Supporting Reflection and Classroom Orchestration with Tangible Tabletops

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PAR

Lenh Hung Son DO

acceptée sur proposition du jury:

Prof. A. Wegmann, président du jury
Prof. P. Dillenbourg, Dr P. Jermann, directeurs de thèse
Dr D. Gillet, rapporteur
Dr K. Inkpen, rapporteur
Prof. E. Klopfer, rapporteur

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To the memory of my mother and my grandfather. . . .
To my family. . . .
To Anh and our coming Panda. . . .

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Lastly, I'd like to dedicate this thesis to my beloved mother and grandfather in Heaven. I hope I made you proud.

Lausanne, January 2012

Abstract

Tangible tabletop systems have been extensively proven to be able to enhance participation and engagement as well as enable many exciting activities, particularly in the education domain. However, it remains unclear as to whether students really benefit from using them for tasks that require a high level of *reflection*.

Moreover, most existing tangible tabletops are designed as stand-alone systems or devices. Increasingly, this design assumption is no longer sufficient, especially in realistic learning settings. Due to the technological evolution in schools, multiple activities, resources, and constraints in the classroom ecosystem are now involved in the learning process. The way teachers manage technology-enhanced classrooms and the involved activities and constraints in real-time, also known as *classroom orchestration*, is a crucial aspect for the materialization of reflection and learning.

This thesis aims to explore how educational tangible tabletop systems affect reflection, how reflection and orchestration are related, and how we can support reflection and orchestration to improve learning. It presents the design, implementation, and evaluations of *three tangible tabletop systems* - the DockLamp, the TinkerLamp, and the TinkerLamp 2.0 - in different learning contexts.

Our experience with these systems, both inside and outside of the laboratory, results in an insightful understanding of the impacts of tangible tabletops on learning and the conditions for their effective use as well as deployment. These findings can be beneficial to the researchers and designers of learning environments using tangible tabletop and similar interfaces.

Keywords: Tangible tabletops, Tangible User Interfaces, Tabletop Interfaces, Augmented Reality, Computer-Supported Collaborative Learning, Vocational Training.

Résumé

Les surfaces interactives tangibles ont été amplement démontrées comme capable d'améliorer la collaboration, la motivation et de permettre de nombreuses activités passionnantes, particulièrement dans le domaine de l'éducation. Toutefois, un doute subsiste quant à savoir si les étudiants bénéficient vraiment de leur utilisation dans les tâches nécessitant un haut niveau de réflexion.

De plus, la plupart des surfaces interactives tangibles existantes sont conçues comme des systèmes ou des appareils indépendants. De plus en plus, cela ne suffit plus, surtout dans des environnements d'apprentissage réalistes. Conséquences de l'évolution technologique dans les écoles, différentes activités, ressources et contraintes sont maintenant impliquées dans le processus d'apprentissage. La façon dont les enseignants s'occupent des classes riches en technologies et des activités et contraintes en temps réel, appelée *orchestration*, devient cruciale pour la concrétisation de la réflexion et de l'apprentissage.

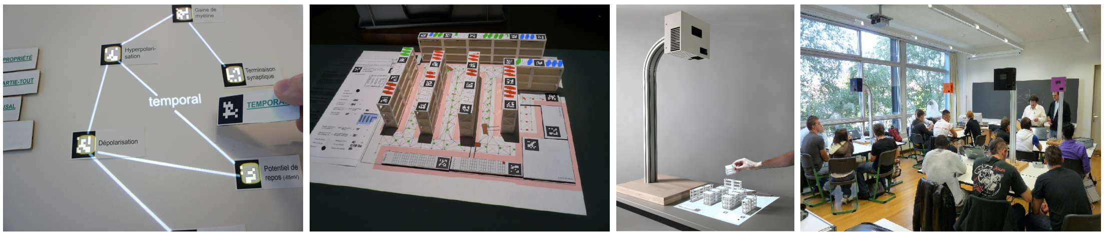
Cette thèse a pour but d'explorer comment on peut soutenir la réflexion et l'orchestration d'une classe avec des surfaces interactives tangibles éducatives. Elle présente la conception, la réalisation et les évaluations de trois surfaces interactives tangibles : la DockLamp, la TinkerLamp et la TinkerLamp 2.0 dans des contextes d'apprentissages différents.

Notre expérimentation avec ces systèmes, à la fois en et hors laboratoire, résulte en une compréhension de l'impact des surfaces interactives tangibles sur l'apprentissage, des conditions pour leur utilisation efficace, ainsi que de leur déploiement. Ces résultats peuvent être bénéfiques aux chercheurs et concepteurs d'environnements d'apprentissage utilisant une surface interactive, une interface tangible, ou similaire.

Keywords : Surfaces Tangibles, Interfaces Tangibles, Surface Interactives, Réalité Augmentée, Apprentissage Collaboratif Supporté par Ordinateur, Formation Professionnelle.

Contents

1 Introduction



1.1 Context

Tabletop technologies have recently attracted significant interest from Human-Computer Interaction (HCI) researchers. An interactive tabletop is a computer interface that works atop a table. It is most often a horizontal surface that is large enough to accomodate several users interacting simultaneously. The visual output is displayed on the tabletop surface by LCD screens or by projectors placed above or below the surface. User interactions with tabletops usually occur through a direct mechanism via touch, multi-touch, or physical objects.

This thesis focuses on a subset of tabletop technologies: tangible tabletops. In tangible tabletops, users issue commands to a computer through interactions with physical objects on a tabletop (Shaer and Hornecker, 2010; Ullmer et al., 2005). The system provides graphics and/or sound as feedback. Tangible tabletops combine the benefits of both Tangible User Interfaces (coined by Ishii and Ullmer (1997)) and tabletop technologies.

- Tangible User Interfaces enable direct and concrete interactions with a physical representation of the digital object. These interactions are easy to learn and use as they take advantage of the intuitive knowledge that people have of everyday objects (Fitzmaurice et al., 1995; Ullmer and Ishii, 1997).

- Tabletop interfaces provide visual feedback directly on the input space, creating engaging and immersive environments where input and output are merged onto the same artifacts. They also offer a shared workspace where a group of people can interact and manipulate simultaneously (Wellner, 1993; Dietz and Leigh, 2001).

