as the present qualitative observations and, in particular, the comments of the participants from the think-aloud protocol we can make this comparison. We discuss the two general approaches in this section, together with the general comments from our participants on

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[5] http://www.paraview.org/

[6] http://www.mathworks.com/products/matlab/

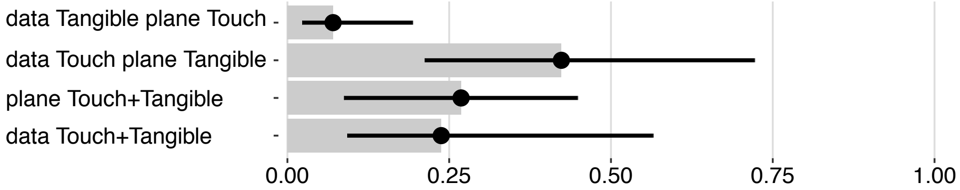


Figure 32: Distribution of time spent interacting with the different plane/data associations while using the hybrid interaction. Error bars: 95% CIs.

Table 4: Results from Likert-based ratings for different statements, with values ranging from 1 (completely disagree) to 5 (completely agree). Ranking is expressed from 1 to 3, 1 standing for the preferred technique

| statement | factor | mean | median | SD |
|---|---|---|---|---|
| I could do what I wanted. | tangible | 3.57 | 4.00 | 0.79 |
| | tactile | 3.57 | 4.00 | 0.98 |
| | hybrid | 4.14 | 4.00 | 0.90 |
| I could achieve my goals quickly. | tangible | 3.57 | 3.00 | 0.79 |
| | tactile | 3.86 | 4.00 | 1.07 |
| | hybrid | 4.14 | 4.00 | 0.90 |
| It could be used without much information. | tangible | 3.57 | 4.00 | 0.79 |
| | tactile | 4.00 | 4.00 | 0.81 |
| | hybrid | 4.00 | 4.00 | 0.58 |
| It required a lot of mental effort to use. | tangible | 3.14 | 3.00 | 0.69 |
| | tactile | 2.71 | 2.00 | 1.11 |
| | hybrid | 3.57 | 3.00 | 1.13 |
| overall ranking (1 to 3, 1=best) | tangible | 2.57 | 3.00 | 0.53 |
| | tactile | 2.28 | 2.00 | 0.76 |
| | hybrid | 1.14 | 1.00 | 0.38 |

the interaction mappings and their reasoning for using particular interaction styles.

### 4.6.1 *Preferences*

Overall, the hybrid interaction was preferred by most participants as seen in Table 4—only one participant did not name it as his first choice but as his second. Participants reported that our approach "was way faster and way more natural. It was more engaging, making people want to try more things, in particular when using the seeding,". They reported that the tangible interaction "adds more options once you get used to it and also allows for axis-constrained interaction.It is more natural and provides more DOFs than a mouse,"and finally reported that our approach "is easier to use. Less powerful for now in the different options that it gives than the traditional Paraview interface, but it is only an implementation problem and could easily be solved. If it were, it would be used for teaching or sharing knowledge. It is more enjoyable to use, even though the mouse seems to provide more precision." One participant said that the system, "is a reproduction of what [he] can do with a PC but with better interactions." This statement was mirrored by P6 who stated that he "could achieve complex rotations or translation difficult to perform with a mouse." Another participant (P2) stated that the prototype could be used as an "extra visualization tool" in the sense that he could carry most of the primary analysis with it, before switching to a PC/-

workstation for a more in-depth analysis that requires scripts, scatterplots, and mathematical functions that are better created with and manipulated on a PC/workstation.

### 4.6.2 *Mappings*

Overall, the two 'redundant' mappings (that associate both input modalities to the same interaction target) and the the tangible to plane/tactile to data mapping were used similarly often. Which of the three mappings was most frequently used still varied quite a lot between participants, and it appears that the choice between them is guided by personal preference—we could not identify particular reasons for a given usage pattern. When asked to explain why they used one over the other, participants said that it would correspond to their way of thinking. This leads, however, to the surprising observation that, contrary to what we expected, participants actually used 'redundant' mappings a lot. They all reported that the tactile modality was a way for them to adjust and fine-tune the final view/cutting-plane following large-grained changes with the tangible modality.

We believe, however, that a single study with one class of domain experts is not sufficient to fully understand the potential of these mappings. It would thus be useful to conduct a study with users from other backgrounds to better evaluate how tactile and tangible inputs can be combined when manipulating a single space or object. From our observations, it is also difficult to conclude whether a participant preferred to have a static cutting plane and a moving dataset, or the opposite. We conjecture that this is a matter of each person's mental model, which may be related to the type of datasets they usually manipulate.

### 4.6.3 *Accuracy and constrained interaction*

Both tangible and tactile input are inherently susceptible to noise and imprecise input, which is partially exacerbated by the integrated control of several DOF at the same time. We thus specifically considered how to support constrained input and control-display gain in order to improve manipulation accuracy.

**Axis-Constrained Interaction.** The possibility to constrain interaction to a given axis was much appreciated by participants, in particular for mappings that relied on tangible input. Participants reported that the tangible condition was a good way to freely explore the dataset, but that being able to constrain the input allowed them to achieve interactions they usually perform in PC/workstation-based environments. Indeed, in our field study we observed that, when using Paraview, experts often place a cutting plane perpendicular to one axis and translate it along this axis through the entire dataset. The use of axis-based input constraints can thus be considered as an important element of both tangible and tactile input mappings, confirming suggestions from previous work (Klein et al., 2012; Lundström et al., 2011). Moreover, P5 and P6 suggested to add buttons for placing data or planes at precise configurations without any manipulation to provide a better way to compare views with Paraview.

**Accuracy.** Even though participants could change the gain factor associated with the tangible and touch interaction, we noticed that this was rarely used. Indeed, P1, P2, P4, and P6 adjusted the gain factor twice, while Participants 3, 5 and 7 only used this feature once. P2, P3, and P4 reported, however, that they used the tactile modality to adjust orientations or positions obtained with the tangible modality. P2, P3, P4 and P6 especially mentioned the lack of accuracy they felt in the tangible condition, even though they did not use the widget we provided to control the interaction's gain factor. This contrasts recent work which found a similar level of accuracy between tangible and tactile control for 3D manipulations (Besançon et al., 2017). From our interviews it also appears that having an explicit widget for setting the control-display gain was not appropriate, confirming the hypothesis stated by Issartel et al. (2016b). One participant stated that he knew the widget could be used but did not think about using it and rather used the tactile modality to adjust the positioning. Perhaps we should thus focus on providing more implicit ways of controlling the gain factor while interacting. One participant suggested a *rate-control* approach—which is inappropriate for isotonic devices not providing a self-centering mechanism (Zhai, 1998).

### 4.6.4 *Particle Seeding*

The ability to seed particles in the data volume to explore its vector component was also appreciated by the experts. Six participants mentioned this feature first among the aspects they particularly appreciated. Participants compared particle seeding to the PC/workstation-based exploration tools, where they place particle sources by editing a script that is then executed. To be able to adjust the particle source they need to edit the script and rerun it. In contrast to this rather crude form of data exploration, our approach allowed them to interactively adjust the placement based on the location and orientation of the tablet (when using tangible control) or the cutting plane (for tactile input). All experts reported that this technique was "engaging," "easy to use," and that it could be "easily and greatly" improved with a few additional visual features such as depth cues or colors to represent tempature, speed, etc.

### 4.6.5 *Use of a Separate Vertical Display*

Five experts reported that the large display was not necessary in a non-collaborative setup. They reported that the screen of the tablet was large enough. Indeed, we observed that these participants actually spent most of their time looking at the tablet. This is surprising since previous observations of a tablet-based interaction with a large vertical screen (López et al., 2016) (albeit using a stereoscopic view) showed a preference of participants to focus on the vertical display. One of them explained that he looked at the tablet because that was "were the interaction was happening." Even in the supposedly eye-free tangible condition these three participants kept looking at the tablet. Participants 4–6, however, used the external display a lot, saying that they would always have access to an external display at their workplace anyway. Still, they did not think that the display had to be this large and that a typical 24" display would be enough. Yet, all of them mentioned that a large display was necessary for demonstration/presentation or collaborative analysis and that, with a larger screen, the tablet could be used alone as an on-the-go device to integrate in their working procedures.

### 4.6.6 *Integration into the Workflow*

We wanted to ensure that our interaction technique would be useful in improving the workflow and we asked participants whether they would use it in their everyday work. P6 reported that with a longer learning phase "it would be a nice tool and that [he] was interested and willing to use it whenever [he] needs to roughly analyze 3D data." P5 stated that he "would use it if it were improved with some extensions" (which we mention below). Overall, only P1 did not consider the tool as being fit for his practical work yet. Other participants welcomed the opportunity and imagined using it for presentations, collaboration, or teaching purposes. When asked whether they could integrate it with their classical interactions, five participants stated they would gladly use it if it synchronizes with their desktop station. Four participants also mentioned they would be interested in combinations of our hybrid technique with a mouse-based approach which worked well with classical software (to be used for further analysis). This way they could avoid a "going-back-and-forth" behavior and actually directly use our prototype for highlighting and selecting data—as it is "easier and more complete"—to further study it with mouse and scripts. We believe that these remarks highlight even further the need for an interaction continuum between new and classical interaction paradigms.

### 4.6.7 *Suggested Extensions*

Like many other qualitative studies, our experiment led to several suggestions for improvement. We discuss the most important ones:

- *provide separate "frozen" views on the large display:* participants wanted to be able to save frozen views on the large display and be able to interact with them at a later point (possibly using tactile interaction on the large display;
- *include the possibility to navigate in time:* datasets in scientific fields are often time-dependent and participants reported that in the seeding interaction they would like to see the influence of time on the particle propagation—a classical slider implementation can easy be added, but other possibilities such as tangible sliders (Jansen et al., 2012) may also be interesting in a hybrid interaction context
- *add widgets to obtain specific, well-defined views and cutting plane positions:* experts reported that they would like to have widgets to set data and cutting plane to specific positions as it is offered by their traditional PC-based software—a feature that they frequently use; and
- *consider interaction mappings for heterogeneous data:* while our dataset was relatively box-shaped with $100 \times 80 \times 54$ samples, extremely thin and long dataset may require adjusted interactions that better fit their

overall shape; based on our study we could envision to address this issue by mapping large-scale motions to the tangible interaction while small-scale motions would be mapped to the tactile interaction.

### 4.6.8 *Limitations*

While our design space exploration and observational study have demonstrated that hybrid tactile/tangible interaction can support 3D data exploration tasks, our work still has some limitations that we want to summarize here. As previously mentioned, our field-study and observational study only focused on one class of domain experts—fluid dynamic namely. Even though fluid dynamic visualization is a scientific field in which experts are often confronted with the manipulation of multiple DOFs, there are other domains to consider that could give complementary/different insights on our hybrid interaction design space exploration. Similarly, during both studies, experts were faced with a rather homogeneous dataset thus avoiding issues that could be encountered with extremely heterogeneous datasets. Our observational study also does not explain why certain mappings worked or were preferred, in particular due to the small number of participants. Similarly, our study does not explain how tactile and tangible input—when assigned to a single target—can be efficiently combined. Further studies with more participants are needed to sketch different possibilities.

## 4.7 CONCLUSION

In this chapter we explored the design space for the combination of tactile and tangible inputs (**R2**) to control 3D spatial visualizations. We proposed several mappings and studied a particular subset of these mappings to understand how the combination of touch and tangible inputs could benefit fluid dynamics experts in their 3D visualization tasks.

The conducted observational study showed that experts appreciated our prototype and that they found it better suited for primary 3D visualization tasks than a traditional mouse-and-keyboard setup. We saw surprising effects such as the participants using interaction mappings we initially did not think would be very useful. Participants especially appreciated that a complex seed point placement task could easily be achieved by combining a tangible manipulation of the cutting plane and a ray-casting with the tactile input, thus demonstrating the potential of hybrid tactile-tangible interactions. The flexible seed point placement enabled them to use an exploratory data analysis style of vector fields. Participants also appreciated having the ability to constrain input to specific DOF.

This work consequently represent a first step towards combining these two complementary input techniques (**R2**) and providing an alternative data exploration platform for scientific visualization. Most importantly, however, we demonstrated that with current hardware it is possible to realize hybrid tactile/tangible interaction techniques that support fundamental 3D data exploration tasks and that no longer rely on external 3D tracking (**R3**). Without the need for constant maintenance, calibration, and support that such hybrid interaction would normally require, it is thus now possible to make the proposed interactive data exploration techniques available to researchers in various domains.

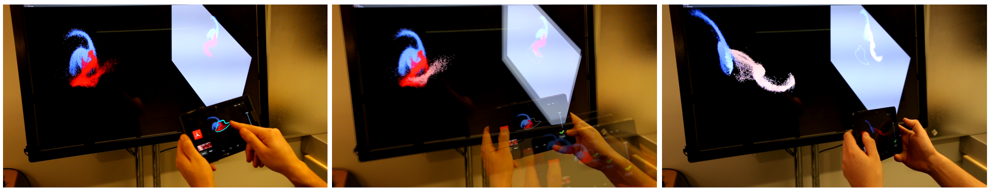
Even though we focused on fluid dynamic experts, some of our findings are generalizable. First, hybrid interaction is easily understood, is largely preferred by participants, and is the most frequently used interaction mode. Second, it appears that the tablet, due to its shape, is a good metaphor for cutting plane manipulations, which affects the interaction mapping preference. Third, the combination with a large display does not seem to be necessary—- regular displays (or none) can be enough. Finally, explicit accuracy adjustments are not useful for tactile/tangible interaction, other accuracy controls are needed. Moreover, while in our work we chose an observational approach that led to these insights, specific application domains may warrant quantitative studies, focusing on a task or domain that requires certain levels of accuracy or has time constraints. For example, doctors in a ER need to analyze medical scans quickly, surgeons need to understand medical images very precisely to plan or adjust a surgery. For such application domains we may thus need to reconsider the interaction design.

If we focus back on our interaction continuum goal, i. e.being able to transition between several interaction modalities, we clearly saw in this chapter that the continuum is useful and needed for two different aspects. On the one hand, being able to combine two interaction paradigms is a first accomplishment towards our goal: we clearly saw that participants were able to transition between tactile and tangible manipulations and to even use them alternatively. On the other hand, experts in fluid dynamics clearly stated that such a hybrid paradigm was more useful for exploration tasks but that the work they usually carry on should be continued on a traditional workstation with a mouse and keyboard. This further emphasizes the fact that an interaction continuum is needed. The hybrid paradigm was more useful for quick explorative findings that should then be further examined with a mouse and keyboard interaction.

Naturally, several question remain open. For example, even though experts reported a lack of accuracy—particularly in the tangible condition surprisingly few of them actually used our display-control gain factor widget to adjust the sensibility of the interaction. This aspect is further investigated in Chapter 6. One could also wonder if our prototype would also yield interesting results in a virtual reality or augmented reality environment. Finally, we only focused on a subset of 3D visualization tasks based on the needs of fluid dynamic experts. The results obtained with this subset are however promising and pave the way for the study of other 3D visualization tasks within the same expertise area or other scientific fields. We propose to study a more generic 3D visualization task in the next chapter.

# 5

# APPLYING HYBRID INTERACTION TO 3D SUBSET SELECTION



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

Figure 33: Tangible Brush technique: (a) creation of selection shape with tactile input; (c) extrusion of the shape with tangible manipulations; and (b) selection result visualization.

This chapter aims at continuing the exploration of the possibilities offered by the hybrid tactile/tangible paradigm. While we focused in Chapter 4 on a subset of needs from the specific expert community of fluid dynamic, in this chapter we try to exploit the hybrid paradigm further. We thus do not place the focus on a specific community but rather on a generic 3D visualization task highlighted in Section 4.3.2: 3D spatial selection.

3D spatial selections of data are primary and fundamental tasks in almost all visualization systems: they are performed prior to other interactions in exploratory data analysis. While 2D selection is efficient for datasets with explicit shapes and structures, it is less efficient for data without such properties. This chapter addresses this specific issue with a technique called Tangible Brush, a 6-DOF tangible interface combined with tactile input. We use tactile input to create a 2D lasso which is then extended into a 3D selection volume with the tangible movements of the spatially-aware device. We present, in this chapter, the description of the technique as well as its quantitative and qualitative comparison to a state-of-the-art structure-dependent selection technique.

Main portions of this chapter are based on currently unpublished work conducted by myself, Mickael Sereno, Mehdi Ammi, Lingyun Yu, and Tobias Isenberg. Some portions are also based on published extended abstracts by the same authors (Sereno et al., 2016; Sereno et al., 2017). Any use of "we" in this chapter consequently refers to the aforementioned authors.

## 5.1 INTRODUCTION

Many visualization systems rely on exploratory data visualization and analysis (Tukey, 1977) that allows domain experts to explore previously unknown datasets and analyze their characteristics. An essential aspect of such exploratory analysis is the selection of specific regions of interest (Wills, 1996) for further examination to then reveal their interesting patterns, properties, or internal structures. 2D selections are usually achieved with techniques such as picking, brushing, or lasso-based selection and can be easily carried out with a mouse/pen or on a tactile screen (both modalities provide the needed two degrees of freedom, DOF).

Three-dimensional datasets, however, often require the specification of 3D volumes for selecting the intended data subset; a task that is not easily supported by the mouse or tactile input paradigms for general volumes. Existing techniques have thus focused on creating constrained selections with these input paradigms (i. e., raycasting (Argelaguet and Andujar, 2009; Olwal and Feiner, 2003; Forsberg et al., 1996; Grossman and Balakrishnan, 2006; Looser et al., 2007), automated 3D projection of 2D lassos (Igarashi et al., 1999; Yu et al., 2012; Yu et al., 2016), and data-dependent picking (Wiebel et al., 2012)). These techniques either rely on contextual data analysis or pre-defined selection volumes and do not offer users the possibility to freely create their selection volume. While these technique have proven to be useful in many different context, they can be limited when the need arises to select regions that do not exhibit any particular and defining structural or contextual features.

The recent development of mobile, spatially-aware devices, however, allows us to consider tangible manipulations as a possible way to go beyond the limit of 2 DOF input. Hence, by combining 2D tactile input with 3D mobile manipulation, we facilitate the creation free-form and context-independent selection (Figure 33). We make use of Project Tango tablet[1] that provides self-3D-tracking features and a tactile screen. Our technique thus relies on a hybrid interaction paradigm similar to the one described in the previous chapter (Chapter 4): tactile input is used to specify a 2D drawn shape and 3D tablet manipulation facilitate the extension of this 2D shape into 3D by “brushing” the 3D space with the 2D shape. This approach complements existing automatic, interactive, and context-aware 3D selection techniques with explicit adjustments of the selection volume in a tangibly spatial manner.

Our corresponding contributions are threefold. First, we classify 3D selection techniques based on input and final shape control, and derive the need and design space for context-free 3D selection techniques. Second, we propose a hybrid tactile/tangible interaction for 3D spatial selection using a spatially-aware device and a synchronized large display that allows users to have a full control of the 3D selection volume they create. Third, we compare our technique to a-state-of-the-art and structure-dependent technique. We report both quantitative and qualitative findings of this comparison and discuss them in context.

## 5.2 RELATED WORK

Within the field of 3D interaction (Bowman et al., 2005; Hand, 1997; Jankowski and Hachet, 2013), our work relates to 3D selection techniques and to mixed/hybrid input paradigms used in 3D exploratory data analysis. We review relevant work in this section, focusing mainly on interactive 3D visualization.