Tangible tabletop interfaces present the unique opportunity of bringing computer support to traditional face-to-face collaborative tasks such as meetings, brainstorming, and another important activity of our interest, learning. Tangible tabletops have been researched and used across many educational contexts (Horn et al., 2009; Price et al., 2009; Piper et al., 2002; Zuckerman et al., 2005b).

As any other novel technology, the tangible tabletop interface has resulted in many studies as well as expectations regarding its effectiveness for learning. Students can interact directly with the interface by touching and manipulating objects. This mode of interaction enables hands-on experience and facilitates the solving of tasks in which concrete manipulations are important for solving the problem (Price and Rogers, 2004). Tangible tabletops also help group members be better aware of each other's actions and facilitate more participation, which, in turn, may support more learning (Rogers et al., 2009; Stanton et al., 2002; Hornecker et al., 2008; Antle et al., 2009).

However, from a Computer-Supported Collaborative Learning (CSCL) perspective, technologies have no intrinsic pedagogical effects. According to this viewpoint, the technology alone does not improve learning (Dillenbourg, 2008). Instead, the CSCL literature stresses that designers and developers need to have an understanding of how learning takes place around the technology and with which affordances the technology can be used to build effective applications.

In fact, the truth is that tangible tabletop interfaces, by themselves, cannot turn any ordinary students into smart, motivated, knowledgable ones. There are a number of other factors that contribute to the learning outcomes, including the following: pedagogical scenarios; how teachers appropriate the tabletop interface; how the tabletop engages the learners; how compatible it is to the many practical constraints in a learning environment, etc. If not designed properly, tangible tabletop environments will not be effective.

The crossing of the two domains, HCI and CSCL, which each have different approaches, has created an interesting challenge. On the one hand, HCI researchers are pushing for an ever-growing set of tangible tabletop applications in learning contexts. On the other hand, the CSCL community indicates a crucial need to explore the interface and its support for learning first, before developing further applications.

In order to take advantage of tangible tabletops for learning, we need to fully understand the situations in which they benefit the learners and teachers. There has been a lack of design guidelines to guide the development of tangible tabletops in learning contexts with tasks requiring a high level of reflection. The goal of this thesis is to explore this issue, examining the effects of tangible tabletops on learning to build sample applications. It aims to advance our understanding of how to design effective tangible tabletop systems for learning.

1.2 Reflection and Orchestration

1.2.1 Reflection

Research in education and CSCL, e.g. (Ackermann, 1996; de Jong, 2010; Davis, 2003; Quintana et al., 2001) has argued that *reflection* is very important for learning. While there have been various definitions of reflection, it is generally agreed that reflection requires critical thinking to examine presented information and ponder experiences, question their validity, and draw conclusions based on the resulting ideas (Hoyrup and Elkjaer, 2006). With reflection, students can derive abstractions about their thinking process and compare it with their earlier performances, or to the performances of others. This enables learners to gain important insights and experiences that can increase their thinking and learning.

Despite these advocacies, current practice in interaction design with respect to explicit design for reflection still leaves much to be desired. Research on tangible tabletops have mostly focused on their “motivating” and “tangible” benefits (Horn et al., 2009; Xie et al., 2008; Price, 2008) and have not paid enough attention to reflection. The benefits of using tangible tabletop technologies in high-level tasks (i.e tasks whose goal is to require reflection and high-level thinking, rather than just manipulating objects) have not been clearly established. Of the few applications that have been evaluated for this purpose (Zuckerman et al., 2005b; Fernaeus and Tholander, 2006; Fjeld et al., 2007), little evidence has been provided that they offer more positive learning outcomes compared to more conventional interaction techniques such as using a mouse on a desktop computer.

This thesis addresses this issue of reflection, aiming to explore the importance of reflection for educational tangible tabletop systems as well as how we can support reflection to improve learning in this context. Our objective is to strengthen the research base in both the CSCL and HCI community by showing that reflection should be carefully considered and supported in order to make tangible tabletops effective for reflection.

1.2.2 Orchestration

CSCL has recently evolved from research about purely collaborative tasks in small groups to integrative scenarios that include many levels of interactions, including individual learning, teamwork, and class-wide activities. This new integrative approach, together with the technological evolution in schools, has given rise to a new trend in CSCL research about orchestration.

While *orchestration* has occasionally been mentioned in the literature (Tomlinson, 1999; DiGiano and Patton, 2002), it has not been until recently that orchestration has received extensive attention from the CSCL community (Dillenbourg et al., 2009; Kollar et al., 2011; Dillenbourg et al., 2011). Orchestration refers to the real time classroom management of multiple activities and constraints conducted by teachers. It emphasizes the classroom constraints and the role of teachers in managing these technology-enhanced classrooms.

Orchestration technologies are tools that assist the teachers in their task of orchestrating integrated classroom activities. While a few early examples of technologies designed to support orchestration have started to emerge (Alcoholado et al., 2011; AlAgha et al., 2010), there has been little work exploring the requirements and guidelines for the design of such technologies in real classroom settings.

The fast development and maturity of tangible tabletop technology has made it possible for its integration into real settings, including classrooms. Designers and practitioners now, more than ever, need a set of guidelines as to how to effectively develop this technology to support classroom orchestration.

1.3 Research Objectives

The principal objectives of this research are as follows:

Understanding learning around tangible tabletops. The evaluations of educational tangible tabletops have mostly emphasized the motivating and engaging nature of the interface. There is a general lack of awareness about the effects of tangible tabletop technologies on learning tasks of a higher level of abstraction and reflection.

Our first research objective is concerned with this issue. We aim to examine *how a tangible tabletop interface affects students' learning outcomes, processes and reflection during high-level learning activities.*

Building effective tangible tabletops for the classroom. Our research efforts are directed toward building tangible tabletop systems in an authentic classroom setting and understanding this technology-enhanced environment. Throughout the thesis, we aim to investigate *the conditions for the effective development, use, and deployment of tangible tabletops in the classroom.*

In our literature review, there was a common assumption among different works that a single, stand-alone device or software interface was adequate. This assumption is no longer sufficient, as the modern classroom has become more and more complex with multiple learning resources, activities and technologies. In light of the orchestration approach, we did not limit ourselves to developing a stand-alone application. We were open to a broader context around the tangible tabletop, exploring other complementary components that can be utilized in combination with the interface to support learning.

Supporting teachers and classroom orchestration. Since the learning environments are becoming open and complex, teachers face a more intensive and challenging task when orchestrating the class. Of course, to support or empower their role in the class does not mean providing them with an overwhelming list of technological features. It is about giving teachers a subtle leadership, an ability to improvise the pedagogical scenarios in real-time.

The authentic classroom setting of our research allows us to explore this issue of orchestration. The aim is to investigate *how classroom orchestration is related to reflection, how tangible tabletop technologies could support classroom orchestration* and present design implications for future developments of such technologies.

1.4 Thesis Overview

This thesis argues that the tangible tabletops designed for learning, especially in real classroom settings, should consider carefully supporting reflection and orchestration. It also presents our experience in developing such technologies. The three main statements that the thesis delivers are the following.

- While tangible tabletops provide potential grounds for fruitful interactions, e.g. more concrete manipulations and more exploration, they can also potentially create a lack of students' reflection.
- In a classroom setting, teacher's orchestration is crucial and is related to reflection. Supporting orchestration can be a solution to the lack of reflection from students.
- Supporting both reflection and orchestration in a classroom setting requires the provision of an ecology of learning tools and resources, facilitating a fluid transition between different activities at different levels and contexts (individual, group, class, real-world).

In order to make these statements, the thesis:

- Describes the use of tangible tabletop technology in learning settings and identifies design requirements for applications to support learning around tabletops. We started by designing two tangible tabletops, the **DockLamp** and the **TinkerLamp**, and then evaluated how learning takes place around these two systems in both lab and classroom settings.
- Builds a full-scale tangible tabletop environment, called the **TinkerLamp 2.0** system, that puts the understanding and design requirements acquired in the first step into practice. This system provides support for reflection and classroom orchestration. We achieved this objective by following an iterative design process and making design choices based on user feedback, insights from our studies, and implications from HCI and learning science research.
- Demonstrates the effectiveness of TinkerLamp 2.0 according to its design goals and proposes a set of design guidelines for future systems based on the findings.

The thesis focuses on three factors that are different from most related works.

- First, we focus on a different student population, vocational apprentices and university students, instead of younger children.
- The tasks used in the thesis were high-level problem-solving tasks.
- The studies range from a lab setting to a classroom setting with realistic learning scenarios, helping us gain more perspectives about the findings.

While our lessons focus on tangible tabletops in authentic classroom settings, they can be applied to other multi-touch tabletop systems, Tangible User Interfaces, and other technologies in the classroom in general.

1.4.1 Research Methodologies

Triangulation of approaches

Three approaches guide this thesis work: empirical findings, technological developments, and theoretical perspectives. We utilized the triangulation framework to navigate among these approaches (Mackay and laure Fayard, 1997). The framework promotes the use of triangulation, the use of more than one research approach to address the same question. It argues that triangulation across scientific and design disciplines, i.e., observation, design of artifacts, and theory is more likely to be beneficial. Consequently, we went back and forth among our three approaches to validate our findings: understanding systems in use, deriving theoretical perspectives, and generating technology tools.

Design-based research

Because a main goal of this thesis is to design and explore the effects of tangible tabletops in real classroom settings, we also followed a Design-based Research approach in the design process of TinkerLamp and TinkerLamp 2.0 systems. This method is rooted in the field of learning sciences which emphasizes evaluations of learning environments in their actual context of use.

According to Wang and Hannafin (Wang and Hannafin, 2005), Design-based Research is defined as:

> a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories (p.6).

Design-based research underlines the importance of context when developing educational technologies. It promotes in-the-wild observations and evaluations to capture the complexity of authentic settings, as opposed to lab experiments. Therefore, we worked in close relationship with the teachers at vocational schools throughout the project and evaluated the technologies in various field observations and studies.

A related design approach that we used to complement the Design-based research is Participatory design. Muller (2003) defines Participatory design as *"a set of theories, practices, and studies related to end-users as full participants in activities leading to software and hardware computer products and computer-based activities"*. Participatory design suggests the integration of users in the design loop, allowing them to make decisions at any step: problem definition, idea generation, prototyping, or evaluation. This approach is compatible with our research objectives and Design-based research in that we could let the teachers share their knowledge and needs, then later let them freely adapt the tools in their teachings and suggest relevant changes.

1.4.2 Thesis Roadmap

Chapter 2 presents an overview of the related work. We describe existing works in relevant domains, summarize the approaches, and present current open issues.

Chapter 3 first presents the DockLamp, a portable tangible tabletop system, and its interaction techniques. We then describe the effects the DockLamp had on learning, collaboration and reflection in a lab study with university students.

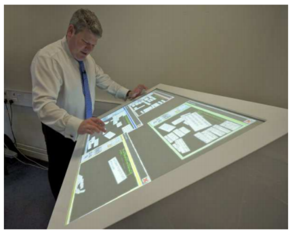
Chapter 4 introduces the TinkerLamp, a tangible tabletop developed to support the training of logistics apprentices, and its evaluation in a classroom setting. The findings confirmed some issues found in chapter 3. Together, they provide insights as to how to improve tangible tabletops for learning.

Chapter 5 describes TinkerLamp 2.0, our final tangible tabletop. After detailing the design response to the evaluations in chapter 4 and 5, it presents the design process and intermediate evaluation of the system.

Chapter 6 evaluates the effectiveness of TinkerLamp 2.0. We test the system in two logistics schools in Switzerland and describe our observations, interviews, logs, and questionnaire analysis.

Chapter 7 summarizes the lessons learned and points to future directions, including designing tangible tabletops as an ecology of tools rather than stand-alone applications.

2 Background and Related Work

2.1 Introduction

Our work lies at the crossroads of several research domains. The tangible tabletop systems we built and studied in the scope of this thesis fall within the field of Human-Computer Interaction, and more specifically, the domain of Tangible User Interfaces and Tabletop Interfaces. Their application belong to the field of Computer-Supported Collaborative Learning. This chapter gives a brief overview of these domains and related works, as they form the basis of our work.