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[1] https://www.google.com/atap/project-tango/

### 5.2.1 *3D Object Selection in VR environments*

Many approaches for 3D object selection in virtual environments rely on 3D ray-casting (or virtual pointers; see survey by Argelaguet and Andujar (2013)). Raycasting techniques are often implemented as a ray originating from the user's hand, with the ray direction being derived from the hand's orientation. Naturally, the first object that is intersected by the ray is selected. This kind of selection suffers, however, from three major limitations. First, there can be a mismatch between the visibility of the object from the user's vantage point compared to along the selection ray, such that a different object than the one expected is selected. This issue is called *eye-hand visibility mismatch* by Argelaguet et al. (2008) who developed *raycasting from the eye* to address this problem, while other techniques such as the selection based only on eye movements (Cournia et al., 2003; Tanriverdi and Jacob, 2000) circumvent it entirely. Second, the desired objects can be (partially) obscured by third-party objects, thus making the selection difficult with pure first-hit raycasting. Techniques such as the *flexible pointer* (Olwal and Feiner, 2003), *3D bubble cursor* (Vanacken et al., 2007), or the *depth ray* (Grossman and Balakrishnan, 2006; Vanacken et al., 2007), however, are able to address this second limitation. The third limitation is that raycasting techniques are often too imprecise for the selection of objects that tend to be small and situated far away from the user. Some approaches have thus focused on solving this precision issue such as, e. g., De Haan et al. (2005)'s *IntenSelect* that uses a scoring system to assist difficult selections and König et al. (2009)'s *adaptive pointing* technique that improves the precision of absolute pointing devices.

To avoid the precision issue, other initial work on 3D spatial selection relied on simple volumetric selection shapes that are easy to manipulate such as cones (Liang and Green, 1994; Steed and Parker, 2004). In this case, objects get selected if they are, at least partially, contained within the manipulated selection volume. Based on this basic metaphor, more advanced cone-based techniques have been developed such the *shadow cone* technique (Steed and Parker, 2004), *aperture* (Forsberg et al., 1996), and *enhanced cone selection* (Steed, 2006). One of the limitations of cone-based selection is, however, that several items can be contained within the cone itself, thus making the selection process difficult if a single item is to be selected. To circumvent this issue, Schmidt et al. (2006) investigated a probabilistic approach, while Olwal et al. (2003) proposed to rely on statistical geometry with different shape primitives to better capture the item intended by the user. Other approaches propose to rely on the manipulation of other primitives such as spheres (Vanacken et al., 2007; Wingrave et al., 2006) or boxes (Zhai et al., 1994). As an alternative, Mine et al. (1997) used hand-held widgets that are 3D objects that appear in the user's virtual hand, while Poupyrev et al. (1996) use the *Go-Go* technique that interactively grows the user's virtual hand to reach and manipulate distant objects.

All these approaches have been extensively used in VR environments and are useful for selecting a pre-defined shape or object in the environment. Most of them can easily be adapted for AR environments (Looser et al., 2007) with varying performances (Kaiser et al., 2003; Olwal et al., 2003). However, some selection tasks require specific yet arbitrary 3D selection volumes as described next.

### 5.2.2 *3D Selection for Exploratory Data Analysis*

Exploratory data analysis (Tukey, 1977) is one such case where users may want to focus on specific *regions of interest* (ROI) that are not necessarily predefined or separate shapes or structures. The data is often unsegmented and thus requires the user to first perform the segmentation of the volume which is often complicated and time-consuming. For such datasets, researchers proposed to manipulate specific 3D shapes (Akers et al., 2004; Sherbondy et al., 2005) (such as a box) in the 3D space to specify the ROI but that can also include undesired objects since target region is usually not cuboidal (Lucas et al., 2005; Yu et al., 2012).

For this kind of dataset, some approaches rely on specific hardware or setups. For instance, Harders et al. (2002) used a 3D mouse with force feedback to facilitate the segmentation of linear structures in the human body. Similarly, Malmberg et al. (2006) used a haptic device and stereoscopic rendering to allow users to draw 3D curves based on the 2D live-wire method. This approach was later improved with *Spotlight* (Top et al., 2010) which added visual guidance to improve the quality of the segmentation. A similar setup and approach was also taken by Nyström et al. (2009). Finally, Jackson et al. (2013) used a similar approach to select linear features—a rolled paper as tangible input to facilitate selection of thin fiber structures. Our technique also allows users to provide 3D tangible input but we combine it with an initial tactile input. Other approaches such as Wiebel et al. (2012)'s are based on the data itself, the transfer function, and the way the volumetric rendering is perceived by the user to facilitate the picking of a given region. However, such 3D picking techniques thus heavily rely on the ability to make sense of the data computationally which hence limits the application of these techniques to some specific goals. For the selection of specific primitives beyond points, specific techniques exist. For example for the selection of linear structures in neuroimaging, selections can be performed by manipulating boxes or ellipsoid-shaped regions (Akers et al., 2004; Sherbondy et al., 2005). Akers (2006) proposed to combine a trackball and a pen to help neuroscientists mark 3D pathways in neural datasets.

For unsegmented data, image segmentation can be used to infer the intended 3D subsets within the data (Chen et al., 2006; Owada et al., 2005; Yuan et al., 2005). Owada et al. (2005) designed *Volume Catcher* which avoids the initial phase of manually segmenting the volume. Users trace the contour of the target region with a 2D free-form stroke, and a segmentation algorithm run by the system returns a corresponding ROI. In other words, 2D user input is algorithmically extrapolated into 3D. This approach was later improved by Yuan et al. (2005) to alleviate the user's commitment when sketching. Chen et al. (2006) also base their approach on this concept, allowing users to draw closed strokes to include free-from drawing. Context-aware and, more specifically, structure-aware techniques rely on a similar concept. These techniques have been shown to be efficient for 2D datasets

(Dehmeshki and Stuerzlinger, 2008; Dehmeshki and Stuerzlinger, 2009) using the perceptual grouping of objects. The third dimension of most spatial datasets, however, increases the complexity of the problem, essentially because most input paradigms have limited degrees of freedom (Yu et al., 2016). Dehmeshki and Stuerzlinger (2008) and Dehmeshki and Stuerzlinger (2009)'s approach was then extended by Yu et al. (2012) with *CloudLasso* and *TeddySelection* which allowed users to create a 3D selection based on 2D lasso input. This 2D shape was then extended into 3D based on the density of particles within that lasso. CloudLasso was then extended by Shan et al. (2014) by analyzing the different clusters created by CloudLasso and only selection the on with the largest 2D projection. Later, Yu et al. (2016) proposed three new interactive context-aware selection techniques so similarly select a single connected component, two of which were based on the shape of the drawn lasso. We also use a drawn lasso with our approach but, instead of algorithmically transforming the 2D shape into a selection volume, we allow the user to specify the 3D selection volume directly by means of tangible input.

### 5.2.3 *Combination of Tactile and Tangible Interaction*

The benefits and limitations of both tactile and tangible input paradigms, highlighted in previous studies (Besançon et al., 2017; Konieczny et al., 2005; Zuckerman and Gal-Oz, 2013) (see Chapter 3 for a complete of these studies and their conclusions), suggest that these modalities are complementary paradigms that can be combined. We thus built on these conclusions and based our approach on each paradigm's benefits.

Previous systems that combine tactile and tangible input paradigms are largely found in tangible additions to tabletop displays (Al-Megren and Ruddle, 2016; Jordà et al., 2007). In particular for 3D visualization, Sultanum et al. (2011) created a table-based system for exploring geologic reservoir data. In their setup, the props are used to facilitate detailed data read-out and to parameterize a focus+context view, while tactile input is used for regular data navigation and dedicated specific exploration techniques such splitting and layer peeling. More linked to our spatially-aware-device approach, Olwal and Feiner (2009) used a spatially-aware small display on a large tabletop surface. The spatially-aware device was tracked in 2D and could show a section of the data displayed on the tabletop at a higher resolution. Tactile input can be used on both the tabletop and the spatially-aware device. With our technique, we built on this idea to use a spatially-aware display which also provides tactile input. However, these tabletop-based systems do not take full advantage of the physicality their tangible props since they remain on the tabletop. Only their 2D positions and orientation are used, thus losing the rich 3D manipulations offered by physical devices.

In contrast, we investigate the use of tactile interaction and full 6 DOF tangible input. In this context, López et al. (2016)'s analysis is important who took Olwal and Feiner (2009)'s concept into 3D space and investigated the use of tactile input on a mobile device for 3D visualization. They combined the mobile device's monoscopic view and a stereoscopic view of the data and included a tangible interaction mode in which the tablet's orientation was used to control the data view. While constrained to tangible 3D rotations only, this approach fully takes advantage of the physicality of the tablet as a tangible interface. Besançon et al. (2017) extended this approach and proposed and evaluated a system that combines tactile and tangible interaction with a spatially-aware tablet for 3D visualization. They implemented interaction techniques that take advantages of both input modalities to improve fluid dynamic researchers' workflow. We base our technique on their approach to also take advantage of both interaction modalities for 3D selection. We use the tactile input for the creation of a 2D lasso, while tangible manipulation extends this 2D shape into 3D.

## 5.3 CLASSIFICATION OF 3D SELECTION TECHNIQUES

A number of previous surveys have covered different taxonomies to classify 3D selection techniques. All of them, however, narrowly focus on either the selection of dedicated 3D objects or the selection of 3D volumes (or regions of interest). While the techniques used for each of these two purposes might be different, the abstract task is still 3D selection. Also, the degree to which the final selection can be precisely influenced or controlled by the user is rarely discussed in existing taxonomies. In our work, in contrast, we are interested precisely in this aspect of control that the user has over how the final selection is made. Consequently, we expand existing taxonomies to include both 3D object and 3D volume selection as well as the level of control over the final selection given to the user. We thus first provide a brief overview of the past taxonomies in Section 5.3.1, before we describe our extended set of classification criteria in the remainder of this section that then allows us to compare our work with that of the state of the art.

### 5.3.1 *Past Taxonomies of 3D Selection Techniques*

As one of the first to survey 3D selection techniques, Poupyrev and Ichikawa (1999) proposed a two-level classification that focused on 3D object selection. They mainly distinguished techniques based on whether the manipulation was *exocentric* or *egocentric*. For each of these two classes, they classified techniques based on the *metaphor* that each technique used. This latter classification is useful because different metaphors are needed in different environments or for different selection targets (raycasting is efficient for object selection but not suited for, e. g., unsegmented data). Also, it was shown (Issartel et al., 2016c) that exocentric and egocentric manipulations can result in a different performance depending on the visualized scene (for tangible manipulation with a spatially-aware display). Moreover, this classification between egocentric and exocentric techniques can also be used to evaluate whether a technique works for AR environments (Looser et al., 2007). This taxonomy is important: it distinguishes techniques based on the metaphor they employ first and also on user's input which we believe to be essential.

Later, Bowman et al. (2001) considered *feedback*, *confirmation mechanism*, and *object indication* as criteria to classify the 3D selection techniques they analyzed. While these criteria are certainly important, Bowman et al.'s taxonomy fails at showing the inherent mechanism of the selection. Moreover, it introduces some redundancy because the choice of feedback is coupled to the object indication. More recently, Argelaguet and Andujar (2013) provided a comprehensive survey and thorough classification of 3D selection techniques for virtual environments, basing their classification on the *selection tool*, the *degrees of freedom, DOF* of the selection tool manipulation, the employed *disambiguation mechanism*, the *control-display ratio*, and the *relationship between motor and visual space*. Their classification centered around the technique and its characteristics and focused on 3D selection techniques for virtual environments that allow users to select dedicated objects. In our classification, however, we also include selection techniques that facilitate the specification of 3D selection volumes/regions of interest that thus are also applicable to volumetric data or particle datasets. Such forms of selection are important, in particular, in exploratory data analysis selection techniques such as those we mentioned in Section 5.2.

Surveys that focus on selecting regions of interest—to the best of our knowledge—usually cover the topic of image/volume segmentation. For instance, as early as 1981, Fu and Mui (1981) proposed to distinguish between characteristic feature thresholding, edge detection, and region extraction. Later, Haralick and Shapiro (1985) proposed to differentiate between measurement space, space-guided spatial clustering, single-linkage region growing schemes, hybrid-linkage region growing schemes, etc. More recently, Khan (2013) provided a taxonomy that distinguished between edge-based, PDE-based, threshold-based, region-based, etc. approaches. However, many segmentation techniques are automatic and do not rely on user input and, hence, differ from the 3D spatial selection scenario on which we concentrate.

### 5.3.2 *An Extended Taxonomy Focusing on User Control*

In our classification that we describe next we try to focus more on the amount of control the user has to define the final selection. While Argelaguet and Andujar (2013) started to put emphasis on input strategies with their taxonomy and, in particular, included the DOF of the selection tool (see Table 5), we go beyond this approach as we include criteria that define whether the user or an algorithm is in control of the different steps involved in the selection mechanism. By doing so, we provide a way to easily distinguish between a technique that gives little to no control to the user and another which is essentially built on the user input. Hence, it would be easier to determine whether a technique can easily adapt to new kinds of datasets or regions/objects of interest or not. We thus extend Argelaguet and Andujar (2013)'s classification by subdividing their *selection control DOF* criterion and adding others as shown in Table 5. We also removed two further criteria because they had no relation with the user's input and control of the technique but rather deal with possible mismatch between visual and motor space (motor/visual space relationship) or how multiple selections were disambiguated. Next we describe the criteria that we use in our classification.

Table 5: Adjusted taxonomy based on Argelaguet and Andujar (2013)'s classification of 3D selection techniques.

| criterion | description | ∈ (Argelaguet and Andujar, 2013) | ∈ (Poupyrev and Ichikawa, 1999) |
|---|---|---|---|
| selection metaphor/tool | ray, cone, cube, brush, 2D lasso, . . . | ✓ | ✓ |
| ~~selection control DOF~~ | refined in *selection tool control* below | ✓ | ✗ |
| ~~disambiguation mechanism~~ | does not concern control or user input | ✓ | ✗ |
| ~~motor/visual space relation~~ | does not concern control or user input | ✓ | ✗ |
| target selection type | dedicated objects vs. spatial selection regions/regions of interest | ✗ | ✗ |
| selection shape creation | parameter-based, semi-automatic, or fully user-controlled | ✗ | ✗ |
| selection shape adjustments | not possible, automatic, manual | ✗ | ✗ |
| selection tool control | input DOF, control DOF, and CD ratio | • | ✗ |

#### 5.3.2.1 *Selection Metaphor*

Poupyrev and Ichikawa (1999) were the first to use this criterion in their taxonomy. It was latter re-used by Argelaguet and Andujar (2013) (*selection tool*). It is defined as the tool used to define the desired selection. For instance, a ray-casting metaphor computes the intersection with scene objects to highlight (possibly combined with different feedback) the currently selected object (Argelaguet and Andujar, 2013). Similarly, the intersection of the box with a volumetric dataset can be computed to obtain a selection of the data (e. g., (Benko and Feiner, 2007; Cabral et al., 2014)). The used metaphor is an important criterion: it affects the control (e. g., w.r.t. DOF) of users over the interaction. It also limits, in most cases, the shape the final selection.

#### 5.3.2.2 *Target Selection Type*

Previous taxonomies only investigated either dedicated object selection or ROI-based selection (Section 5.3.1). We want to cover both types with our taxonomy, thus add this criterion as a primary classification criterion. Specifically, we distinguish between single-object selection, multiple-object selection, and ROI-based selection.

#### 5.3.2.3 *Selection Shape Creation*

ROI-based selections need some form of specification of the selection region. Simple approaches specify this region based on the adjustment of predefined geometric shapes (e. g., (Benko and Feiner, 2007; Akers et al., 2004; Sherbondy et al., 2005; Zhai et al., 1994)). These techniques quickly provide selections, but with limited control over the result. Hybrid approaches rely flexible user input (e. g., 2D drawings with respect to a projection of the 3D data) and the data/view context (e. g., lasso-based (Chen et al., 2006; Owada et al., 2005; Yu et al., 2012; Yu et al., 2016; Yuan et al., 2005)). These techniques provide more control over the result but also require more input to specify the selection. Finally, the highest level of control would be facilitated by approaches that rely purely on (3D) user input, without any system assistance that would control parts of the selection process. To the best of our knowledge, no existing technique relies solely on user input so far to define the selection volume—the tangible selection technique we introduce in this paper falls into this category. Even the *3D Lasso* technique employed by Zhou et al. (2008) does not really create a 3D selection volume but rather computes which tracts of interests are within the 3D-drawn lasso. Similarly, the 3D live-wire technique (Malmberg et al., 2006) does not allow the user to draw the full selection volume but rather creates the volume that connects the two 2D shapes created by the user.

#### 5.3.2.4 *Selection Shape Adjustments*

Once the selection has been specified, users may still want to adjust it. As part of the core selection approach, there is either no post-creation control at all, or automatic system-based control, or user-based control. For example, for ray-casting or cone-casting techniques there is generally no control over the ray itself once the selection has been made. Some techniques such as the *flexible pointer* (Olwal and Feiner, 2003), however, employ user-controlled ray-bending to assist with the disambiguation of targets.Similarly, *Aperture* (Forsberg et al., 1996) uses a cone-casting selection whose size can be manually adjusted (by adjusting the apex angle).

We can also make this distinctions for other techniques. For instance, the *Silk Cursor* (Zhai et al., 1994) uses a pre-defined shape whose size cannot be adjusted. The *Bubble cursor* (Vanacken et al., 2007) relies on a sphere selection tool that can dynamically be extended to reach objects close to its center. This extension, however, is made automatically and does not involve user input. *Aperture* (Forsberg et al., 1996), in contrast, allows users to dynamically control the size of the selection cone. Similarly, context-aware techniques (Yu et al., 2012; Yu et al., 2016) allow users to adjust an initially system-derived selection threshold—for instance to control the particle density of the selection region.

#### 5.3.2.5 *Selection Tool Control*

In their taxonomy, Argelaguet and Andujar (2013) consider *tool control* as the way the "user is able to control" the defined selection shape. They distinguish two aspects: the selection tool DOF and the control-display ratio. We add an additional factor: the input device DOF (that Argelaguet and Andujar briefly mention, after their classification, as a factor affecting performance) that is essential to understand correspondances between the physical input and the virtual selection operators.

**Selection tool DOF:** To alleviate the lack of control given to the user on the volume selection creation, most techniques provide the users with mechanisms to adjust the selection volume's origin and orientation. Techniques lacking such controls which do not allow the users to create their own selection volume would have a negative impact on the variety of possible selections. Similarly, techniques that provide control over the origin of the selection tool only (Zhai et al., 1994) are necessarily more limiting than techniques also providing orientation control (Argelaguet et al., 2008; Forsberg et al., 1996).

**Input Device DOF:** While the number of available DOF for the control of selection tool is important, it is similarly important to consider the DOF provided by the used input device. Having a mismatch between these two variables could lead to a bad performance. On the one hand, having more input DOF than necessary could be confusing for users as they do not see the changes provided by the additional unused DOF (Wingrave et al., 2005). On the other hand, having less DOF than necessary is also a problem as users can report being confused by integrated manipulations (Besançon et al., 2017) or the interaction requires excessive mode switching.