2.2 Tangible User Interfaces

2.2.1 Overview

Tangible User Interface (TUI) is an interface type that is concerned with providing tangible representations of digital information. Research on TUIs reflect an emphasis on the role of natural physical interaction.

The tangible objects used in TUIs are computationally coupled with digital information and serve as tangible representations of this information. They usually function as both input and output devices, providing users with physical and digital feedback. The physical feedback is the haptic feedback that informs users about the physical manipulation they have just completed. The digital feedback, on the other hand, is any visual, auditory feedback that informs users about the effects that the physical manipulations have on digital data.

2.2.2 Origins

The Tangible User Interface was pioneered by Fitzmaurice et al. (1995) and Ishii and Ullmer (1997). Fitzmaurice et al. (1995) introduced the notion of a "Graspable Interface" where graspable handles are used to manipulate digital objects (Figure 2.1) on top of a table called the ActiveDesk. The ActiveDesk allowed users to perform operations like selection, resizing, moving, and rotating through their physical manipulations with the "bricks", i.e. wooden objects. Placing a brick on top of a digital object on the monitor caused the brick to be anchored to that object. Moving and rotating the brick moved the digital object accordingly. Placing two bricks on an object activated a zoom when the blocks were moved closer together or further apart. This demonstrated bi-manual gestures that we now use on multi-touch surfaces.

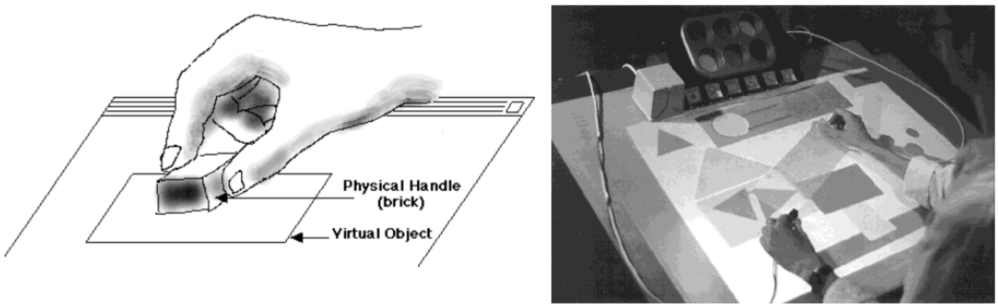


Figure 2.1: Fitzmaurice et al. (1995) proposed the concept of Graspable User Interfaces with users manipulating wooden "bricks" on top of a display surface.

Ishii and Ullmer (1997) presented the term "Tangible User Interface" to refer to interfaces based on the use of physical objects. One of their first prototypes, the metaDesk (Figure 2.2), is a geographical information system augmented with tangible user interface features. The geographical information is projected on the desk in the form of a two-dimensional map. The user can interact with this map using a set of different objects callled "phicons" (for physical icons) and other tangible tools such as a passive lens (a transparent wooden frame augmented with digital data), an active lens (a movable small display in a 3D space), trays (menus), and instruments (other widgets like sliders). As the user moves the phicon (e.g. one representing a building), the system adjusts the map to center around this building. By rotating the phicon on the desk, the user causes the map to rotate.

Since these early prototypes, TUIs have rapidly grown into a research area that has expanded in many directions. Although the early systems used tangible inputs on a tabletop surface, other systems explored various ways to augment existing media and artifacts in very different settings and forms. These systems, although addressing different areas of interest, can all be defined under the category of Tangible User Interfaces.

Figure 2.2: The metaDESK (Ishii and Ullmer, 1997) is one of the first tangible user interfaces. Users interact with a set of "phicons" and tangible tools to control a digital map underneath.

Because of these different settings and forms, TUI examples are diverse and difficult to classify. While some of the interfaces we present here are examples that are considered a TUI by the traditional definition of the term, others may only have some TUI-like characteristics. The goal of our review is to describe these characteristics and provide ways for thinking about and discussing them rather than bounding what a TUI is or is not.

We present the review of relevant work in the field of TUIs according to four categories. The first three categories of systems (Figure 2.3) were proposed by (Ullmer, 2002; Ullmer et al., 2005): *constructive assembly systems, token+constraint systems and interactive surface TUIs.* The fourth category is *paper-based input.* Paper-based is not a pure tangible user interface in the traditional sense. However, since, like other physical objects, paper is graspable and easy to manipulate, we still refer to it as a kind of tangible input and review it in this section.

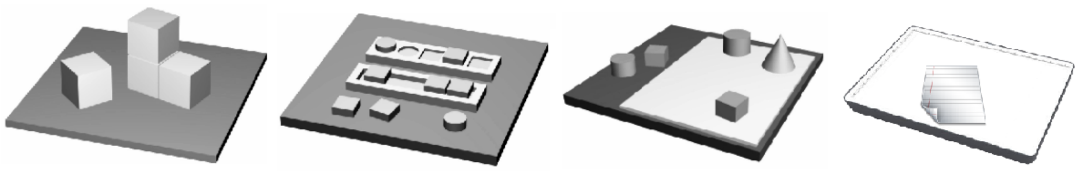


Figure 2.3: Illustrations of four types of TUIs: (left) constructive assembly systems, (center left) token+constraint systems, (center right) interactive surfaces, and (right) paper-based input. Image modified from Ullmer et al. (2005)

Application areas for TUI are diverse. We mostly limit this review to TUIs developed for learning and education which is the focus of this thesis. Other common domains include planning and problem solving (Underkoffler and Ishii, 1999a; Patten and Ishii, 2007; Underkoffler and Ishii, 1999b), entertainment (Jordà et al., 2007; Leitner et al., 2008; Ryokai et al., 2004; Zigelbaum et al., 2007), and social communication (Chang et al., 2001; Kalanithi and Bove, 2008).

2.2.3 Constructive assembly TUIs

Constructive assembly systems are usually based on modular elements which can be assembled together to trigger events or create 3D models. They are computationally enhanced versions of physical objects that allow users to explore concepts, which involve temporal processes and computation, taking advantage of users' familiarity with these objects.

When used for learning purposes, constructive assembly TUIs can make concepts that are normally considered to be beyond the learner's abilities or age-related level of abstract thinking accessible on a practical level.