**Control-display (CD) ratio:** The CD ratio determines the conversion of translations and rotations of the input devices into manipulations in the virtual world. It is usually isomorphic (i. e., a one-to-one mapping) but can also take other static values. Because 3D selection is based on 3D input, a down-scaling CD ratio could lead to many user manipulations and, hence, to user fatigue. Similarly, having an up-scaling CD ratio could lead to imprecise selections of small targets (Kopper et al., 2011). Dynamic CD ratios can address both problems. While Argelaguet and Andujar (2013) based their classification on (König et al., 2009)'s distinction between CD manual switching, target oriented CD, and velocity-oriented CD, we argue here that a velocity-oriented technique still provides a manual control of the CD ratio to the user. We thus gather manual switching and velocity-oriented techniques under the manual control of the CD ratio. A further distinction can be made by distinguishing between explicit manual control (setting a value with a slider or mouse buttons or using specific gestures to switch (Vogel and Balakrishnan, 2005)) and implicit manual control (e. g., velocity-based (König et al., 2009) or pressure-based (Besançon et al., 2017)).

## 5.4 TANGIBLE SELECTION BRUSH

Our technique is inspired by Lucas (2005) and Lucas et al. (2005)'s *Tablet Freehand Lasso* which allows users to draw a lasso on a 2D projection of the data, and then to extend this lasso shape as a generalized cone into the 3D data space. Our algorithm, however, relies on both tactile and tangible inputs, it thus creates a hybrid tactile/tangible paradigm that has already been useful for 3D data exploration (Besançon et al., 2017). Specifically, we ask users to draw a 2D brush on the tangible device that they can then extended into 3D by physically moving the device. In contrast to existing techniques for 3D selection, we thus give users full interactive control of the final selection volume, without algorithmic extrapolation. Next, we describe the our approach and our setup in detail.

### 5.4.1 *Overall Interaction Design*

Similar to the mentioned previous approaches, we start by asking users to draw a closed shape on the mobile device with respect to the displayed 2D projection of the data. We handle non-closed strokes in two different ways. We first compute the Euclidean distance between the start and the end point. If this distance is smaller than 0.2 (units on the device screen whose length is 2) then we connect the start and end points with a straight line. Otherwise, since we advocate for free-form drawing, we remove the drawn path so that users can start anew.

In contrast to sketch-based modeling techniques (e. g., (Igarashi et al., 1999)) or context-aware selection (Yu et al., 2012; Yu et al., 2016), we then facilitate the 3D extension of the 2D shape in an entirely user-controlled fashion. In this second step, we link the drawn 2D brush to the physical location of the tablet. Users can thus move the brush through the volumetric dataset by physically manipulating the tablet in 3D space. During the user-controlled selection phase, the algorithm thus records all the positions and orientations of the brush at each sample point. Then, we compute a 3D selection volume from the recorded brush positions and apply it to the data.

We generally allow users to use the full 6 DOF of their tangible manipulations (3 DOF for translation, 3 DOF for rotation) of the tablet to extend the 2D shape. Such a fully-integrated manipulation, however, may be difficult to achieve for some users and it is possible that other users may want to consider manipulations only along a single axis. We thus also offer a way for users to constrain their (virtual) movements when moving the brush to along the tablet's normal.

### 5.4.2 *Selection Computation*

To facilitate an efficient computation, we apply a regular grid to the 2D space of the tablet's surface with an adjustable resolution (200 × 200 in our implementation). We then use the drawn lasso shape to mark cells as inside or outside the selection brush using Boolean values. For each sampled position/orientation of the tablet during the selection interaction, we then derive the position of the Boolean grid within the data space and connect two consecutive grid arrangements. We then use the resulting 3D grid slice to carry out the actual selection operation: either we select/deselect 3D particles directly or we manipulate a 3D regular selection datastructure (i. e., a discretized 3D selection volume).

While most 3D selection techniques rely on simple selection shapes that can lead to imprecise 3D selections, some existing techniques make use of progressive refinement strategies to improve the precision of the final 3D

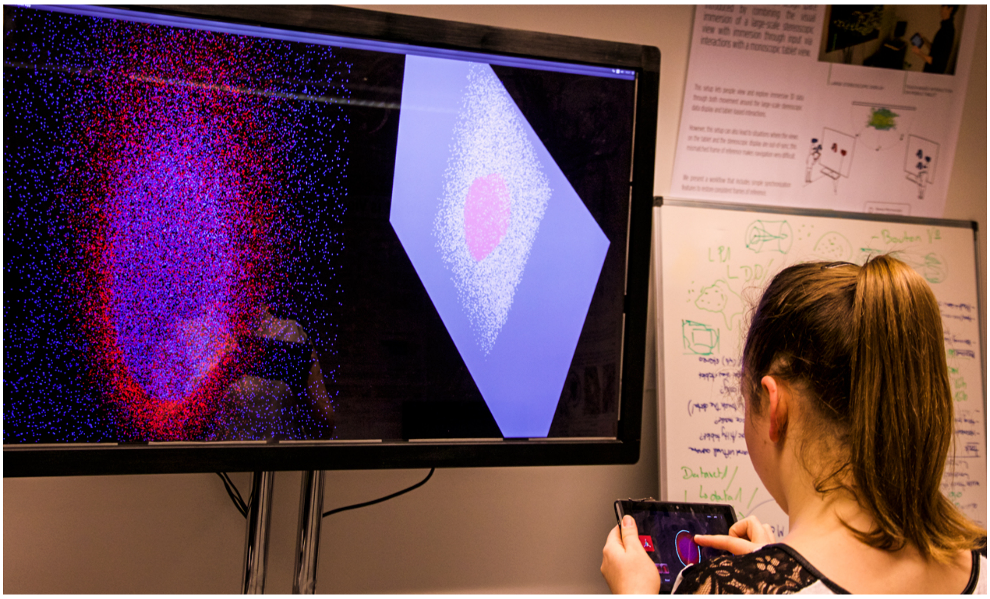

Figure 34: The tablet being used together with the synchronized split-screen view that is shown on a separate, large display.

volume (e. g., (Bacim et al., 2013; Elmqvist et al., 2008; Kopper et al., 2011; Yu et al., 2012; Yu et al., 2016)). We use a similar approach based on Boolean operations, either adding to (Boolean OR), intersecting with (Boolean AND), or subtracting from the previous selection. We can then use the resulting selection volume to process both volumetric data and large particle clouds. Moreover, we carry out the processing dynamically (updating the selection with each new sample) to allow users to receive immediate feedback from their interactions.

### 5.4.3 *Setup and User Interface*

Our setup uses two displays (Figure 34): (a) a spatially-aware mobile device with tactile input and (b) a stationary large display. Users of the system perform all interactions on the mobile device, including the drawing of the 2D selection brushes and the tangible movement of the selection brush through the 3D data space. The stationary device, in contrast, shows a high-resolution view of the dataset as a frame of reference for the interaction. Both devices display 2D projections of the 3D data—the larger stationary display from a static vantage point and the mobile device based on its 3D location and orientation. The more expensive computations beyond input processing and rendering (e. g., the 3D selection volume creation and its application to the dataset), finally, are carried out on the PC that also drives the stationary display.

The tablet interface (Figure 35) allows users to control the selection interaction in detail. Menus on the top allow users to load datasets and change general view settings. The toggle button on the right controls whether selection extrusion uses all 6 DOF of the tangible interaction or whether it is constraint to the tablet's normal. The slider on the right reflects the current CD factor which obtain from pressure sensors on the back of the device,

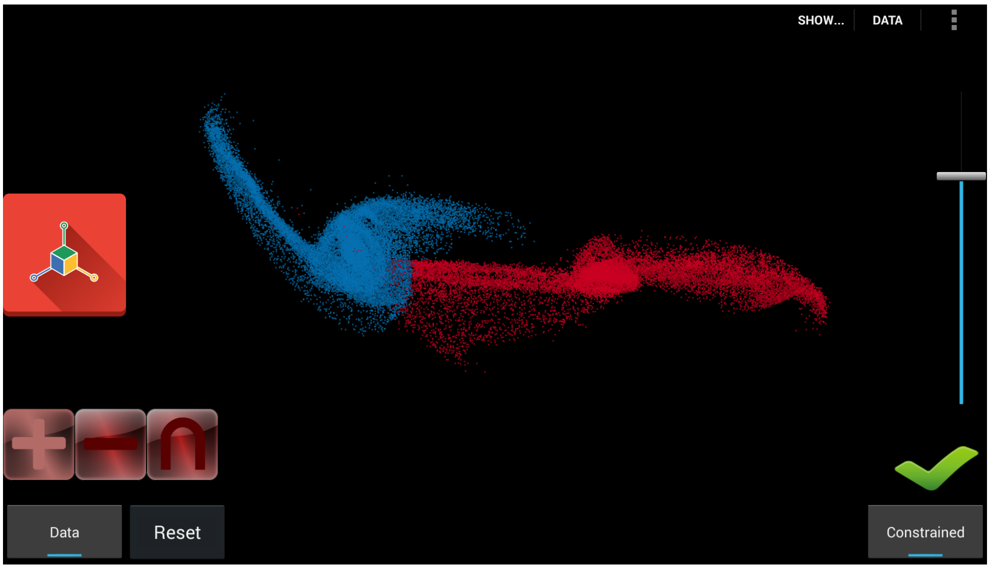

Figure 35: The tablet's interface which controls the selection operations.

similar to Besançon et al. (2017)'s recent design. In addition to isomorphic mappings, users can thus also be either more precise in their interactions or can cover larger space ranges using a single motion, with the slider always providing the visual feedback recommended for pressure-based input (Cechanowicz et al., 2007; Herot and Weinzapfel, 1978; Wilson et al., 2010). Users can switch between view manipulation and selection mode using the toggle button on the bottom left. The remaining toggle buttons on the left control the used Boolean operation (addition by default). In addition to these system-controlled states, the user-controlled red button located on the left starts or stops the tangible manipulations of either the view or the selection extrusion during the interaction. The tangible manipulation with the tablet is interpreted in such a way that, during normal handling of the tablet, the data retains its location with respect to the tablet and thus appears to be attached to it. Only during active manipulation (red button pressed), the tablet is relocated with respect to the dataset.

The projection of the data in the center of the tablet provides both visual feedback and the canvas for the drawing of the 2D selection brush. We specifically use an orthographic projection of the data to allow users to relate the drawn 2D shape to the visible features of the data. While this projection lacks perspective depth clues, data features do not shrink or grow with respect to the drawn brush due to perspective forshortening during the selection extrusion when the tangible is moved through the dataset. This physical motion is also reflected in the data view (while either the data manipulation or the selection is actively engaged by the user) because the tablet is interpreted as a cutting plane, thus adding perceptual depth cues through the interaction.

Moreover, the separate stationary display shows two synchronised views of the data (see Figure 34), both using perspective projection. In this split-screen arrangement, the left view represents the data as it is shown on the tablet—the display thus acts as a physical representation of the tablet position with respect to the projected data. On the right, we show a view rotated by 45° around the vertical $y$-axis from this view on the left. This right view also shows a representation of the tablet (which thus remains at the same screen-space location all the time) and the 2D selection brush within the data space. This tablet-specific plane is also interpreted as a cutting plane such that the data between tablet and viewer is removed. This combined arrangement thus gives the viewers a good impression of the location of the data with respect to the tablet, allowing them to control their selection actions in detail.

### 5.4.4 *Implementation and Performance*

We realized our system in a modular way: the tablet runs a native Android app and the PC a separate Linux-based software. Both tools use VTK as their basis (VTK 6.0 on tablet and VTK 6.3 on PC), rendering the visualizations using OpenGL (OpenGL ES 2.0 for the tablet and OpenGL 3.0 on the PC). For that purpose we use shaders based on GLSL 1.0 on the tablet and GLSL 1.3 on Linux. The tablet communicates with the PC over UDP (via Wifi). It sends status updates that allow the PC application to adjust its view and compute the selection. The communication lag was largely negligible in all our experiments.

We compute the actual selection on the PC. Depending on the type of data we used, we employed different ways to show the selection. For particle datasets we highlight the particles in a different color (a lighter shade of their initial color). For other datasets (e. g., volumetric data or geometric shapes), we show a semi-transparent selection volume. While we did not implement it, we also envision to directly adjust the transfer function of volumetric datasets to highlight the selected voxels.

The resulting rendering performance for both the tablet and the desktop applications is in the order of 60 fps, independent from the size and characteristics of the datasets with which we have experimented. Only for large selections (brushes that take approx. 3/4 of the actual tablet size), the processing of the selection computation by the desktop application led to the view on the stationary display to somewhat lag behind during extrusion. We believe that a multi-threaded implementation of the desktop application would address this issue.

### 5.4.5 *Classification*

Let us now revisit the taxonomy we described in Section 5.3 with respect to our Tangible Brush selection. As a *selection metaphor/tool* we obviously use a combination of brush-based selection and 2D lasso. Our *target selection type* is based on ROIs because we extrude the 2D brush into 3D space. With only a few modification, however, we could also easily apply the Tangible Brush to dedicated object selection (i. e., the objects touched during the extrusion interaction). In contrast to existing techniques that always rely on some form of automated computation of the final selection volume for their *selection shape creation*, our Tangible Brush solely relies on user input to define the selection volume. Since users already have full control over the created final selection volume with Tangible Brush, the technique does not implement any possible post-interaction *selection shape adjustments* that are required for most techniques that rely on an automated process. We could, however, add such an adjustment later-on as suggested by the participants of our study (see Section 5.6). Nevertheless, we do not need to provide any technique to adjust the selection volume's origin and orientation that most technique provide because our technique is already flexible in its selection volume creation.

To provide *selection tool control*, our technique relies on two separate steps to create the final selection volume. The first step only requires 2 DOF to draw the lasso which are provided by regular single-finger tactile input. The second step, i. e., the extrusion, can either rely solely on movements along the tablet's normal (1 DOF) or on the full 6 DOF provided by the spatially-aware device; and users can freely switch between these two modes. Finally, we provide a CD ratio manual control based on 1 DOF pressure input. In other words, with our Tangible Brush we provide a fully manual and structure-independent selection tool that has not yet, to the best of our knowledge, been explored. We thus believe that our tool could easily be used in a variety of application scenarios and with virtually any kind of 3D dataset, without relying on internal structure arrangements to produce a good selection.

## 5.5 CONTROLLED STUDY

A valid question to ask, however, is how such a manually-controlled technique performs when compared against the existing structure-dependent selection techniques. We thus present a controlled experiment to compare with an existing and state-of-the-art structure-dependent selection technique to quantitatively and qualitatively assess and understand the differences.

### 5.5.1 *Structure-Dependent Selection Technique*

Among the related work covered in Section 5.2, a number of techniques drew our attention based on related interaction aspects. More specifically, all techniques that are based on a drawn 2D lasso were potential candidates for a comparison (i. e., (Chen et al., 2006; Malmberg et al., 2006; Owada et al., 2005; Shan et al., 2014; Yu et al., 2012; Yu et al., 2016)). Ultimately we chose the SpaceCast approach from the recently published CAST selection techniques (Yu et al., 2016). Our reasons for this choice was that it is a semi-automatic structure-dependent technique, that all CAST techniques select only single connected components, that SpaceCast specifically constrains the selection to the drawn lasso shape (similar to our technique), and that SpaceCast had already been compared to the other CAST selection techniques, to selection based on generalized cylinders/cones (Lucas, 2005; Lucas et al., 2005), and to the CloudLasso technique (Yu et al., 2012).

### 5.5.2 *Hypotheses*

Based on our general experience with spatial selection and our pilot studies, we formulated the following hypotheses:

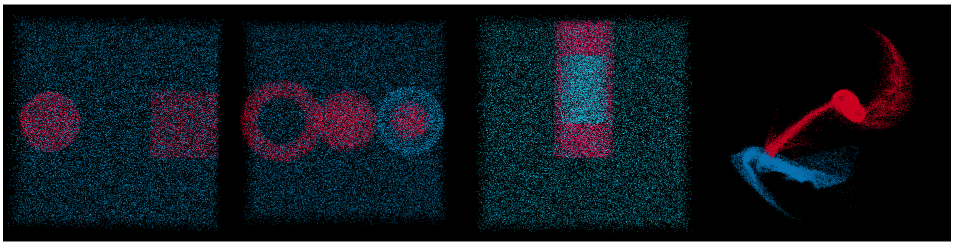

Figure 36: The 4 datasets used in our study. Particles of interest are in red and unwanted particles in blue

H1 Since SpaceCast was explicitly designed with density-based selection in particle datasets in mind, its accuracy will be better than that of Tangible Brush for datasets where the target can be identified based on density. However, if the target cannot be identified based on particle density, Tangible Brush will provide a better accuracy.

H2 Since SpaceCast is partially automated and only requires a 2D lasso as an input, it will be generally faster to use than our Tangible Brush that also needs the tangible motion of the tablet in space.

H3 Technique preference will depend on the dataset characteristics: for simple shapes that can easily be identified based on particle density participants will prefer SpaceCast, for other datasets where this identification of selection target based on particle density is not possible participants will prefer Tangible Brush.

### 5.5.3 *Apparatus*

Our setup included the 7 inch Google Tango tablet ("Yellowstone," 370 g, 7.8 cm diagonal, 1920 × 1200 pixel resolution, 323 ppi) and a 55 inch (139.7 cm diagonal, 3840 × 2160 pixel resolution, 79 ppi) static vertical screen mounted at approx. shoulder height. This display was equipped with a PQLabs overlay, capable of recognizing up to 32 simultaneous touch input points. We used the vertical screen as the primary input and output screen for the structure-dependent SpaceCast selection technique and as the secondary synchronized screen for Tangible Brush. For the Tangible Brush technique, input was captured by the tablet but elaborate computations were restricted to the vertical display (to save battery power and to increase the performance).

### 5.5.4 *Datasets*

We used the four particle datasets illustrated in Figure 36. We designed each dataset to have different features that would be either problematic for structure-dependent selection or for Tangible Brush. Particles to be selected are shown in red, noise or unwanted particles are blue.

D1 Simple shapes (Figure 36a): two simple shapes, a cylinder and a cube, both having a higher density than the noise around them.

D2 Shell and ring (Figure 36b): a ring, a sphere, and half-ball surrounded by a semi-spherical shell of interfering particles (both having the same density).

D3 Pipe (Figure 36c): a target cylinder at the bottom, immediately followed by a hollow target cylinder shell in the middle that surrounds an unwanted cylinder, again followed by an other solid target cylinder at the top; all had the same density.

D4 Simulation (Figure 36d): a simulation of two colliding galaxies with varying densities, the selection target was one of the galaxies.

We hypothesized that both D1 and D2 would be easy for SpaceCast. We did not expect D1 to be difficult for Tangible Brush, but D2 to be more difficult for it because the non-target shell is very close to the ball, thus requiring a high precision. D3 was designed to be difficult for SpaceCast because the selection target could not be identified by the particle density, requiring several Boolean operations. D4 was supposed to be a difficult dataset for both techniques.

### 5.5.5 *Participants*

We recruited 16 unpaid participants (5 female; ages 21–53, mean = 25.8, med = 24.5, SD = 7.4). 11 of them had at least a university degree (bachelor or equivalent), while the remaining five had at most an A-level equivalent. Nine of them were experienced with 3D manipulation through extensive use of video games. All of them had extensive experience with tactile interaction, in particular through the daily use of their smartphones. Three participants had previously been exposed to tangible interaction through their job, one of them on a daily basis. Other had no or very little exposition to it. Three participants were left-handed. All participant had normal or corrected-to-normal vision.