Topobo (Raffle et al., 2004) is a well-known 3D constructive assembly system targeted at children (Figure 2.4). It supports users in manipulating objects with different physical shapes to create 3D models, for instance the skeleton of an animal. The physical objects have a kinetic memory, which allows them to record and replay movements. SmartBlocks is an augmented mathematical manipulative that allows learners to explore the concepts of volume and surface area with 3D objects. (Girouard et al., 2007).

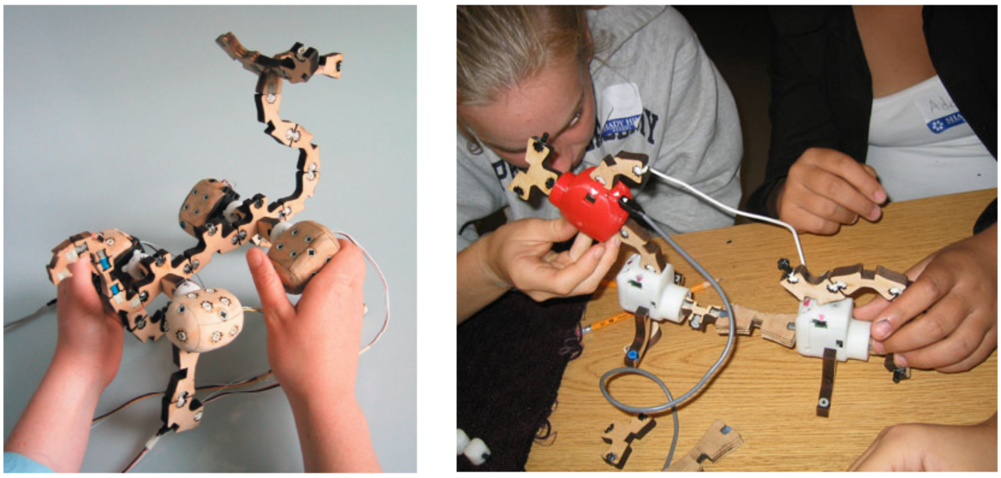


Figure 2.4: A model of a creature created with Topobo (Raffle et al., 2004), made of passive and active components.

SystemBlocks (Zuckerman et al., 2005a) is an educational TUI for simulating system dynamics. It can be used independently with the electronic blocks that are capable of providing both input and output modalities. Dynamic systems are created by attaching blocks together with electrical wires. The system runs a simulation of the network and outputs feedback through different representation types such as digits, graphics, and sound.

What these constructive assembly systems have in common often is the capability to run participatory simulations (Soloway et al., 2001; Klopfer and Woodruff, 2002). They often rely on distributed and ubiquitous computational devices to display information about the state in the simulation to communicate and engage learners.

2.2.4 Token+constraint TUIs

Ullmer (2002) referred to token+constraint systems as TUIs that take advantage of the physical constraints of tangible objects to guide the interaction. Token+constraint systems can be described based on two components: tokens act as containers and parameters representing digital information and constraints structure the way tokens can be arranged or associated.

An example of a token+constraint TUI is the Senseboard (Jacob et al., 2002). It is a tangible interface for manipulating discrete pieces of information such as note cards or sticky notes (Figure 2.5). The Senseboard consists of a vertical board, marked with a rectangular grid of multiple columns and rows (the constraint), covering most of its surface, giving it the appearance of a spreadsheet layout. Small rectangular plastic objects, called "pucks" (the tokens), can be placed into these cells, sticking magnetically. Each time the user moves a puck, the board sends the identity and the grid location of each of the pucks in the grid to a computer for updating the information about the model.

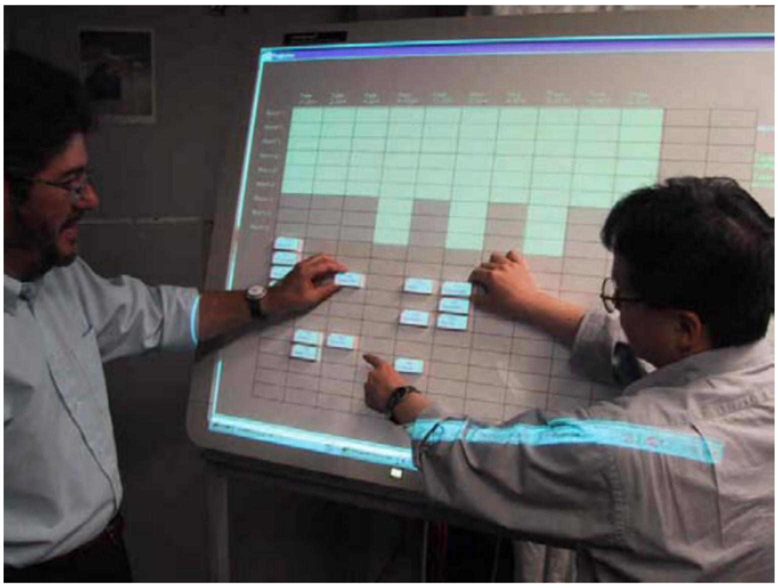


Figure 2.5: Users using the Senseboard (Jacob et al., 2002) to organize information on a vertical board with tagged pucks.

Other TUIs, like those designed to support children and novice programmers in educational settings to learn programming, exist as well (Wyeth and Purchase, 2002; Horn et al., 2008b,a). These tangible programming systems use physical constraints to form a physical syntax that adheres to the syntax of a programming language. Tern (Horn et al., 2008a) is a TUI that allows users to create physical computer programs using interlocking wooden blocks that represent actions to be performed (Figure 2.6). Each block represents either a command (e.g., repeat) or a variable (e.g., 2). The physical form of the blocks determines what type of blocks (command or variables) and how many blocks can be connected to each piece.

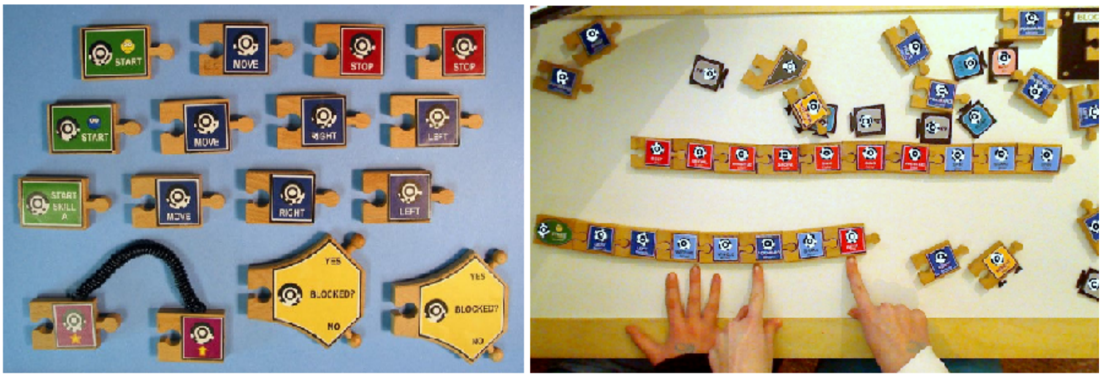


Figure 2.6: Tern (Horn et al., 2008a): using tangible interaction for informal science learning.

2.2.5 Interactive surface TUIs

According to Ullmer et al. (2005), interactive surface TUIs are those that allow users to manipulate physical objects on an augmented planar surface. The spatial relationship between tangible artifacts on these interfaces is usually important. In fact, interactive surface TUIs are also classified as a type of tabletop interface. These so-called tangible tabletop interfaces are the focus of this thesis, and are presented below, in the review of tabletop surfaces, section 2.3.5.

2.2.6 Paper-based input

Johnson et al. (1993) define the concept of a paper user interface as systems where ordinary paper controls or works in coupling with computers. Two main approaches have been prominent in the field of paper-based interface: paper is either used as a document, with digital capabilities aiming at enhancing its content and possibilities (called *augmented document*), or as an interface to control computer applications, where affordances of paper are used to create intuitive and rich interactions (called *paper-based input*). The second approach, i.e. paper-based input, can be considered a special type of TUI since it takes advantage of paper for its physical affordances, replacing other interfaces such as the mouse or the keyboard, as opposed to the first approach, i.e. augmented documents, where the content of the paper is the main goal for interactions.

Palette (Nelson et al., 1999) is a system that allows people to control electronic slideshows through a paper-based interface. It allows presenters to control slideshows through a set of index cards. Each card is printed with a thumbnail of the corresponding slide, text notes and a machine-readable marker. Slides are shown by sliding a card below a reader placed on the presentation table. A later extension to Palette is PaperButtons (Pedersen et al., 2000). Buttons were added to original presentation cards as a response to users' requests for additional features and mobility during presentations. It adds new features to applications and allow users to interact with a system by touching buttons on a piece of paper to control the presentation from far away. PaperButtons were implemented with an electronic tagging technology that is embedded in the paper and has to be worn by the users on their fingers.

ANOTO[1] paper is typically designed by printing some invisible or nearly invisible patterns on top of ordinary paper. The system uses a digital pen to recognize strokes made on the 'digital' paper printed in the previous step. The pen can see the underlying patterns and recognize its current position. Although still used exactly like normal paper, this ANOTO paper can communicate its content and the strokes created on it back to the computer.

VoodooSketch (Block et al., 2008) mixes real sketches on paper and physical interfaces to allow users to create shortcuts to an application's functionalities. The system consists of a tablet integrating two technologies: ANOTO, which captures users' sketches and VoodooIO, which provides a toolkit of physical control devices. Also using ANOTO paper, Brandl et al. (2008) combines with ARTags as a control board to sketch drawings and send commands to a remote digital whiteboard.

ARTag is another technology for paper-tracking. It uses two-dimensional visual patterns printed on a small region of each paper, allowing the user to track content on these papers (Fiala, 2005). Using the ARTag technology, Cuendet et al. (2011) presented augmented paper-based interfaces such as sheets and cards can be used in complement with regular tools, and wooden blocks for geometry teaching and learning. They provided examples of how these paper-based artifacts can support the activities and classroom orchestration.

PaperWindows (Holman et al., 2005) is an environment that allows users to simulate the use of digital paper (Figure 2.7). The PaperWindows system captures the user's interactions with real paper using computer vision techniques and projects data windows on this paper. By tracking its motion and shape, the system allows the use of paper as an input device to the computer.

2.2.7 Technological approaches

There have generally been three common approaches in terms of technologies for TUI: RFID, computer vision, and microcontrollers.

RFID-based systems

Radio-Frequency Identification (RFID), a wireless radio-based technology that senses the presence and identity of a tagged object is used in multiple TUIs. Some examples include the MediaBlocks (Ullmer and Ishii, 1999), a TUI that consists of a set of tagged blocks that serve as containers for digital media; Senseboard (Jacob et al., 2002), and SmartBlocks (Girouard et al., 2007), the two TUIs presented in previous sections are also two more examples that used RFID technology. The advantage of RFID lies in its simplicity. However, the RFIT tag can only be detected when it is within range of a tag reader.

[1] http://www.anoto.com

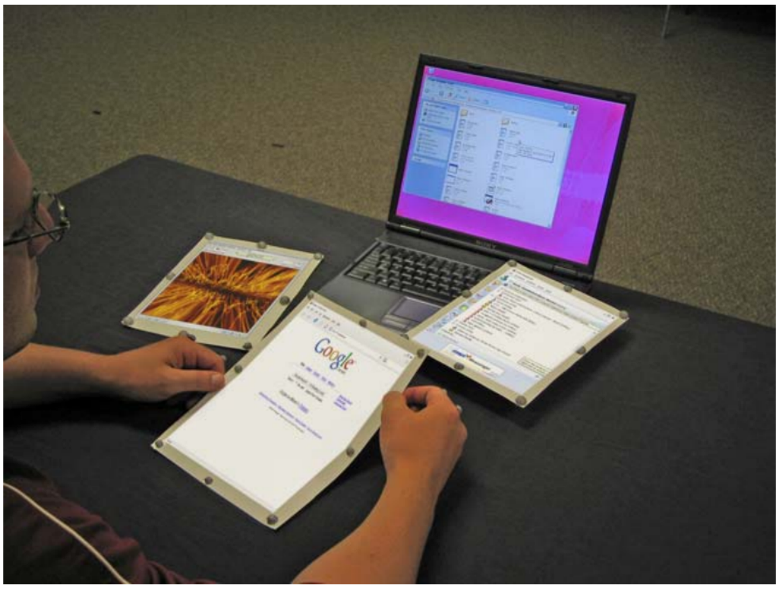


Figure 2.7: The PaperWindow system enables users to use paper to interact with web-browsers (Holman et al., 2005).