### 5.5.6 *Procedure*

We started the experiment by gathering the participants' demographics and explaining the purpose of the study/setup. Generally, the experiment consisted of having each participant perform selections using both techniques on the described datasets. We first introduced each technique and then provided a training phase on four simple 3D shapes to let participants get accustomed to the selection techniques. Then, we asked participants to achieve selection on the four other datasets. We repeated each task three times and, each time, from a different starting angle. Before each task, participants could freely explore the dataset to understand its structure and the targets. After participants had fully understood the selection tasks, we asked them to complete the selection as fast and accurately as possible. We did not stress any factor more than the other (thus mirroring Yu et al. (2016)'s study design). We also pointed out to them in advance that a perfect selection was generally impossible to avoid overly long interaction times.

Overall, we thus had a within-subjects study design with 2 selection techniques × 4 datasets × 3 repetitions = 24 trials per participant. We counter-

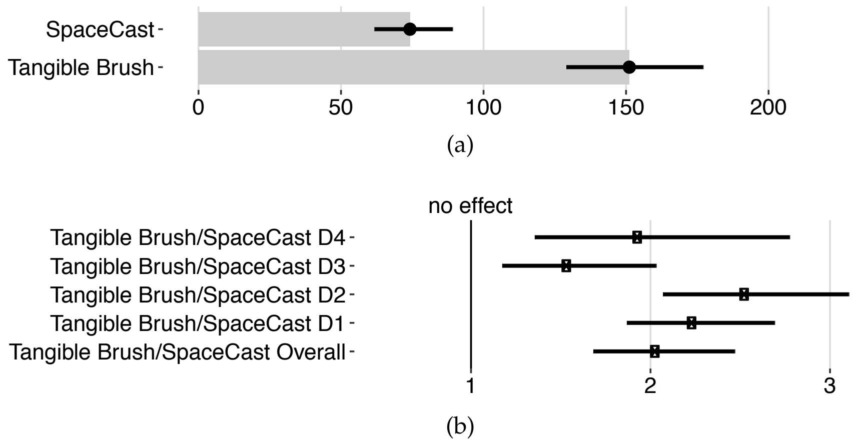

Figure 37: Task completion time in seconds (a) and direct comparisons by dataset and overall (b). Error bars are 95% confidence intervals (CIs).

balanced the sequence of the selection techniques to avoid order effects. We also counter-balanced the order of the datasets using a Williams design Latin square (Williams, 1949) to balance the number of times a condition precedes and follows another. After each selection technique, we asked participants to fill in a questionnaire to assess the workload (using NASA's Task Load Index)[2] and the fatigue. At the end of the experiment, we asked the participants, for each dataset, what technique they preferred using and why. We also told them to think aloud throughout the study so that the experimenter could take notes about their different observations and comments. The entire experiment took approx. 75 min on average per participant.

## 5.6 QUANTITATIVE RESULTS

We gathered a total of 384 trials (24 tirals per participant × 16 participants) for quantitative analysis. We analyze this data using estimation techniques (seeAppendix A).

### 5.6.1 *Completion Time*

We analyzed log-transformed time measurements to correct for positive skewness and present our results anti-logged, as it is standard in such cases (Sauro and Lewis, 2010). We show the completion times in Figure 37 where one can clearly see (Figure 37a) that the confidence intervals are not overlapping, thus providing strong evidence that SpaceCast is about twice as fast as Tangible Brush on average. There is also strong evidence of SpaceCast being faster for all datasets as displayed in Figure 37b, with the difference being strongest for the second dataset for which it is more than 2.5 times as fast. The effect is smaller, however, for D3.

### 5.6.2 *Accuracy*

Similar to Yu et al.'s work (Yu et al., 2012; Yu et al., 2016), we computed two accuracy scores, F1 and MCC. Both are based on three factors: the number

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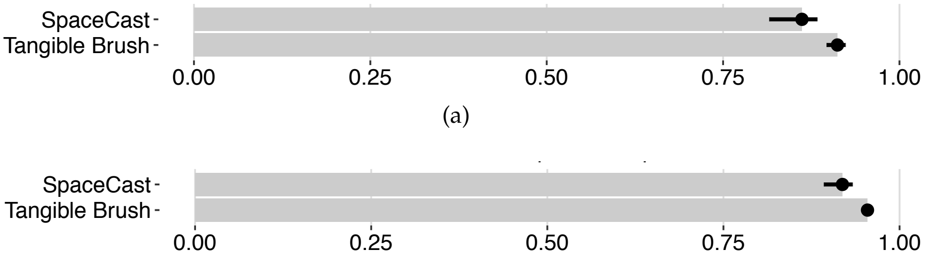
[2] https://humansystems.arc.nasa.gov/groups/tlx/downloads/TLXScale.pdf



(a)

(b)

Figure 38: MCC (a) and F1 (b) accuracy per technique. Error bars: 95% CIs.

of true positives (rightfully selected particles, TP), false positives (incorrectly selected particles, FP), and false negatives (number of particles that should have been selected but were not, FN). F1 is computed as $F1 = 2 \cdot (P \cdot R)/(P + R)$ with $P = TP/(TP + FP)$ being precision and $R = TP/(TP + FN)$ being recall. MCC is computed by also considering the number true negatives (particles correctly omitted, TN) as

$$MCC = \frac{TP \cdot TN - FP \cdot FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}}.$$

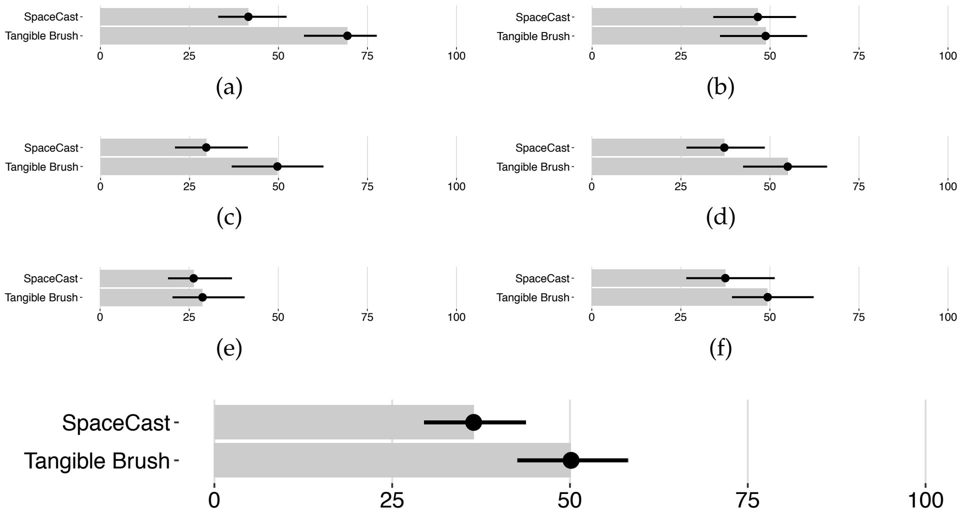
We present the results of these two scores in Figure 38. For F1, 1 indicates a perfect performance and 0 the worst possible performance, while MCC results range from $-1$ (worst performance) to 1 (perfect performance). We see that both selection technique obtained good MCC (0.95 for Tangible Brush and 0.92 for SpaceCast) and F1 (0.91 for Tangible Brush and 0.86 for SpaceCast) scores. Both scores (Figure 38a and (b), resp.) show strong evidence for Tangible Brush being more accurate. Both figures, however, also show that there is only a small effect for the accuracy difference between the two techniques.

### 5.6.3 *Workload*

We gathered workload measurement with a Raw-TLX (which has been demonstrated to be equally well suited as a regular TLX (Hart, 2006)) and which we present in Figure 39. Our data shows no evidence of a difference between SpaceCast and Tangible Brush for physical demand (Figure 39b), estimated performance (Figure 39e), or frustration (Figure 39f). There is clear evidence, however, for the mental demand being higher for Tangible Brush than it was for SpaceCast (Figure 39a) and weak evidence for effort also being higher for Tangible Brush (Figure 39d). As a consequence, we can see in Figure 39g evidence for the overall workload being higher for Tangible Brush than it is for SpaceCast.

### 5.6.4 *Fatigue*

We present the overall fatigue measurements and their sub-aspects in Figure 40. The finger fatigue shown in Figure 40a seems to be higher for SpaceCast but the overlapping confidence intervals suggest that there is no clear evidence that it is higher than Tangible Brush overall. The overlapping confi-



(a) (b) (c) (d) (e) (f) (g)

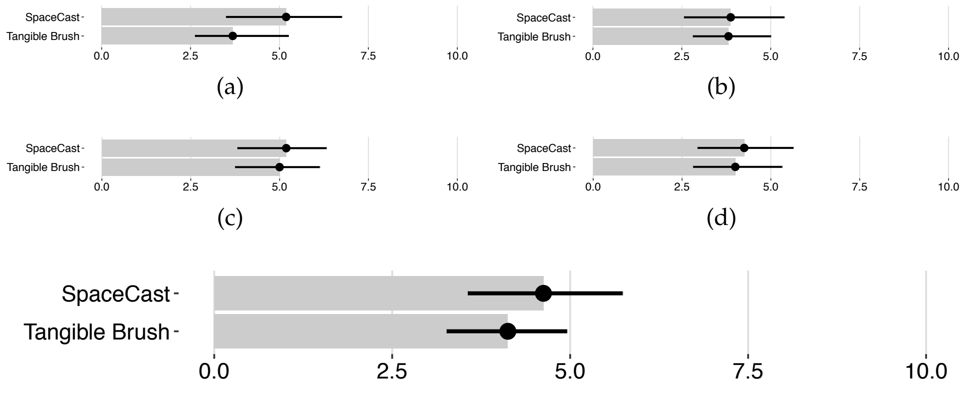
Figure 39: Workload measurement in NASA TLX units ($\in [0, 100]$) with respect to (a) mental demand, (b) physical demand, (c) temporal demand, (d) effort, (e) performance, (f) frustration, and (g) total; for all lower is better. Error bars: 95% CIs.

dence intervals for hand fatigue (Figure 40b), arm fatigue (Figure 40c), shoulder fatigue (Figure 40d), and the total fatigue (Figure 40e) suggest that it is not possible to find evidence of a difference between the two techniques based on our experiment.

### 5.6.5 *Preferences and Qualitative Results*

At the end of each study we asked participants to report on their preferred technique per dataset. We report these preferences in Figure 41. Our results show a slight preference for SpaceCast (7 ×) over Tangible Brush (5 ×)for the first dataset (D1). For the second dataset (D2) which we had designed to be easier for SpaceCast, SpaceCast was largely preferred by participants (10 ×) over Tangible Brush (3 ×). For the third dataset (D3) which we had designed to be easier for Tangible Brush, the preferences expectedly show a strong advantage for Tangible Brush (11 ×) over SpaceCast (2 ×). Finally, the preferences for the last dataset (D4, the galaxy simulation) exhibit a slight preference for Tangible Brush (8 ×) over SpaceCast (6 ×).

Participants also voiced a number of interesting comments during the study. Many of them (11 ×) stated that they wish they could draw the lasso on the tablet in a more precise way. Among these participants, five suggested to use a stylus, five suggested to allow zooming for drawing only, and one suggested both options. Six participants voiced the opinion that SpaceCast was “way easier for simple shapes” or shapes with a homogeneous density. However, five others reported that they did not understand why or how SpaceCast derived the final selection volume for shapes along a varying density (with D4 mainly). One even reported that he considered the technique to be plainly “a pain” for the fourth dataset. Finally, two participants sug-



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

Figure 40: Fatigue measurements on a scale from 0 to 10 for (a) fingers, (b) hands, (c) arms, (d) shoulders, and (e) total. Error bars: 95% CIs.

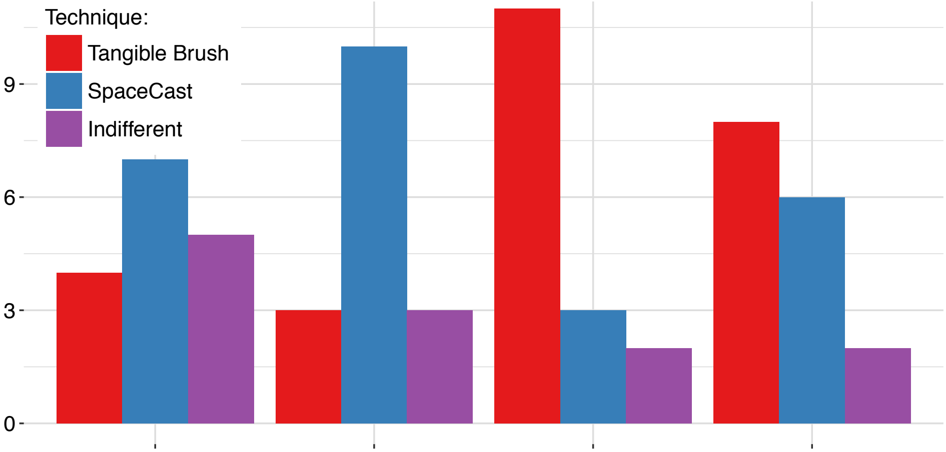


Figure 41: Technique preferences per dataset.

gested to combine SpaceCast and Tangible Brush as it would allow them "to use SpaceCast for simple shapes or continuous densities," and then to "adjust the selection for more complicated cases with Tangible Brush."

### 5.6.6 *Discussion*

## 5.7 DISCUSSION

Based on these results, we now discuss our most relevant and interesting findings. Our ultimate goal is to see whether a structure-independent selection technique can be efficient and to understand the benefits and limitations when comparing it to a structure-dependent technique.

### 5.7.1 *Completion Time*

Based on our results, we can clearly state that our hypothesis H2 is verified. SpaceCast is indeed faster than Tangible Brush for all datasets we tested. Of course, our participants were generally less familiar with tangible interaction than they are with tactile input, probably causing at least a part of the increased interaction times. Users are likely to get faster with the Tangible

Table 6: Our taxonomy applied to a selection of techniques to illustrate the design space exploration of control.

| technique | metaphor | target | shape creation | shape adjustement | selection DOF | input DOF | CD control |
|---|---|---|---|---|---|---|---|
| RayCasting (Mine, 1995) | ray | object | no control | no control | 5 DOF (transl.: 3, rotat.: 2) | up to 6 DOF | none |
| Silk Cursor (Zhai et al., 1994) | box | object | no control | no control | 3 DOF | 6 DOF | none |
| Bubble Cursor (Vanacken et al., 2007) | sphere | object | no control | automated adjust. | 6 DOF | 6 DOF | none |
| Aperture (Forsberg et al., 1996) | cone | object | no control | manual size adjust. | 5 DOF (transl.: 2, rotat.: 3) | 6 DOF | none |
| Cylinder Selection (Lucas et al., 2005) | lasso | ROI | semi-autom., 2D input | no control | 2 DOF | 2 DOF | none |
| Volume Catcher (Owada et al., 2005) | lasso | ROI | semi-autom., 2D input | no control | 2 DOF | 2 DOF | none |
| CAST (Yu et al., 2016) | lasso | ROI | semi-autom., 2D input | threshold adjust. | 2 DOF | 2DOF | none |
| Tangible Brush | lasso + extrusion | ROI or objects | fully manual | none | up to 6 DOF | up to 6 DOF | manual |

Brush as they would get more used to tangible interaction, in the same the way they are now used to tactile interaction—but, of course, we cannot say this for sure. Furthermore, we noticed during our observations of all participants that most of them wasted time redrawing the lasso shape several times for Tangible Brush because they were not satisfied with their first few tries, mirroring qualitative feedback we reported earlier (unfortunately we could not quantitative this behavior with our data). We thus hypothesize that with a zooming capabilities for the lasso drawing or by providing stylus-based input the completion time with Tangible Brush could have been shorter. It is also worth to note that none of the participants reported that any of the techniques would take too long to use or that it became frustrating to a level that prevented them from using the technique.

### 5.7.2 *Accuracy*

Surprisingly, our hypothesis H1 is partially disproved: Participants obtained better accuracy scores with the Tangible Brush than with SpaceCast, overall and for each dataset. Yet, while there is clear evidence for the better performance of Tangible Brush, the effect—while noticeable—is still rather small. Both techniques exhibit an excellent performance overall, leading us to assume that both techniques are well suited for spatial selection.

### 5.7.3 *Workload*

The results we obtained for the workload evaluation are surprising as we expected Tangible Brush not to require much mental demand. Our results, however, show that it requires more mental effort than SpaceCast. This observation could be explained by the fact that tangible interaction is not, in contrast to tactile interaction, a widely released or adopted technology as we noted before. This lack of "expertise" on tangible interaction may also be the cause for the temporal demand being higher in the Tangible Brush case. Moreover, the mismatch between input and output space for the Tangible Brush may also contribute to a high mental demand: While the Tangible Brush is moved through 3D space during the selection extrusion, the participants could only observe the effects on either projected 2D view of the dataset. Our observations that some participants struggled when attempting even with simple dataset rotations with the tangible tablet also support this interpretation. Finally, the need to decide on a specific brush size and shape before the extrusion operation may have been difficult for some participants as the brush does not adapt during extrusion but the selection target's cross-sections frequently do.

### 5.7.4 *Fatigue*

The fatigue results were, overall, similar for both techniques. While it can be surprising that SpaceCast is also causing arm or shoulder pain, this fact is due to the position that our setup enforced as nine participants remarked: standing in front of the screen and having to lift up the arms to interact with the screen. Even though the fatigue results we present here are high, no participants reported that the fatigue was unbearable or had to take a break during the experiment (even though they were allowed to do so). This suggest that both techniques can be used interchangeably without worrying about fatigue.

### 5.7.5 *Preferences and Suggested Improvements*

Generally, our hypothesis H3 is confirmed. Participants tend to prefer SpaceCast for datasets in which the selection target can be easily obtained based on simple shapes or particle density (D1 and D2). For more complicated datasets, their preference leans towards Tangible Brush strongly (D3) or slightly (D4). Three participants reported that it was "nice to be able to control the selection based on spatial input" and that it was "helpful particularly for the galaxy dataset [D4] and the cylinder dataset [D3]." We also note that no participant reported a single technique to be their favorite for all datasets, mirroring and reinforcing the suggestion by two participants to ultimately combine SpaceCast and Tangible Brush. While Tangible Brush is already a hybrid interaction technique, a combination of a partially automated approach with a fully manual approach would allow users to choose the technique to engage depending on the dataset and the selection target.

Our participants also suggested a number of possible improvements when thinking out loud throughout the tasks. With our current method, users can extrude any 2D shape by moving the tablet in any direction. One participant suggested, for instance, that only forward movements should be considered and that backward moves could be used to cancel what had previously been selected. He actually said that, for him, going backward was a way to unselect as if doing "Ctrl+Z." This is an interesting idea that would enable undo operations in a tangible way and that could be explored with our system or in other tangible systems. In addition, when a new dataset is loaded, we currently compute a dataset-dependent scale factor on the tablet to show the whole dataset as large as possible without touching the borders of the screen. In some cases this negatively affects one's ability to select small sections of the dataset. Five participants suggested zooming operations (for drawing purposes) to address this issue. This zoom could be combined with the use of a stylus to even further improve accuracy when drawing by avoiding the fat-finger issue. The suggestion to combine CAST selection with Tangible Brush (made by two participants) is also very interesting. In this case, not only would the resulting technique be a hybrid tactile/tangible interaction paradigm, but also a hybrid selection technique combining both semi-automated extrusion of the selection shape and a fully manual control of the extrusion. We envision such a solution to be useful for complex datasets and selections that cannot solely be based on one input or the other. We also believe that such a combination would allow us to combine the benefits of both approaches: a shorter task completion time and a high accuracy. Multiple combination scenarios can be envision. First, simple shapes or data-dependent selection could easily be achieved by a CAST technique, while Tangible Brush would be used to handle more complex and data-independent selections. We also envision that the data-dependent strategy could only be used to assist the drawing of the lasso correctly and that the extrusion is still achieved manually. Such a combination would also reduce the need for a better and more accurate drawing of the lasso. This hybrid selection technique does not necessarily have to merge Tangible Brush and CAST: we believe that any combination of a structure-independent and structure-dependent techniques would be interesting.

### 5.7.6 *Limitations*

Despite our careful experimental design, some limitations should be mentioned. First, the tablet screen was a lot smaller than the screen on which we recorded SpaceCast's interaction, leading to precision issues for the drawing of the lasso when using Tangible Brush as highlighted by our participants and observations. We believe that a larger screen would have led to better results especially for the task completion time since we observed that participants had to redraw their lasso several times before being satisfied. While a larger tablet could solve this issue, it would also be heavier and more difficult to handle. So the temporary zoom suggested by some participants may be a better solution.

We also did not recruit any expert used to selecting ROIs in our study—experts may have used different strategies for both interaction techniques which could have led to different study results. Indeed, our participants sometimes failed to see possible Boolean strategies that would have helped them which most experts would probably have used.

Participant preferences could also have been biased by the novelty effect of tangible interaction (Besançon et al., 2017). However, to try and avoid this kind of bias we were careful to ask for participants' preferences per dataset, thus trying to get them to focus on the possible benefits of each technique rather than their possible entertaining values. We also asked them to justify their preferences and did not find any justification to be based on possible enjoyment or novelty of tangible interaction. We thus believe that the novelty effect of tangible interaction had only little influence on the preference results we presented.

Finally, the mentioned mismatch between output and input space could be an important issue for Tangible Brush. For SpaceCast and similar techniques, in contrast, users see a 2D projection of the data and provide matching 2D input—even if the data arguably lives in 3D. To avoid the space mismatch for Tangible Brush one could envision an augmented reality setup (e. g., using Microsoft's HoloLens[3] or a stereoscopic data projection on the large display: the sterescopic data view would provide an ideal context for the tangible operations, thus linking output and tangible input spaces. While the 2D lasso that provides the brush would probably still require the tablet's display to show a 2D projection (to avoid parallax issues (Bruder and Steinicke, 2013; Colley et al., 2015; Valkov et al., 2010; Valkov et al., 2011b)), we would like to explore such setups in the future to further examine the potential of tangible interaction for the control of visualization environments.

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[3] https://www.microsoft.com/microsoft-hololens/

## 5.8 CONCLUSION

In this chapter, we have further explored the design space of spatial selection for 3D datasets, adding a structure-independent and fully manual selection to the spectrum. Our taxonomy of previous work showed that new classification criteria were needed that describe the input and shape control offered to users by several techniques. Filling a hole that existed in the scope of selection techniques, our Tangible Brush, in contrast to past approaches, gives full control to the user performing a selection. Our controlled study and observations clearly showed the potential of such a technique for 3D selection, highlighting its excellent accuracy even in complicated cases.

Our specific technical contribution, the Tangible Brush, can directly be applied to various types of data because it is structure-independent. While in our experiment we used particle-based data, for example, from astronomy, it is easily possible to apply our approach to volumetric data (e. g., from medicine) and explicit shapes (e. g., molecular models from structural biology). It would even be possible to extend it to the selection of linear structures (e. g., DTI fibertracts or trajectories in a FTLE dataset) by using the direction of motion during selection.

In addition to supplementing the spectrum of 3D spatial selection techniques, we have also, with this work, filled a hole in the spectrum of possible hybrid tactile/tangible interactions for 3D visualzation (**R2**). Our work in Chapter 4 focused on several 3D visualization tasks for the specific needs of fluid dynamic researchers. In this chapter however we only focused on one task useful in several scientific fields. We have thus further extended the possibility that our interaction continuum offers with this focus on 3D spatial selection of data and highlighted its potential yet again. Our technique, moreover, relies again on an affordable and commercially available device (**R3**).

Furthermore, our study also highlighted the need for more hybridation at an other level. While we distinguished with the taxonomy presented here manual and assisted selections, our study revealed that a hybrid approach combining several selection techniques/strategies to better suit at minimum the dataset, the selection targets, and the interaction environment. Ultimately, it seems ideal that an application should provide several different selection approaches from the entire spectrum that cover different aspects of our taxonomy. Table 6 illustrates a selection of such possible techniques with their classification, and designers can choose the ones best suited for a particular domain or application.

While our specific setup with a 2D projection on a separate screen facilitated effective selection as we demonstrated in the study, it also showed limitations as we have outlined above. Exploring our hybrid interaction paradigm in other environments could not only probably solve the input-to-output-mismatch, but would also further expend the idea of an interaction continuum that spreads on even more environments. We thus believe that augmented reality environment have a great potential and should be explored further in order to push the boundaries of our interaction continuum theory.

# 6

# COMBINING TANGIBLE INTERACTION WITH PRESSURE INPUT

Most of the work presented so far focused on a possible implementation of an interaction continuum through the combination of complementary input paradigms ( as seen in Chapter 4 and Chapter 5): namely tactile interaction and tangible interaction. The previous chapters clearly showed the potential of such a hybrid interaction paradigm for 3D visualization tasks. However, tactile interaction was limited to its simplest and most naive implementation so far, as only the finger's position on the screen has been considered.

However, tactile interaction, is actually much more than just a position of fingers in the 3D space, or even 2D space when we consider that it happens on a screen. Other information are being transmitted through the use of tactile interaction. One of these, pressure, is definitely useful for interaction with buttons, doors, etc.

In this chapter we thus analyze the possibilities of pressure input when combined to tangible interaction. Chapter 3 clearly highlighted the lack of feeling a of precision obtained with tangible manipulations while Chapter 4 clearly showed that study participants did not like using a tactile sliders to adjust the accuracy of their tangible manipulations. In this chapter, we thus describe a way to combine tactile interaction (through pressure) and tangible interaction to alleviate this issue.

Main portions of this chapther were previously published at CHI (Besançon et al., 2017). Thus, any mention of "we" in the following chapter refers to myself, Mehdi Ammi, and Tobias Isenberg.

## 6.1 INTRODUCTION

We present the design and the evaluation of a prototype that adds pressure-based input sensing to the back of a mobile device. Pressure or isometric force is a continuous form of input that is increasingly used in HCI systems. The recent release of devices equipped with *3D-touch*[1] may well encourage an even higher number of manufacturers to provide to equip their systems with this input channel—so our research enables future developers to design pressure-based control effectively.

We use pressure as an input channel to provide users with a manual control of the gain factor associated with the tangible manipulations of 3D content shown on the device. Gain factors (also called control-display gain, CD gain; (Blanch et al., 2004; MacKenzie and Riddersma, 1994; Worden et al., 1997)) play an important role in interaction. Hinckley et al. (1994a) even state that one of the major hurdles with 3D interaction is to be able to "provide an interface which effectively integrates rapid, imprecise [...] object placements with slower but more precise object placement, while providing feedback

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[1] https://developer.apple.com/ios/3d-touch/

that makes it all comprehensible." Past work has focused on techniques to set the CD gain for mouse or tactile interaction (e. g., (Benko et al., 2006; Casiez et al., 2008; MacKenzie and Riddersma, 1994; Worden et al., 1997)), but some work for direct 3D input (Issartel et al., 2016b; Keijser et al., 2007) and interaction in VR (Frees and Kessler, 2005) exists as well. In the special case of tangible manipulations, different gain factor for the same interaction mapping can make a manipulation extremely exhausting and frustrating (e. g., when the gain factor is low and the user has to make many different arm/hand/shoulder movements) or really frustrating (e. g., when the gain factor is high and the manipulation not precise enough).

Previous work in the context of 3D manipulations (Besançon et al., 2017) has shown that tactile manipulation of a slider widget during tangible manipulation was not appropriate: even though users could precisely set the gain factor, they did not want to stop their current interaction to reset the gain factor. With our pressure-based control we present a new approach to control the gain factor independently from the other input modalities.

Our contributions are thus threefold. First, we present the design of a back-of-device pressure-sensing system controlling the gain factor associated with tangible manipulation of a mobile device. Second, we study the pressure-based control of gain factors to learn which interaction mapping is preferred by participants and used most efficiently by them. Finally, we compare this pressure-based form of gain control with established mappings including velocity-based, slider-based, and rate control. Our evaluation comprises performance workload and fatigue measures as well as subjective preferences. Our results show that pressure-based control was not only clearly preferred but also that pressure-based gain control allows people to be more precise in the same amount of time compared to established input modalities.

## 6.2 RELATED WORK

Work related to our own comes from one of three major fields: interaction with the back of (mobile) devices, the use of pressure as an input modality, and the use of pressure to augment other input techniques. We discuss these aspects next.

### 6.2.1 *Back-of-Device Interaction*

Several research projects have investigated interaction on the back of the device as a way to eliminate on-screen occlusion. For instance, systems like *BehindTouch* (Hiraoka et al., 2003) and *BlindSight* (Li et al., 2008) use a 12-key pad on the back of a mobile device. In particular for small devices, occlusion is one of the biggest usability issues. In the context of very small screens, Baudisch and Chu (2009) as well as Wigdor et al. (2007) thus propose to combine back-of-device interaction with a see-through effect to improve pointing. Liang et al. (2013) also propose to use a secondary mobile device attached to the the back of the first one to facilitate tactile input above and under the mobile device and thus support task such as rotation, translation, stretching or slicing. Similarly, Shen et al. (2009) propose a set of gestures for 3D interaction with back-to-back devices. In addition, back-of-device interaction has been used on larger devices. For instance, Wigdor et al. (2006) propose to use a two-sided interactive touch table to add a new dimension of input for co-located collaborative work. Finally, back-of-device interaction has also been used combined with other types of input; e.g., with stylus input on a PDA (Sugimoto and Hiroki, 2006) or to detect bending using a position sensor on the back of the Gummi device (Schwesig et al., 2004). We build on the general approach of back-of-device input to provide easily accessible pressure control when interacting while holding a tablet.

### 6.2.2 *Pressure as an Input Modality*

Pressure input is a continuous input data (Buxton et al., 1985; Cechanowicz et al., 2007; Ramos et al., 2004; Stewart et al., 2010) that has been shown in the literature to be usable as a primary modality for a variety of tasks. Early work conducted by Buxton et al. (1985) includes an example of a drawing application. Buxton et al. map continuous pressure data to a continuous scale that varies the width of the painting brush, allowing users to control both width and path with a single finger. Brewster and Hughes (2009), for instance, use pressure to control text entry. They map the pressure input to two discrete states: a light pressure will be mapped to lowercase letters while a strong pressure will be mapped to uppercase letters. Similarly, McLachlan and Brewster (2015) and Wilson et al. (2010) use pressure-based menu selection on mobile devices. Ren et al. (2007) use pressure values of pen-based interfaces to control the continuous size of a circular cursor (or its contexts) to assist users for selection tasks. Other non-touch-enabled devices also make use of pressure as a primary input. For instance, Issartel et al. (2016a) use pressure input to realize a grasping metaphor on a tangible volume. In their case, pressure controls a state representing whether the user is trying to grasp—for pressure larger than a given threshold—or release a virtual object. In our work we map the pressure input to a continuous range of gain-factor values.

Pressure input can be captured by means of force-sensing resistors (FSRs) (McLachlan and Brewster, 2015) or can be indirectly captured on touch screens. One of the techniques used for this purpose builds on the fact that a higher pressure on a point leads to a wider point of contact between the finger and the surface (Buxton, 2007) and was implemented by Forlines et al. (2005) or Benko et al. (2006). Arif and Stuerzlinger (2013), for instance, use it to create a technique to bypass incorrect word predictions of text entries on a tactile device. While this indirect sensing of pressure on touch-screen is promising, in our work we only consider sensor-captured pressure. Indeed, even though our prototype has a touch screen, we take advantage of back-of-device pressure sensing which is easier to achieve with simple FSRs.

A vast majority of studies conducted on pressure in the HCI community have focused on determining how many distinct levels of pressure can be applied by users. Early work conducted by Herot and Weinzapfel (1978) already suggested that accuracy with pressure input methods is achievable with a continuous and real-time visual feedback. With the presence of a visual feedback, pressure-based interaction has been proven to be highly accurate. For instance, Cechanowicz et al. (2007) proved that users could differentiate between 64 modes on a dual-pressure augmented mouse, while Wilson et al. (2010) showed that users could distinguish accurately up to 10 levels of pressure with adequate feedback on a mobile device. The value obtained in the former is high enough for us to consider it as a virtual continuous scale. The value obtained in the latter can still be seen as close to continuous for our purposes. Indeed, participants in our study had to use pressure input to vary the gain factor from 0.3 to 3 (i. e., by a factor of 10).

### 6.2.3 *Pressure as Augmentation*

Pressure can be a direct and primary way to interact on mobile devices and thus can replace touch interaction. We are investigating, however, the use of isometric force as a supplementary, auxiliary input that could augment or complete other input technique. Touch and pressure input have been combined in the past, for example, by Arif et al. (2014) to increase the security of conventional digit-lock of recent smartphones. McLachlan et al. (2014) investigated this characteristic of the pressure input in the context of bimanual interactions on mobile devices. They could not find evidence that would suggest that the pressure input had effects on the accuracy of the dominant-hand performing touch inputs. Similarly, McLachlan and Brewster (2015), demonstrated that the ability to perform simultaneous pressure inputs and touch gestures depended on the complexity of the gesture. Tangible 3D manipulations are regarded as natural since they are based on skills people have developed through their everyday interactions (Ishii and Ullmer, 1997). We thus hypothesize that these results may be generalizable to tangible 3D manipulations of a mobile devices and that thus the pressure input facilitates an additional and independent form of control to be used to adjust the gain factor in 3D interactions. Ramos and Balakrishnan (2005) proposed such a combination of pressure and touch input. The first modality is used to provide a fluid integrated manipulation of the scale while the touch input is used to provide parameter manipulation within the pressure-obtained scale. Similarly, Ramos et al. (2004) combined position (obtained via touch input) and continuous pressure input (obtained from a stylus) to provide Pressure Widgets on mobile devices. Our design builds on their ideas but we use pressure to adjust the gain factor, while 3D navigations are still carried through physical manipulation of the tablet.

## 6.3 PROTOTYPE

To test this interaction concept we used an existing mobile device as a locally-coupled[2] tangible 3D exploration tool and fitted it with pressure sensors (see Figure 42). We used a Google Tango tablet[3] as it provides both a tactile screen and a position-aware mechanism that facilitates tangible manipulations. We then augmented the tablet with back-of-device pressure FSR sensors that are located right under users' fingers on the back of the tablet. The FSR sensors

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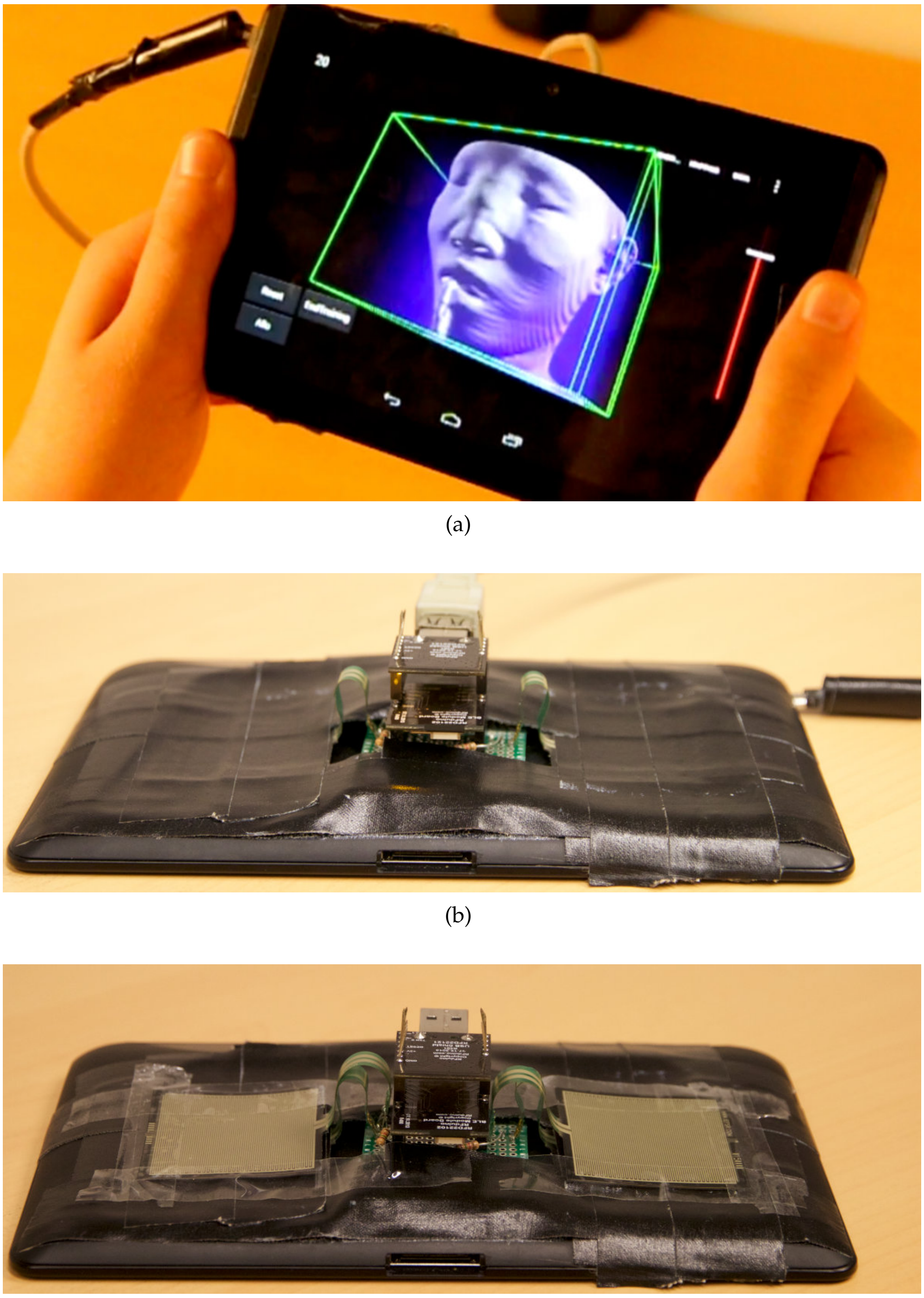
[2] A locally-coupled device is both display and input device (Issartel et al., 2016b; Rahman et al., 2009).

[3] https://get.google.com/tango/



(a)

(b)

(c)

Figure 42: Interaction prototype: (a) prototype in use, (b) electronics installation on the back with taped pressure sensors, and (c) mock-up of the arrangement of the pressure sensors (hidden by the tape in (b)).