Vision-based systems

Computer vision techniques are especially useful for TUIs because they have an advantage of enabling the systems to detect the position of multiple objects at once, allowing multi-users to interact at the same time. They are also capable of recognizing other object properties such as orientation, size, and color. Many existing TUIs are developed using this approach, most in combination with a tabletop. For example, URP (Underkoffler and Ishii, 1999a) is a tangible user interface for urban planning. Users arrange small-scale models of buildings and road structures on an interactive surface. This allows physical architectural models to cast accurate shadows depending on the time of day as well as simulate traffic, pedestrian movement, and reflections from windows, allowing designers to better visualize the resulting layout.

Tangible artifacts are associated with a unique digital object and have a physical shape that corresponds to that object. Designers' Outpost (Klemmer et al., 2001) is a vision-based TUI that support desingers in their process of designing websites (Figure2.8). It allows users to arrange post-it like pieces of paper on a vertical board and make connections between them. Another example includes reacTable (Jordà et al., 2007), a tangible electro-acoustic musical instrument. ReacTIVISION (Kaltenbrunner and Bencina, 2007) is among other programming libraries and toolkits that support the development of computer vision-based TUIs.

The drawback of vision-based systems usually lies in the size of the setup. The cameras used for detection need to be place quite far from the surface, or object. This limits the portability of the system.

Figure 2.8: Designing websites using post-it paper on the Designers' Outpost system (Klemmer et al., 2001).

Micro-controllers

Another approach for TUIs is micro-controllers, i.e. small devices that can be embedded in a tangible object or the physical environment. Micro-controllers can make use of a wide range of sensors to capture physical properties such as light intensity, noise level, motion, acceleration, touch, temperature, etc. Multiple TUIs are developed using this technology, such as Topobo (Raffle et al., 2004), Digital MiMs (Zuckerman et al., 2005a), ActiveCube (Watanabe et al., 2004), and AudioCubes (Schiettecatte and Vanderdonckt, 2008). Systems developed with micro-controllers can often be used independently in the environment. However, the robustness and reliability of sensors and actuators vary, and the wiring may need to be checked to make sure the system work.

2.2.8 Evaluation

Research on TUIs have initially put much emphasis on proof-of-concept prototypes. However, there have gradually been evaluation works over the years. The most frequent types of evaluation of TUIs are comparative studies, conducted in the lab or in the field. Comparative studies attempt to quantify the costs and benefits of tangible interaction, compared to other interaction styles, typically a graphical user interface with mouse and keyboard, or to compare different variants of a tangible interface. Jacob et al. (2002) compared the speed of performance of four different conditions, including tangible, graphical and paper interfaces using a scheduling task. They suggested that the tangible interface can provide a more effective means of organizing, grouping, and manipulating data than either physical operations or graphical computer interface alone.

Similarly, Couture et al. (2008) conducted a study at the workplace of geophysicists using the task of selecting cutting planes on a geographical map. They compared four interaction techniques in terms of task completion time and questionnaire data. They concluded that tangible interaction results in better efficiency than using the standard mouse/keyboard GUI. This finding is consistent with that of Xie et al. (2008) where pairs of children were found to have more difficulty completing puzzles with a GUI than with a TUI due to the single user access.

Field comparative studies, on the other hand, focus more on higher-level interaction qualities such as awareness, engagement, and collaboration (Horn et al., 2009; Parkes et al., 2008). For example, Horn et al. (2009) conducted a field study in a museum during two weeks. They compared the effectiveness of a tangible and a graphical programming interface to investigate the percentage of visitors interacting with each interface, and how visitors write programs using them. They concluded that the TUI for programming was more inviting and more supportive of active collaboration than the mouse-based interface. Unfortunately, field studies of TUIs are still rather rare. This is one of the domains that this thesis aims to address.

There are several studies that use observation and interviews to evaluate TUIs. Labrune and Mackay (2005) evaluated Tangicam, a tangible camera for children by asking young children at a science fair to explain the toy to another child. They found that the affordances of the Tangicam allow imitation learning and free playing in a context of tangible and augmented reality. FlowBlocks (Zuckerman et al., 2005b) was evaluated through users' interview while they were working to complete a set of tasks, probing their understanding of the tasks and the system. They concluded that their tangible interfaces are accessible to young children, engaging, and encourage learning of abstract structures of dynamic behavior.

Despite these many studies conducted on the TUIs, the educational effects of TUIs are still unclear, especially when the goal of the activity is to promote learning. While most studies have shown that TUIs are engaging, there is also a common yet unproved assumption that the physical manipulation and simultaneous actions lead to improved learning. This belief has been questioned by Marshall (2007).

2.3 Interactive tabletop interfaces

2.3.1 Overview

Interactive tabletops are horizontal surfaces that work both as an input device and a feedback display. An interactive tabletop is usually large enough to allow for simultaneous inputs by multiple users. In recent years, the advance of new tabletop technologies has spurred a lot of research and commercial projects.

One of the earliest works in interactive tabletop research is the Digital Desk (Wellner, 1993), a computer vision-based desk consisting of a projector and two cameras (Figure 2.9). The projector mounted over the desk displays graphical information directly on top of items in the workspace. The cameras were used to track the position of a pen held by the user as well as finger touches and paper documents. It supports interaction with digital objects that are projected on the table through these devices, e.g. pressing virtually drawn buttons, entering data into columns on the paper, etc.