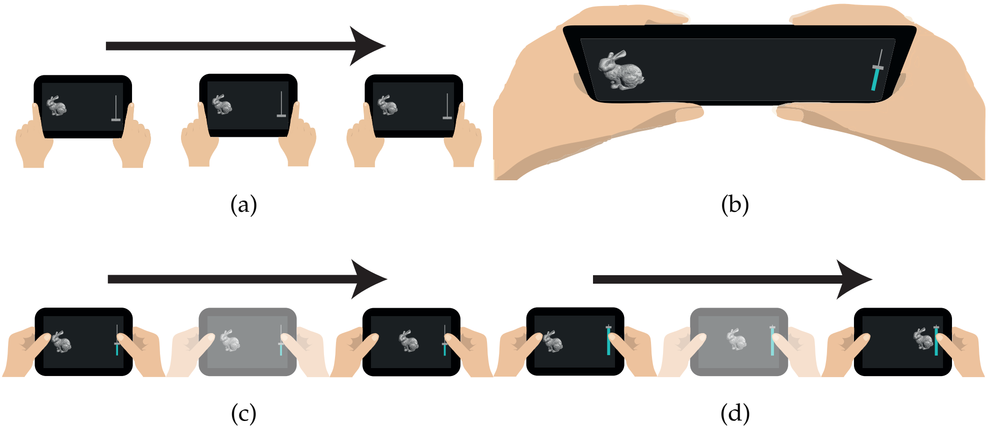


Figure 43: Illustration of the clutching mechanism: (a) fingers are not on the pressure sensors, thus movements sensed by the tablet are not propagated to the virtual object; (b) the force applied to the pressure sensors is mapped to the slider such that movements are now propagated to the virtual object; (c) if the pressure is low the slider value and the gain factor value are low such that the virtual object is translated only by a little; (d) if the pressure is high the slider value and the gain factor value are high such that the virtual object is translated more than in (c).

are often used in pressure-sensing prototype (McLachlan et al., 2014) and we coupled them to a RFDuino board, each one of them with a 3.3kΩ resistance. The sensitivity of the FSRs depends on the value of the resistance and a pilot study with six participants allowed us to determine that 3.3kΩ was ideal in our case. To keep the prototype fully portable, the RFDuino board is powered by a cable that connects it to the micro-USB port of the tablet. The pressure values are computed by the RFDuino board and sent over Bluetooth Low Energy (BLE) to the tablet. Clutching is achieved by putting/removing the fingers from the pressure sensors Figure 43. While we first wanted to realize the clutching through touches on the screen, another pilot study showed us that it was easier for people to clutch with the pressure sensors. Because previous work (Cechanowicz et al., 2007; Stewart et al., 2010; Wilson et al., 2010; Wilson, 2013) has shown that pressure input is made more precise with the help of visual feedback, a cursor (aka slider) was added to the GUI on the tablet to reflect the gain-factor value obtained with pressure input. This kind of visual feedback has been used before in various studies and setups such as the ones used by McLachlan et al. (McLachlan et al., 2014; McLachlan and Brewster, 2015).

## 6.4 EXPERIMENT 1: CHOICE OF FORCE MAPPING

We conducted a first study to compare two possible pressure-based gain factor adjustment techniques. The first technique (P1) maps the pressure of the sensors directly to the gain factor: a high pressure results in a higher gain factor, i. e., to larger/stronger motions. The metaphor for this mapping is that the stronger pressure forces are equivalent to stronger and larger motions, and that lower pressure thus yields a more precise control. The second technique (P2) does exactly the opposite: a high pressure results in a lower gain factor, i. e., to more precise motions. The metaphor of this second technique is that with stronger pressure the interacting person holds on more tightly to be able to better control a precise manipulation. Our goal with this experiment was to determine whether one of these two technique yield better results and/or is preferred by users and thus to to determine which mapping we should use in our follow-up experiment.

### 6.4.1 *Participants*

For this first study we recruited 12 unpaid participants (2 female; ages 21–39, mean = 26.75, med = 26, SD = 5.01). Six of them had at least university degree, while the remaining six had at most an A-level equivalent. Five of of the participants were used to 3D manipulation through the extensive use of video games or 3D software. All participants were right handed and had normal or corrected-to-normal vision.

### 6.4.2 *Procedure and Task*

We first presented participants with the tablet device and told them they would have to perform translation and rotations in a 3D virtual world. We presented them the application and showed how the clutching was achieved. An initial docking target was already present during this training phase of the experiment. We asked participant to try and use the tablet so as to match the target docking. The purpose of the training was twofold. First, as highlighted by Issartel et al. (2016c), we wanted to assert whether the participant preferred allocentric or egocentric mapping.[4] Because our docking task was similar to the first environment used by Issartel et al. (2016c) which showed a 70% preference for the egocentric mapping, we set the initial mapping to egocentric. However, this initial training could be used to set it to allocentric if participant felt that they could not use the mapping correctly. Four participants did so and set their mapping to allocentric. Second, the gain factor was set by the experimenter for the initial training once to both a high value (i. e., 3) and to a low value (i. e., 0.3)—to let our participant understand the need for a manual control of the gain factor. Achieving a precise positioning was almost impossible with the high gain factor because it was too sensitive, while it took more than a minute for participant to do it with a low gain factor. Each participant thus experienced both extreme gain factors, in a counter-balanced order. During training, participants had an unlimited time to get used to the manipulation of the tablet and the purpose of the docking task.

Once they expressed to be familiar with the interaction techniques and task type, the experimenter launched the actual experiment. Participant were

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[4] These two notions are frequently discussed in the literature (Burgess et al., 2004; Klatzky, 1998; Poupyrev et al., 1998b). In general, the egocentric term seems to be associated with the idea of the viewing perspective, and the allocentric term with the idea of a fixed, external reference point. In other words, when the manipulated object is being moved in the same direction as the tablet, the mapping is allocentric. When the manipulated object moves in the opposite direction of the tablet, the mappings is egocentric.

asked to complete 20 docking tasks for each technique (i. e., a total of 40 docking tasks), for each of which they had a maximum of 30 seconds. The order of technique was counter-balanced to avoid learning biases. The pool of possible docking targets had been manually created ahead of time to ensure that participants had to frequently manually change the gain factor. For each trial, the target was randomly picked from this pool and then removed from the pool. At the end of the experiment, each participant's preference was asked by the experimenter and a semi-structured interview was conducted to determine whether participant could use the technique properly.

### 6.4.3 *Hypotheses*

We hypothesized, based on previous work (McLachlan et al., 2014; McLachlan and Brewster, 2015), that (**H1**) the use of pressure as an input modality to control the interaction gain factor would not endanger the use of tangible control of 3D manipulations using the mobile device. We also hypothesized that (**H2**) it would be more natural for users to use P2 than it is to use P1 and that P2 would thus outperform P1—due to our own observations that people playing video games often put a lot of effort in being precise and, as they perform these precise interactions, tend to squeeze their game controller.

## 6.5 RESULTS OF EXPERIMENT 1

We collected a total of 480 docking trials from our 12 participants, i. e., 240 per technique, analysed using estimation techniques (Appendix A). In addition, we recorded the answers of the participants in the semi-structured interview and analyzed our participants' subjective preferences and a comparison of their subjectively rated intuitiveness. First, to analyze our hypothesis H1, we specifically asked our participants during the semi-structured interviews about whether the additional pressure-input was harmful to their 3D manipulations. None of them reported so. We thus fond no evidence that would refute H1, making the pressure-based gain factor manipulation a viable option for tangible 3D interaction.

To assess the docking precision and thus to analyze H2, we then compared the Euclidean distance of and the angular difference between the manipulated object and the docking target. We first discuss the Euclidean and the angular distance to the target, for both technique. The Euclidean distance is computed as the distance between the centers of the two objects. The angular difference $d_a$ is computed as

$$d_a = 2 \cdot \arccos(q_{d\omega}) \; ; \quad q_d = q_o^{-1} \cdot q_t \tag{1}$$

with $q_o$ being the quaternion of the manipulated object, $q_t$ being the quaternion of the target, thus $q_d$ being the difference quaternion, and $q_\omega$ being the $\omega$ component of an $\omega + xi + yj + zk$ quaternion with $i^2 = j^2 = k^2 = ijk = -1$. We then aggregated and averaged both the angular and the Euclidean distances per participant. The distribution is not normal, so we estimated population means using 95% bootstraped confidence intervals (CIs). Figure 44 clearly shows that there is no evidence of a better performance of P2 over P1 for both the Euclidean distance and the angular distance to the target.

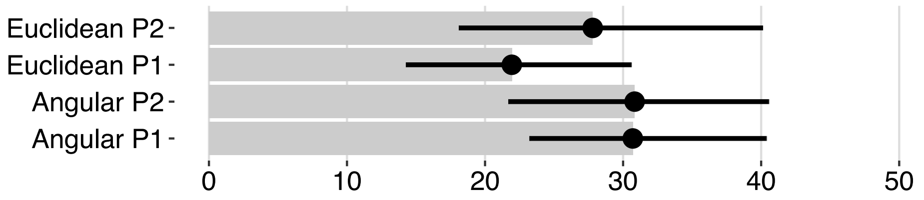

Figure 44: Euclidean and angular distance to the target for both P1 and P2. Error bars are 95% bootstrapped confidence intervals.

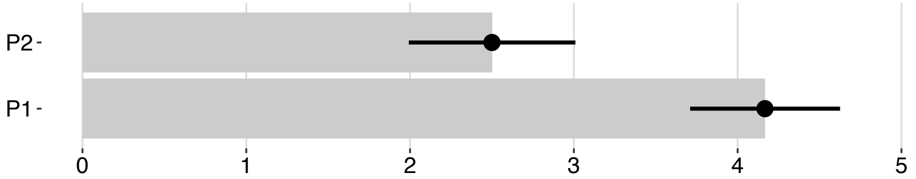

Figure 45: Likert scale score of intuitiveness for each technique. Error bars: 95% bootstrapped CIs.

Even though we found no evidence of a performance difference between the two techniques, there were differences in preference. Figure 45 shows aggregated ratings of the intuitiveness of each technique on a five-point Likert scale, and 11 out of our 12 participants reported that their favorite technique was P1 which maps a strong pressure input to a high gain factor. They all explained during the semi-structured interview that it felt more logical to have such a mapping. The remaining participant had no overall preference but stated that P1 also seemed more logical. Furthermore, four participants reported that P1 was less tiring than P2 and another six stated that P1 was easier to use. Finally, three participants reported a higher exit error issue—often found in tactile interaction (Tuddenham et al., 2010)—with P2. Indeed, when leaving a state of high pressure to release the fingers and clutch, the gain factors gets from a very low value to a high value and any involuntary movement of the tablet at that time is thus followed by a relatively big movement of the manipulated object in the virtual world. For all the above reasons, we thus refuted hypothesis H2 and decided to use P1 as the primary mapping for the following experiment.

## 6.6 EXPERIMENT 2: USABILITY OF GAIN FACTOR CONTROL

Our second study used the same prototype and task as Experiment 1. However, we asked participants to perform the docking task with one of four different techniques to compare our pressure-based technique to three established mappings: slider-based control, velocity-based control, and rate control. The first one used a touch-based slider on the dominant hand's side of the screen that allows users to manipulate the gain factor. Arguably, sliders are the most commonly used ways to provide values within a specific range in regular interfaces and, in contrast to keyboard input, are effective on mobile devices. We told each participant that they could change the placement of the slider to the left or right side regardless of their dominant hand. The second technique used the velocity of the tablet's movements (rotations and translations) to derive the gain factor—similar to mouse-based gain factor control (Casiez et al., 2008; Foley et al., 1984; Frees and Kessler, 2005). The third technique used a rate-control approach: the further the tablet was translated/rotated away from its initial position, the higher was the gain factor for translation/rotations. However, because rate-control has been proven to be inappropriate for devices without a self-centering mechanism (Zhai, 1998), we compensated by adding a centering mechanism based on clutching. Still, rate-control is frequently used for 3D games with remote controls or joysticks so we deemed it an appropriate candidate for a comparison with the added centering mechanism. For the sake of fairness, the value of the gain factor was represented on the (potentially inactive slider in all cases. We also note that the gain factor ranges were identical for all conditions. We used the pilot studies to find appropriate (linear) mappings from the available input value ranges of these three techniques to the range of gain factors.

### 6.6.1 *Participants*

For this study, we recruited 24 new unpaid participants (9 female; ages 20–53, mean = 31.6, med = 26.5, SD = 11.1). Twelve of them had at least a university degree (bachelor or equivalent), while the remaining half had at most an A-level equivalent. Half of them were experienced with 3D manipulation through extensive use of video games (9×) or 3D modeling software (3×). Two participants were left-handed and all participants had normal or corrected-to-normal vision.

### 6.6.2 *Procedure and Task*

This experiment was largely based on the precudure of Experiment 1, using the same docking task. Participants were first greeted and introduced to the tablet device, before being told that they would perform translations and rotations with it. We explained the clutching mechanism and made them perform the docking with the high and low gain factors to allow them to understand the necessity of a manual gain factor control. We asked participants to complete 20 docking tasks with each of the mentioned 4 different techniques (total of 80 docking tasks). For each docking task we allowed participants up to 20 seconds, a time span that is based on the average time of 19.2 seconds it took participants to complete the task in Experiment 1. The second experiment thus lasted a bit more than 26 minutes overall.

Similar to Experiment 1, the second study also used an egocentric mapping but participants could change it during this training phase. Eleven participants stated that this mapping was not completely natural for them and switched to an allocentric mapping. In between each technique, participants were asked to fill in a questionnaire to assess their workload and their fatigue. For the former, we used NASA's Task Load Index (TLX).[5] For the latter, we created our own questionnaire based on Shaw (1998)'s approach . To avoid seemingly random choices made in the second part of the TLX (which were often seen as confusing by participants in our pilot studies) that would

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[5] http://humansystems.arc.nasa.gov/groups/tlx/downloads/TLXScale.pdf

lead to inconclusive or even incorrect results, we removed the second part of the TLX questionnaire. We thus performed a *RAW TLX* (RTLX) which, according to Hart (2006)'s survey, is equally well suited as a regular TLX. Finally, at the end of the experiment—and following Nielsen (1993)'s recommendation for the evaluation of subjective preferences—we asked participants to rank each technique based on their preferences and we conducted semi-structured interviews.

To avoid participant response bias (Dell et al., 2012), we told our particpants that all the techniques were state-of-the-art techniques, that none of them was invented by us, and that we simply wanted to evaluate how they performed with each of them. Our participant number of 24 ensured that each sequence of conditions was tested exactly once in a counter-balanced fashion).

### 6.6.3 *Hypotheses*

Based on pilot studies and previous work results, we formulated a number of hypotheses:

H3 Even with the clutching mechanism to reset the interaction center, participants' performances using rate control will be poor and it will not be preferred by our participants. The reason is that, even with an added clutching for re-centering (Zhai, 1998), on locally-coupled devices the interaction will not be natural due to the conflict of the rate control for the gain factor with the tangible position-based control of the 3D manipulation and it will thus not be understood correctly by most participants.

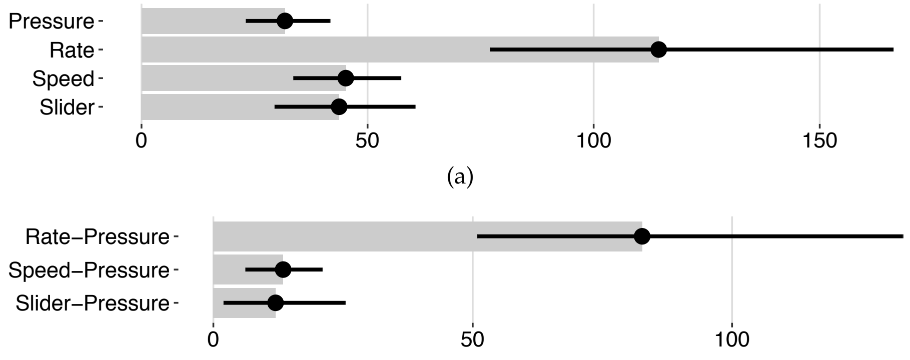
H4 Pressure-based control will have a higher performance (accuracy) than the three other techniques because it facilitates gain factor manipulation using a separate input channel that does not disrupt the tangible manipulation.

H5 Pressure-based control, however, will cause a higher fatigue in participants' fingers due to the additional force that is necessary compared to the other interaction techniques.

H6 Speed-based control will be the cause of a high overall fatigue and physical demand, even though the mental demand would be low compared to other techniques—we noticed that participants in our pilot studies tended to resort to overly fast movements to ensure that the gain factor will be high, causing sore arms and shoulders.

## 6.7 RESULTS OF EXPERIMENT 2

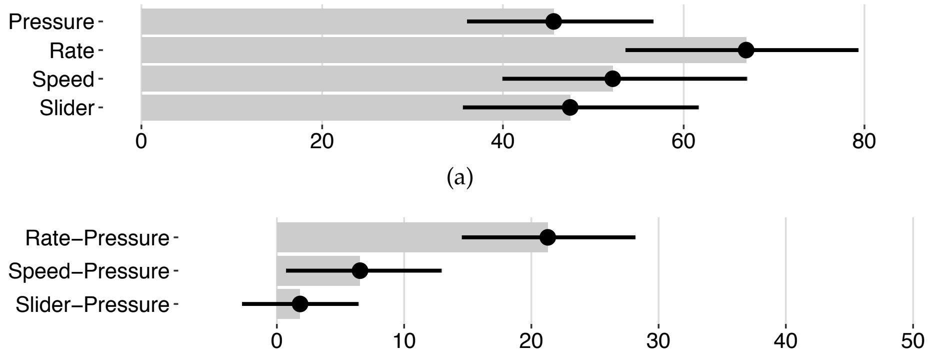
We now discuss the measured performance values in form of the Euclidean and the angular distance to the target. We also present participants' subjective preferences as well as their self-assessed fatigue, and workload. Similar to Experiment 1 we report our results using simple effect sizes and estimation techniques (see Appendix A).



(a)

(b)

Figure 46: Euclidean distance to the target: (a) absolute values and (b) pair-wise differences. Error bars: 95% bootstrapped CIs.



(a)

(b)

Figure 47: Angular distance to the target: (a) absolute values and (b) pair-wise differences. Error bars: 95% bootstrapped CIs.

### 6.7.1 *Euclidean and Angular Distances*

We collected a total of 1920 trials from our 24 partcipants, 480 per technique. We averaged our distance observations per participant and computed population means using 95% bootstrapped confidence intervals.

The Euclidean distances to the target for all four techniques is shown in Figure 46a. These results show strong evidence for a better performance of pressure-based, speed-based, and slider-based control compared to rate control. There is also weak evidence for a better performance of pressure-control over the slider-based and speed-based methods. To assess this difference in detail, we looked at the difference between pressure-control and the three other condition as shown in Figure 46b. The fact that none of the confidence intervals for these differences overlaps with zero supports our finding of pressure-based control of the gain factor being more accurate than the other techniques: it leads to 3.6 smaller Euclidean distances than rate-control, 1.4 smaller than speed-based control, and 1.3 smaller than slider-based control.

The angular distances to the target for all four techniques are shown in Figure 47a. Again, there is a strong evidence that rate control is outperformed by all three other techniques. While there is no evidence for a difference in performance between speed-based and slider-based control or pressure-based

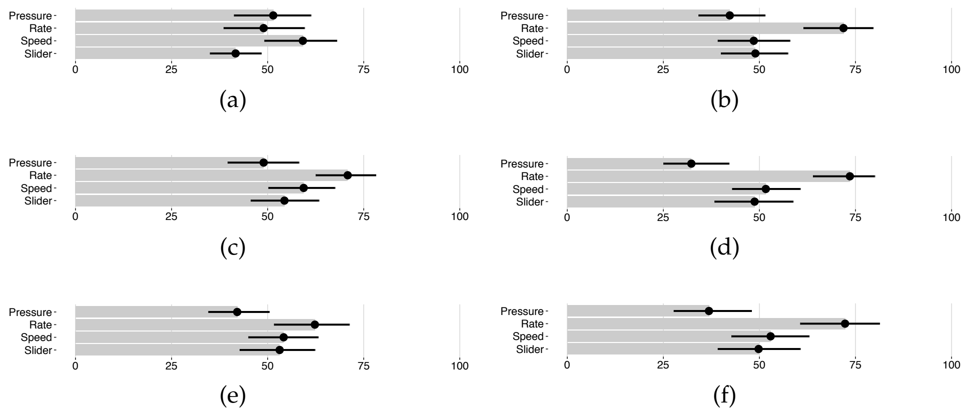


Figure 48: Workload measurement in NASA TLX units ($\in [0, 100]$) with respect to (a) physical demand, (b) mental demand, (c) temporal demand, (d) performance (lower is better), (e) effort, and (f) frustration. Error bars: 95% bootstrapped CIs.

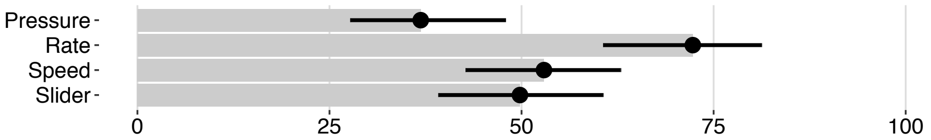
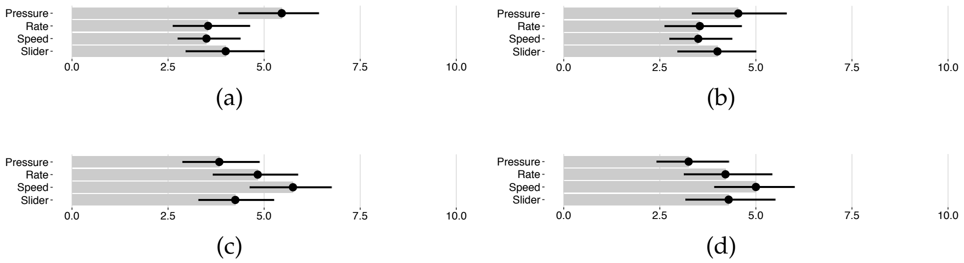


Figure 49: Total workload per factor. Error bars: 95% bootstrapped CIs.

and slider-based control, there is slight evidence that pressure-based control may also perform better than speed-based control for rotational distances. Similar to the analysis of the Euclidean distance, we computed the pair-wise differences between pressure-based control and the other techniques and show them in Figure 47b. These values confirm that pressure-based control of the gain factor allowed participants to obtain a better angular accuracy than rate-control and speed-based controls The confidence interval of the difference between slider-based and pressured-based control, however, overlaps 0 so that we claim a difference between these two modalities.

### 6.7.2 *Workload*

The individual results of the TLX questionnaire are shown in Figure 48. Figure 48a suggest that strong evidence exists of speed-based control being physically more demanding than slider-based control, but we cannot make any further conclusion with respect to the other techniques. Figure 48b, however, shows strong evidence of rate control being approximately 1.5 times more mentally demanding that the other three techniques. Figure 48c exhibits strong evidence of rate control being temporally more demanding than pressure-based, speed-based, and slider-based control. We conjecture that this observation results from participants being more stressed with a technique that they did not master, thus suggesting that rate control does not give them the level of control they wanted. This hypothesis is further reinforced by the confidence intervals shown in Figure 48d which provide strong evidence for rate control giving a much higher (at least twice and



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

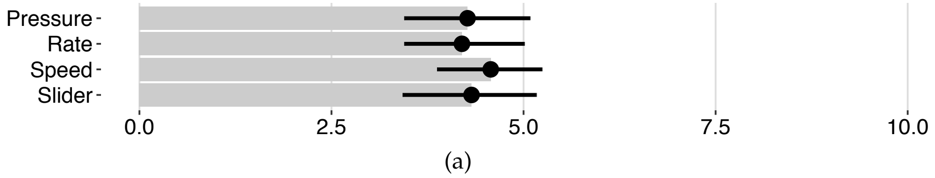
Figure 50: Fatigue measurement on a scale from 0 to 10 for (a) fingers, (b) hands, (c) arms, and (d) shoulders. Error bars: 95% bootstrapped CIs.

almost three times as much when compared to pressure-based control) perceived performance than the other three conditions. Figure 48d also provides strong evidence of a better perceived performance for pressure-based control than for the slider-based or speed-based conditions. While there is no evidence for an difference in effort between rate control, speed-based, or slider-based control, Figure 48e provides strong evidences of pressure-based control being less effort-demanding than the three other techniques. Similarly, Figure 48f has strong evidence that pressure-based control is less frustrating by a factor of two than rate control, and strong evidence for speed-based and slider-based control to be less frustrating than rate control.

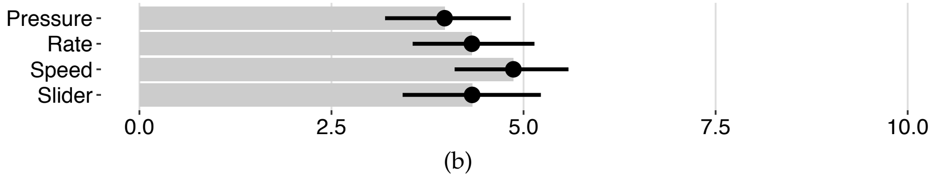
The overall TLX workload is shown in Figure 49. There is strong evidence for a higher workload of the use of rate-control compared to the other techniques. While we cannot find evidence for differences in workload between speed-based and slider-based control, there is evidence that pressure-based control is overall less demanding than all the other techniques.

### 6.7.3 *Fatigue*

Figure 50 presents the results of the fatigue questionnaire that each participant filled in after each condition. We used a 11-point Likert scale (0 meaning no fatigue at all and 10 meaning extreme fatigue) for fingers, hands, arms, and shoulders. Figure 50a suggest that there is strong evidence of the pressure-based control being slightly more tiring (between 1.3 and 1.5 times) for the fingers than the other three techniques. It appears, however, that the overall finger fatigue caused by a pressure-based control is still not too high. We also can see in Figure 50b that all techniques result in a similar hand fatigue. Figure 50c and Figure 50d provide strong evidence of speed-based control causing more arm and shoulder fatigue than pressure-based and slider-based control. However, there is no evidence of a fatigue difference between rate control and the other three conditions for arms and shoulder. The total fatigue measurements are shown in Figure 51. Figure 51a treats all four fatigue aspects equally and derives the total fatigue measurements as a sum of the individual factors. From these sums we cannot find evidence for a difference in the overall fatigue measure between the different technique. However, the different fatigue aspects may be more or less important to people, so we also asked our participants about the importance of the individual fatigue aspects and derived a weighted aggregated fatigue rat-



(a)



(b)

Figure 51: Aggregated fatigue measurements: (a) non-weighted and (b) weighted, both from 0 to 10. Error bars: 95% bootstrapped CIs.

ing in Figure 51b. The mean weighted aggregated fatigue rating is lowest for pressure-based control, with weak evidence of it being different from speed-based control.

### 6.7.4 *Preference and Qualitative Feedback*

After the experiment, we asked participants to rank the technique from their preferred (1) to their least preferred (4) method for which we present the results in Table 7. The pressure modality was most preferred 15× and the slider-based control, the speed-based control, and the rate-control were most preferred by 3 participants each. These results show a strong preference for the pressure-based control of the gain-factor. Similarly, we found that most participants did not like the rate control technique. It is more difficult, however, to state a definite difference between speed-based and and slider-based control. To better analyze this result, we determined the number of times each technique was picked as the favorite with simultaneous confidence intervals (that are applied on a multinomial distribution) and show the result in Figure 52. The non-overlapping confidence interval of pressure-based control with all three other techniques allows us to infer that pressure-based control is likely to be the preferred technique by a vast majority of the population.

Participants also voiced interesting comments during the study. Two participants stated that the pressure-based control gave them a better feeling of precision and of being in control, thus “eliminating all the temporal pressure of the experiment.” Two other participants also reported that, although the “speed-based control [was] interesting,” it was difficult to evaluate and find the correct speed needed to achieve what they wanted. Three participants who picked the slider as their favorite technique stated at the end of the experiment that it was “easy to use” and that it gave “the more precise control of the gain factor.”

## 6.8 CONCLUSION

With our design and evaluation of a pressure-based interactive control of the gain factor for 3D navigation we identified an appropriate channel for

| *technique* | *median* | *mean* | *SD* | #1$^{st}$ | #2$^{nd}$ | #3$^{rd}$ | #4$^{th}$ |
|---|---|---|---|---|---|---|---|
| pressure | 1.0 | 1.5 | 0.8 | 15 | 7 | 1 | 1 |
| rate | 4.0 | 3.4 | 1.0 | 3 | 0 | 3 | 18 |
| speed | 3.0 | 2.6 | 0.8 | 3 | 8 | 12 | 1 |
| slider | 2.5 | 2.4 | 0.9 | 3 | 9 | 8 | 4 |

Table 7: Participants' preferences between their most favorite (1) and least favorite (4) technique to control the gain factor.

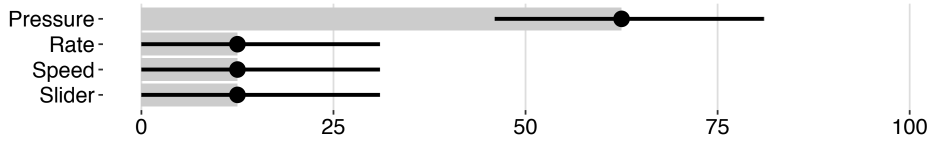


Figure 52: Percentage of times of each technique to be named the number one favorite. Error bars: 95% bootstrapped CIs.

such manipulations–one that is independent from the otherwise dominant channels such as tactile and tangible input. Our first experiment guided our interaction design and the specific pressure mapping we used, while the second experiment provided clear evidence for the advantages of the new design over other types of input.

One of the most important insights we derive from our experiments is that the use of pressure input allowed our participants, in particular, to focus on their 3D manipulation task without the need to constantly reflect the interaction mapping (as it was the case for speed-based and rate control) and without the need to constantly change their interaction focus to be able to interact with a separate widget on the display (like it was necessary for slider-based control). We argue that our participants were thus more effective in their interaction (better performance), without pressure-based control causing any additional cost on workload or fatigue.

In the work presented here, we used a specific back-of-device design to enable pressure-based interaction. While we believe that this setup has advantages with respect to the ergonomics of the interaction with the tablet and the use of screen real estate, the general use of pressure as an input channel for gain factor control does not require the use of such a back-of-device design. Input could thus also be provided on the front of the device—and there are already commercially available devices that offer such display-based pressure sensing. Moreover, due to the specific character of the gain factor control that only requires the input of differences—and not of precise, absolute input values—it is also possible to use existing pseudo-pressure sensing (Arif and Stuerzlinger, 2013; Arif et al., 2014) which could be explored in the future.

This chapter thus provides guidelines to implement gain factor control for 3D manipulations and other forms of interaction, for a variety of mobile devices. As such, the work presented in this chapter can give more precise control of tangible manipulations of mobile devices with the use of an other input paradigm that can be sensed with no (pseudo pressure) or almost no specific hardware (**R3**) and is thus readily available. The results presented in this chapter may also be generalizable to the control of other scalar values where only relative changes are important and constant visual feedback is provided.

# 7

# CONCLUSION

The work presented in this thesis takes the first steps towards an interaction continuum for the visualization of three-dimensional datasets. Such a continuum of interaction can be achieved if the three different requirements exposed in Chapter 1 are met. These requirements were:

**R1**: It needs to be possible to connect and sync several devices together.

**R2**: It needs to be possible to use several interaction paradigms to solve a specific problem.

**R3**: Both the first and second requirements should be met in an easy-to-maintain, easy-to-integrate, and affordable devices and setups.

In our background section (see Chapter 2) we explained how the first two requirements have been extensively studied in the literature. Many research papers have focused on device communication (**R1**) and synchronization and have succeeded in increasing the overall synchronization between multiple devices in several different environments. Concerning the second requirement (**R2**), while it is true that many possible hybrid interaction paradigms have been studied, most of the research done either narrowly focused on hardware and sensing systems or did not try to focus on 3D tasks and visualizations. In most cases, research prototypes relied on expensive or complicated setups that cannot be easily integrated into resarchers' workflow, hence violating **R3**. In this thesis however, we have focused on cheap and easy to use spatially-aware mobile devices. They provide tactile and tangible sensing, which can be combined to suit the needs of visualization practitioners (**R3**).

A first step towards our interaction continuum goal has been to focus on these two interaction paradigms as well as the most common and famous one so far: mouse and keyboard interaction. The aims of Chapter 3 was to better understand the inherent benefits and limitations of each interaction modality for 3D interaction in order to be able to use them for what they do best afterwards. The work presented in this chapter highlighted many different usability parameters and qualitative feedback from a pool of 36 participants. All three interaction paradigms were found to be equally precise, though tangible interaction was faster than tactile interaction, which was in turn faster than mouse interaction. Qualitative feedback highlighted the lack of feeling of precision for tangible manipulation as well as the overall preference for this interaction paradigm. Noteworthy, we also proposed and detailed the implementation of a setup that fits the three interaction paradigms. This setup can easily be integrated with classical workstations and affordable devices (**R3**).

Based on these findings, we gathered that both tactile and tangible interaction could be used in order to manipulate 3D data for exploratory analysis of scientific datasets. We thus proposed in Chapter 4 to combine them on a spatially-aware device and explore the design space for such a hybrid interaction paradigm for 3D visualization tasks. We then designed a first prototype that implemented several of the possibilities highlighted by our design space exploration, and that could fit the studied need of fluid dynamic experts. We then evaluated this prototype with 7 domain experts in an exploratory task. Practitioners highlighted and praised the flexibility offered by our prototype when compared to their classical mouse and keyboard interface, which would still be needed for more in-depth analysis. The modularity of our interface which could easily be integrated in a traditional workplace, made five of our participants want to integrate it into their workflow, thus demonstrating that focusing on both (**R2**) and (**R3**) can lead to practical solutions that are useful and easy to integrate and adopt. As such, the prototype has a good potential to pave the way towards a continuum for interaction in visualization tasks.

In Chapter 5, we then focused on an other essential 3D data visualization task: 3D spatial selection. Such a selection is usually achieved by techniques that rely on a combination of initial 2D-user inputs which are then extended into 3D by algorithms. However, with our hybrid tactile/tangible prototype presented in Chapter 4, we envisionned that a full control could be given to the user. As such, our interaction technique, Tangible Brush, is the only one that does not rely on additional automated computation to derive 3D volume selections. An initial 2D input is made by the user on the tactile screen and the motions of the tablets are then used to extend the selection shape into a selection volume. An evaluation against a partially-automated solution approach highlighted that our fully manual hybrid technique positively impact the selection's accuracy but also results in a higher completion time. The qualitative feedback further highlights the potential of hybrid interaction mappings for visualization tasks.

Building on the findings from Chapter 3 and Chapter 4 that tangible interaction does not provide the same feeling of precision that can be offered by others (mouse or tactile interaction for instance), in Chapter 6, we propose a new hybrid tactile/tangible interaction to improve the precision that can be acquired with tangible manipulations of a tablet. In this chapter, we further explored tactile input before combining it with tangible interaction. We wanted to consider the additional information that human fingers can provide. While positioning information ($x$ and $y$) is used in most cases, we focused on pressure information in this chapter. We use the pressure input to control the gain factor of 3D tangible manipulations on a tablet. Possible mappings and prototypes are described and evaluated through two studies. In a first study we wanted to compare to possible pressure mappings to gain factor values. Taking the best of these two mappings, we then compared our hybrid technique with three common techniques to control gain factor: a regular tactile slider, the speed of the tangible motions of the tablets, and a rate-control mode. This second study highlighted the large preference for pressure-based control of the gain factor and its better performances over the other three possibilities we tested.

Through these four chapters, we have thus focused on easy to integrate and maintain as well as affordable solutions (**R3**) that provide hybrid interaction paradigms (**R2**) for applications linked to visualization tasks. We thus believe that our investigated solutions can pave the way towards more investigations of solutions that would help design and implement the interaction continuum that has been mentioned throughout this thesis.

Nonetheless, a lot of work remains to be done. Several remaining research questions and possible solutions are thus detailed below.

First of all, this thesis has so far focused mostly on tactile and tangible interaction because of the numerous advantages they exhibit (see Section 2.2 for more details). Yet, mouse and keyboard interaction is still predominant in most workplaces and essential to visualization practitioners (see Chapter 4) and cannot easily be combined with our spatially-aware device. In order to be able to integrate the three of them and thus promote the transfer of insights from one platform to the other, one should probably build on the tremendous work that has been done so far to provide middlewares that connect devices (see Section 2.1.1 for instance) and thus work again on the first requirement for an interaction continuum (**R1**).

Second, while the hybrid 3D selection techniques we have described in Chapter 5 is generic and can be applied in many different scientific fields, the hybrid interaction techniques we have developed for fluid dynamics (Chapter 4) have not been explored in other domains. It would be interesting to see how this work could help practitioners in other domains but also to try and adapt the hybrid interaction technique to better suits the needs of other domains.

Third, throughout the three years of this thesis work, VR headset have garnered a lot of attention and are now affordable products that could also be easily integrated with classical workstations without high-maintenance or setup costs. The work conducted in this thesis mostly focus on classical 2D rendering on regular displays but made use of the three-dimensionality of the data nonetheless through the use of tangible interaction. It thus appears that with VR headsets, the possibilities and capabilities of tangible interaction would only increase. One could then wonder how our hybrid interaction techniques should evolve for such cases. Indeed, with these affordable headsets the mismatch between input and output spaces (mentioned in Chapter 5) could be solved and the hybrid interaction techniques we have designed could perhaps be more efficient. In such contexts, one could explore stereo visualization combined with tangible (i.e., pseudo-stereo input) and tactile (i.e., mono input). As a consequence, the mapping between the different spaces for both input and output should be investigated.

Finally, while we have mentioned collaborative work (in particular in Chapter 4), we have not investigated how our work on hybrid interaction paradigm could affect co-located collaborative work on 3D data visualization. Indeed, in the setup we have presented in both Chapter 4 and Chapter 5, the additional large screen could be used to provide tactile input as well. Such a configuration is currently not supported by our hybrid setup. Particular attention could thus be placed on how to correctly sync both devices and handle concurrent manipulations (**R1**). This aspect is specifically important for domain experts because the sense-making process of 3D datasets can also be done collaboratively. This further highlights the fact that, while we have focused on two of the requirements presented in this thesis (namely **R2** and **R3**), all of them play a role in the building of an interaction continuum for visualization.

We thus believe that the work presented in this thesis, thanks to its focus on hybrid interaction paradigms for 3D visualizations (**R2**) and its use of affordable and readily available devices (**R1**) is a first step towards the creation of an interaction continuum for 3D data visualizations. By combining the effort we presented in this work to the already accomplished work on the synchronization of several devices (**R1**) and the studies on hybrid interaction paradigms (**R2**) we believe that this continuum of interaction can, in general, be achieved. For the specific case of 3D visualization however, it seems that other efforts still need to be done.

In particular, what matters with visualization is to be able to *gather*, *share* and *transfer* insights on the presented data. The scenario which we envisioned throughout this thesis included all three possibilities. We focused in this work on the possibilities that an interaction continuum can leverage for *gathering* data, which is a first step. We have also partially tackled the *sharing* as, with our prototypical setup, experts can easily interact with the tablet and change the view on the large display for teaching or sharing purposes.

Still, a focus should be placed on the concept of sharing and transferring. On the one hand, *sharing* could be done with colleagues or students but also with the world. For this purpose, we believe that a specific focus should also be placed on syncing datasets and their gathered insight in an approach very similar to a git/svn one. With such an approach, transitions between several setups and collaborations would be improved: scientist would not have to share notes or save on a usb stick to transfer knowledge or specific views, but could simply use a branch/merge approach with an online tool to update their work. In a way, one could see this work as going even further with the linking and syncing of devices (**R1**). By enabling such an easy sharing process, it would be easy for researchers to simply put their findings online in an accessible-to-the-public-way if needed. On the other hand, while *transferring* could be achieved with the kind of technology we have just described, we believe that, to really leverage the possibilities of all devices and interaction paradigms, domain researchers should also be able to transfer their insights/views/captured data to the software they generally rely on for further in-depth analysis with scripts or GUIs such as Matlab or Paraview (see Chapter 4). To achieve this, focus should be placed on adapting existing softwares to this possibility to *share* and *transfer* data and insights offered by, for instance, the branch/merge approach we have just described.

In summary, we have demonstrated that a continuum of interaction had interesting benefits for 3D data visualization. However, we have but scratched the surface of all the possible hybrid interaction techniques and much work remains to be done in order to create a proper interaction continuum as we have defined in Chapter 1. Our focus on hybrid paradigms (**R2**) and affordable systems (**R3**) combined with the already large amount of work on device synchronization (**R1**) are necessary initial steps towards the creation of an interaction continuum. But for this continuum to be even more efficient for 3D data visualization, much work remains to be done (as highlighted before). We hope that this thesis work will inspire the creation of more hybrid interaction techniques for 3D data visualization and also emphasize the needs for approaches that enhance the sharing and transferring of insights gained from 3D data visualization.

# Part I

# APPENDIX

# A

# ON STATISTICAL ANALYSIS AND INTERPRETATION

All the statistical analysis conducted in the papers in which I was a co-author are presented with Confidence Intervals and propose nuanced interpretation. The goal of this appendix is to explain our motivations for such a method as well as how to use it in papers. By doing so, we hope that readers will be able to make the most of the graphics presented in this work.

The following work is mostly based on work previously published at Alt.IHM in French. A more in-depth example on how to conduct data analysis and interpretation with real study data is provided in the paper and can also be found at http://www.aviz.fr/ci/. In the following lines, the use of *we* refers to the authors of the paper, Lonni Besançon and Pierre Dragicevic.

This appendix first exposes our motivations and the main reasons why this thesis and its attached publications made use of estimation techniques. Then, it provides highlights the central role of interpretation in science. Finally, we focus on how to read, interpret figures using confidence intervals.

## A.1 MOTIVATIONS

### A.1.1 *Limitations of the Traditional NHST*

In addition to the wrong interpretations it often causes, binary significance testing tends to generate a false impression of confidence in scientific publications. Still, NHST (Null Hypothesis Significance Testing) has been considered as a central tool of most scientific communications. However, it has come under heavy criticism in different scientific domains. NHST limits have been highlighted by statisticians (Baker, 2016; Cumming, 2014), but also recently by researchers of the HCI community as well (Dragicevic et al., 2014; Dragicevic, 2016; Kay et al., 2016a; Kay et al., 2016b).

NHST is a statistical tool used to return a binary answer thus removing part of the data and possibly leading to wrong interpretations (Dragicevic, 2016). Results are categorized into being statistically significant or not whether the value of $p$ is lower or greater than a given threshold (usually 0.05). This vision of statistical results, falsely comforting is simplistic: it removes all the nuances that may exist in the collected data. Indeed, the evidence strength in the data is by nature continuous. With NHST, a value $p1 = 0.052$ will be considered as a not statistically significant while a value $p2 = 0.048$ will be statistically significant. Similarly, let us suppose we collected two additional p-values: $p3 = 0.3$ (not statistically significant) and $p4 = 0.005$ (significant). It does not seem logical to treat $p1$ and $p3$ similarly on the one hand and $p2$ and $p4$ on the other hand since $p1$ and $p2$ are by far the most similar results.

Blindly applying a threshold to statistical significance also raises other problems and paradoxes such as the p-hacking and the different publication biases (Amrhein et al., 2017; Dragicevic, 2016). Some researchers who still wanted to keep using p-values suggested to forget about the threshold (Amrhein et al., 2017; Lew, 2013) thus considering p-values as a continuous measure.

### A.1.2 p-*Value Limitations*

Even if one was to considered p-values as a continuous measure, the information brought by p-values themselves is fairly limited. Indeed, p only focuses on the nul hypothesis (e. g.the absence of effect or difference) and its converse (e. g.there is an effect or a difference). By doing so, p only allows us to determine the certainty with which we can conclude that there is an effect or a difference. The direction of the effect and its magnitude are however not given by p. Trying to counter that by only reporting on the sample mean (without interval) also leads to wrong interpretations: a significant p-value does not infer the accuracy of the sample mean (Dragicevic, 2016).

### A.1.3 *The Benefits of Confidence Intervals*

Using confidence intervals (CIs) allows on the other hand not only to communicate about statistical significance but also allows readers to infer what effect magnitude are likely or not. To begin with, a graphical analysis of confidence intervals can be simplified to the reasoning done with p-value interpretation: the further a confidence interval is from 0, the more the results are statistically significant (Krzywinski and Altman, 2013). Furthermore, this graphical representation also indicates the effect size. In particular, confidence intervals provide an approximate maximum threshold to the effect size. Therefore, even a result considered as not significant with p way above the threshold can be interpreted: if the confidence interval is small, we can conclude that the effect is negligible. Last but not least, confidence intervals are more easily read and understood than p-values numbers and they do not convey a false impression of accuracy and certainty (Dragicevic, 2016).

However, even though confidence intervals are represented in a binary fashion (a value is withing the interval or not) using estimation means that they should not be interpreted in a binary way. Interpreting that results are significant (or not) based on the fact that the confidence interval contains (or not) the value 0 is basically coming back to a disguised NHST interpretation.

### A.1.4 *The Central Role of Interpretation*

The subjective nature of interpretations when using estimation technique is very much critiqued and a central barrier to its use. However, this subjectivity is inevitable and HCI researchers are, probably more than others, able to understand that statistical analysis should put more emphasis on the human perception.

Indeed, HCI focuses on human beings, their perceptions, their capabilities and their needs. HCI research strives to assist, to augment human beings but never to replace them. Still, to analyse the results of an experiment conducted by a human being with other human beings, HCI researchers rely on algorithms and statistical tools to find a binary response. This striking opposition is still seen in most of published work in the best HCI conferences.

Without questioning these publications and their findings, it would be more interesting to integrate human interpretation in the loop of result analysis.

There are several definition of statistics. One of them given by the Merriam-Webster is "a branch of mathematics dealing with the collection, analysis, interpretation, and presentation of masses of numerical data."(Merriam-Webster, 2017). The word *interpretation* itself, comes from old french *interpretacion* which is now in modern French *interpretation* (Dictionary, 2017). According to the very famous French dictionnary Larousse, one possible definition of interpretation is the act that consists in giving a personal meaning within a range of possible meanings (Larousse, 2017). It would then seem that, by definition, statistical analysis should rely on personal, and hence subjective, interpretation of results. This subjective interpretation can occur at three different levels:

1. The author's own personal interpretation of their results in their communication (paper or presentation).
2. The reviewer's level when evaluating a submission.
3. The reader's level, in order to help him/her decide whether results should be used in the work conducted or instead discussed.

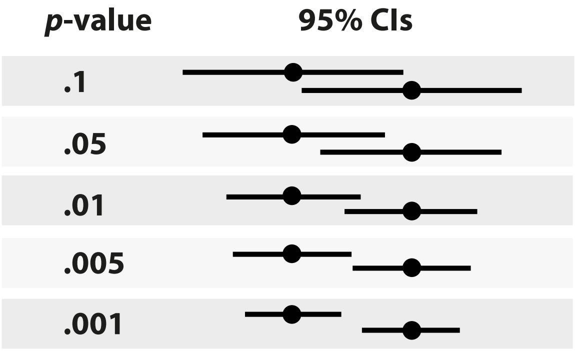
Each of these "users" has its own experience, expertise domains, goals... A human-based interpretation would then allow each and every one to evaluate the importance, the strength and the impact of results within a specific context.

Human-based interpretation also highlights the inherent uncertainty of experimental results and their statistical analysis (Dragicevic, 2017; Giner-Sorolla, 2012). Highlighting statistical uncertainty also encourages replication, crucially important activity in science. Yet, in spite of its importance, replication studies are still very hard to publish. A potential explanation is that the current presentation of statistical results demonstrate a feeling of confidence, certainty about the viability of the results. A group of researchers then trying to replicate a study will only confirm or disprove known results and their communication will very likely be rejected for that reason. Conversely, an approach based on estimation could emphasize the inherent iterative nature of user experiments.

## A.2 INTERPRETING CONFIDENCE INTERVALS

We first need to explain what confidence intervals are. There are several exact definitions of confidence intervals and several approximate definitions that are still useful (Cumming, 2014; Dragicevic, 2016). A N% confidence interval is an interval capturing the true value (the sample mean) N% of time when replicating the same experiment. That means that a 95% confidence interval capture all the values of the sample mean that would be obtained for 95 experiment out of 100.

A more intuitive interpretation of confidence interval, the Bayesian interpretation, offers an reasonable approximation which is useful in most cases:



(a) b

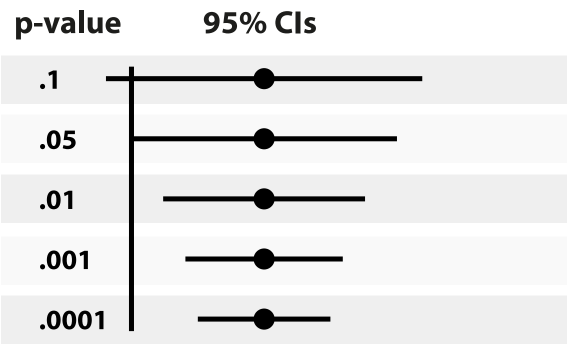
Figure 53: CIs and p-values equivalence for independant samples (Krzywinski and Altman, 2013).

a confidence interval indicates the range of possible values for the sample mean (Cumming, 2014; Dragicevic, 2016; Schmidt et al., 1997). In order to keep on discouraging the binary interpretation, it should be mentioned that values outside of the confidence interval are still possible and that values close to the current estimation point (sample mean) are more likely than values on the ending of the interval.

Oftentimes, it is necessary to interpret the gap or the overlap between two confidence intervals (e. g.the sample mean of technique A and technique B). Cumming (2014) gives a simple rule: for two independent variables (between subject), if the overlapping between two confidence intervals is less than a third of the average length of the two intervals, then the difference is significant with p = 0.05. The danger of such an approach is to get back to binary thinking. Krzywinski and Altman (2013) thus proposed a figure Figure 53 to interpret confidence interval overlapping as different values of p (once again, these only holds for between-subject experiments).

The 0.05 threshold is useful given its importance in the history of statistics. However, the overlapping must be interpreted in a nuanced fashion instead of strict thresholds. The gap or the overlapping between confidence intervals allows to continuously quantify the certainty with which we can state that a difference exist between the two means. The closer they get (and the more they overlap) the weaker the evidence. A huge overlapping should lead to the conclusion that there was no evidence (but absolutely not to the conclusion that the means are the same). We can thus with confidence intervals show that some results may be more certain than others and more generally embrace the uncertainty of our results.

While confidence intervals on sample means can already be quite informative as we have explained before, it is often recommended to go further and report on confidence intervals on effect size. An effect size allows researchers to quantify the answer to their research questions with a unique value that does not require to compare sample means (Cumming, 2014). For instance if the goal of the study were to compare two techniques, the effect size allows to quantify the performance difference between these two techniques. The interpretation must then focus on the effect size and its confidence interval



(a) b

Figure 54: CIs overlap with the nul hypothesis and it p-value equivalent.

Figure 54, in addition to sample means (especially if the study is within subject).

An effect size can be simple or standardized. The later is rarely needed and even discouraged (Baguley, 2009), so that it is often enough to compute and report simple effect size. A simple effect size can be a difference or a ratio between two means with their associated confidence intervals. A difference is ideally and usually presented on a plot with a 0 origin, while a ratio would ideally be presented with a 1 origin. In both cases, the confidence interval will facilitate the visual interpretation of the effect direction as well as the range of possible magnitudes.

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université PARIS-SACLAY

ÉCOLE DOCTORALE
Sciences et technologies
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**Titre :** Un continuum d'intéraction pour la visualisation de données 3D

**Mots clés :** Manipulations 3D, Interaction, Visualisation, Interaction Tactile, Interaction Tangible

**Résumé :** Un nombre croissant de paradigmes d'interaction et de dispositifs ont été développés et étudiés pour les manipulations 3D. Ce développement bénéficie, en particulier, aux domaines scientifiques tels que la visualisation qui s'appuie sur la manipulation de données 3D. De nombreuses études ont démontré les avantages de chacun d'entre eux pour des tâches spécifiques liées à la visualisation. Pourtant, les interfaces graphiques classiques ainsi que la souris et les claviers prédominent toujours dans la plupart des environnements interactifs: de tels environnements sont toujours utiles pour des tâches spécifiques et parce qu'ils sont facilement disponibles et accessibles par rapport aux nouveaux paradigmes d'interaction et aux dispositifs innovants.

Contrairement à l'approche habituelle qui consiste à créér ou étudier un nouveau paradigme, une nouvelle technique ou un nouveau dispositif d'interaction, les travaux présentés dans cette thèse ouvrent la voie à un continuum d'interaction: la possibilité de passer d'un paradigme d'interaction à l'autre et de combiner deux ou plusieurs paradigmes d'interaction pour en tirer profit. Pour atteindre cet objectif, nous prenons plusieurs mesures.

Tout d'abord, en se basant sur l'observation que la souris et le clavier, l'interaction tactile et l'interaction tangible sont maintenant des normes ou se rapprochent d'être des paradigmes d'interaction standard pour les cas d'utilisation occasionnelle ou spécifique, cette thèse étudie et compare leurs avantages et limites inhérents aux manipulations 3D.

Sur la base de ce travail, nous créons ensuite un paradigme d'interaction hybride tactile et tangible. Basé sur les besoins de la visualisation scientifique pour la mécanique configuration facile à maintenir, facile à intégrer et abordable. Il fournit les premières des fluides, nous mettons en œuvre des techniques spécifiques d'interaction exploratrice 3D avec le paradigme hybride et les évaluons avec des experts du domaine. La mise en œuvre prototypique de ce paradigme hybride est une tablette tactile capable de quantifier ses propres mouvements (rotations et translations). Sur la base des retours d'expérience des experts du domaine, une telle combinaison est plus flexible que l'état de l'art et permet des manipulations 3D précises.

Avec le potentiel de ce paradigme hybride, nous abordons ensuite la tâche complexe de la sélection des sous-ensembles 3D ---une étape initiale majeure pour la compréhension des données. Alors que la sélection de sous-ensembles 3D est généralement effectuée avec une entrée 2D initiale étendue ultérieurement par la machine, notre combinaison d'interactions tactiles et tangibles permet aux utilisateurs d'avoir une technique de sélection entièrement manuelle avec la même tablette : un lasso 2D peut être dessiné avec une entrée tactile qui peut ensuite être étendue en 3D lors du déplacement de la tablette. Non seulement cette combinaison comble un vide dans la taxonomie des techniques de sélection de sous-ensembles 3D, mais qui plus est, elle est plus précise que les solutions partiellement automatisées, quoique plus lentes.

Enfin, en nous appuyant sur l'observation selon laquelle une interaction tangible avec un dispositif localement couplé pourrait nécessiter des ajustements de facteur de gain, nous proposons d'utiliser un aspect spécifique de l'interaction tactile, la détection de pression, pour contrôler les facteurs de gain des manipulations tangibles.

Les travaux présentés dans cette thèse démontrent donc le potentiel d'un continuum d'interaction pour la visualisation en proposant des paradigmes d'interaction hybrides dans une étapes nécessaires pour un continuum d'interaction qui, espérons-le, inspirera la création de plus de techniques d'interaction hybrides pour l'interaction de données 3D.

**Title :** An interaction continuum for 3D dataset visualization

**Keywords :** 3D Manipulations, Interaction, Visualization, Tactile Interaction, Tangible Interaction

**Abstract :** An increasing number of interaction paradigms and devices are being developed and studied for 3D manipulations.
This development benefits, in particular, scientific domains such as visualization which rely on manipulation of 3D data.
Numerous studies have proven the benefits of each one of them for specific tasks involved in visualization. Yet, classical graphical user interfaces as well as mouse and keyboards still prevail in most interactive settings: such environments are still useful for specific tasks and because they are readily available and accessible when compared to innovative interaction paradigms and devices.

In contrast to the usual approach to create or study a new interaction paradigm, technique, or device, the work presented in this thesis paves the way towards an interaction continuum: the possibility to transition between and combine two or more interaction paradigms to benefit from their inherent advantages. To achieve this goal we take several steps.

First, building on the observation that mouse and keyboard, tactile interaction and tangible interaction are now standards or are getting close to being standard interaction paradigms for casual or specific use cases, this thesis studies and compares their inherent advantages and limitations for 3D manipulations.

Based on this work, we then create a hybrid tactile/tangible interaction paradigm. Based on the needs of scientific visualization for fluid dynamics, we implement specific 3D explorative interaction techniques with the hybrid paradigm and evaluate them with domain experts. The prototypical implementation of this hybrid paradigm is a tactile-enabled and spatially-aware tablet. Based on the feedback from domain experts, such a combination is more flexible than the state of the art and still facilitates precise 3D manipulations.
With the potential of this hybrid paradigm, we then tackle the complex task of 3D subsets selection---a major initial step for data understanding. While 3D subset selection is usually conducted with an initial 2D input later extended by the machine, our combination of tactile and tangible interaction allows users to have a fully manual selection technique with the same spatially-aware tablet: a 2D lasso can be drawn with tactile input which can then be extended into 3D when moving the tablet. Not only does this combination fill in an empty space in the taxonomy of 3D subset selection techniques, but we also found it to be more precise than partially-automated solutions---albeit being slower.

Finally, building on the observation that tangible interaction with a locally-coupled device might need gain factor adjustments, we propose to use a specific aspect of tactile interaction, pressure-sensing, to control the gain factors of tangible manipulations.

The work presented in this thesis thus demonstrates the potential of an interaction continuum for visualization by proposing hybrid interaction paradigms in an easy-to-maintain, easy-to-integrate, and affordable setup. It provides the necessary initial steps for an interaction continuum that will hopefully inspire the creation of more hybrid interaction techniques for 3D data interaction.

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