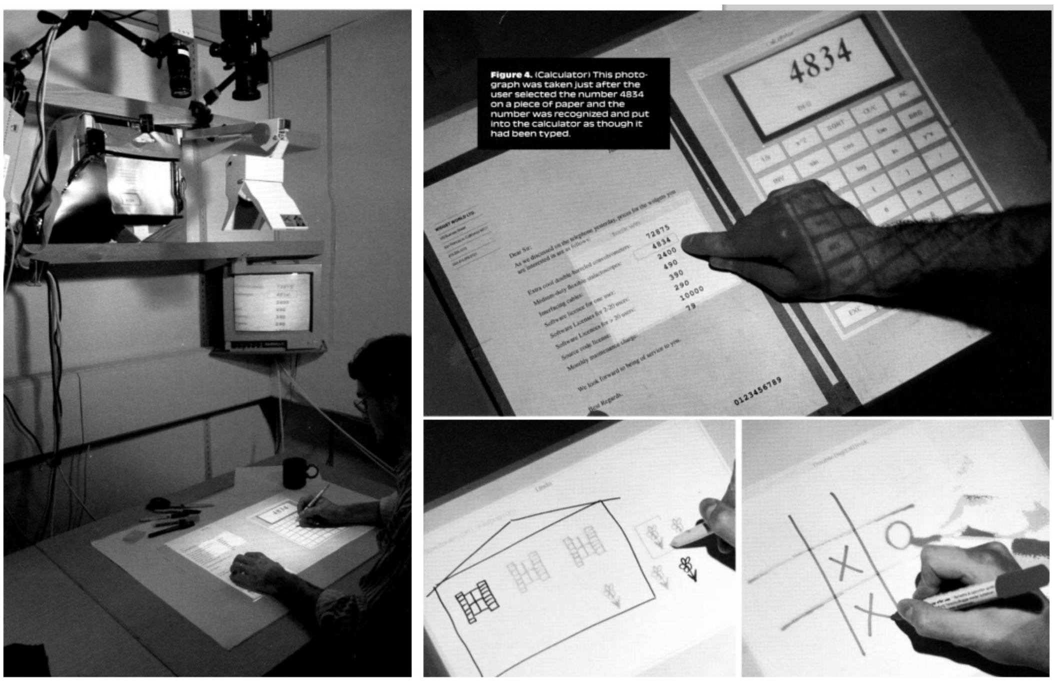


Figure 2.9: The setup of the first tabletop interface: the DigitalDesk (Wellner, 1993).

The main focus of the Digital Desk, however, was on single user interaction with physical desks rather than face-to-face collaboration around tables. Yet it demonstrates several fundamental ideas that guide other interactive tabletop systems, offering the potential to cater to multi-user interactions and bridge the gap between the digital and physical world.

There have generally been three typical setups for tabletop interfaces (Figure 2.10). In the first setup, the system is mounted on the ceiling and projected vertically on the table underneath, e.g. (Wellner, 1993; Dietz and Leigh, 2001; Koike et al., 2000; Wilson and Benko, 2010). In the second setup, it is integrated in some piece of furniture behind a diffuse screen such as the Microsoft Surface[2] and works by Leibe et al. (2000); Matsushita et al. (2004); Mazalek et al. (2006); Tabard et al. (2011).

With his PlayAnywhere system, Wilson (Wilson, 2005) explored a third setup approach that takes advantage of the introduction of short focus projectors based on aspheric mirrors

[2] http://www.microsoft.com/surface/

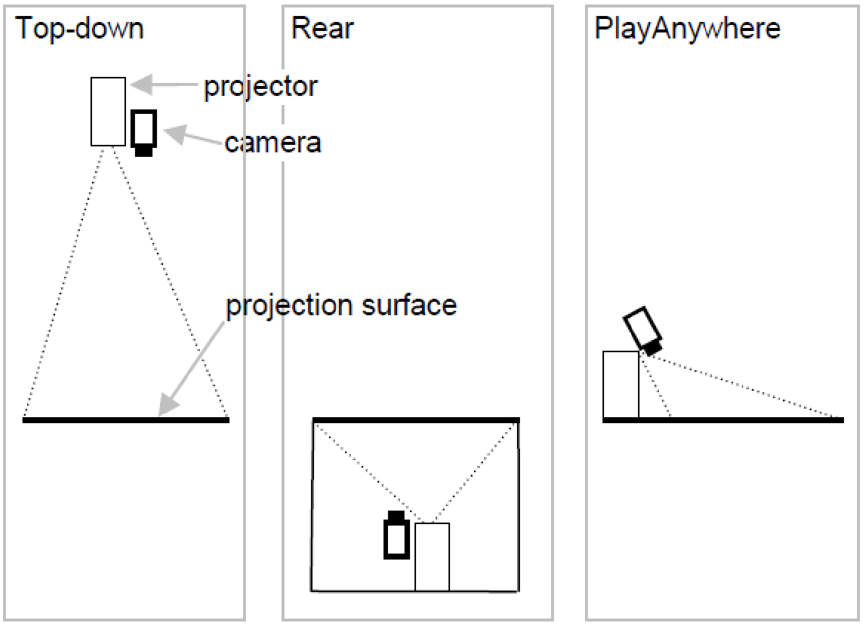


Figure 2.10: Three setups of projector camera systems in the literature. (left) Top-down projection. (center) Rear projection. (right) PlayAnywhere system (Wilson, 2005). Image by Wilson (2005)

(Figure 2.11). This kind of projector permits the consideration of the possibility of a compact self-contained system, placed on one side of the table, that still projects a large enough image.

Tabletops have been used in combination with several interaction techniques: touch, stylus, laptop, mobile devices, and tangible objects, which are described next.

2.3.2 Finger-based and touch interaction

Finger-based and touch interaction is a common mode of interaction with interactive tabletops. It provides a direct and natural way to interact with the computer (Dietz and Leigh, 2001; Wilson, 2005; Han, 2005; Letessier and Berard, 2004; Malik and Laszlo, 2004; McDonald et al., 2004).

The technologies used for these systems are mainly categorized into two approaches: vision-based and capacitive.

The *computer vision-based approach* often uses one or more cameras to capture images and videos of user's hands, implementing image processing algorithms to detect gestures and interactions. Certain TUIs perform finger detection by using a hand's depth map such as (Malik and Laszlo, 2004; Wilson, 2004; Wilson and Benko, 2010). The cameras used in computer vision systems can be near-infrared (Ullmer and Ishii, 1997; McDonald et al., 2004; Wilson, 2005), far-infrared (Oka et al., 2002), or ordinary color cameras (vonHardenberg and Francois, 2001;

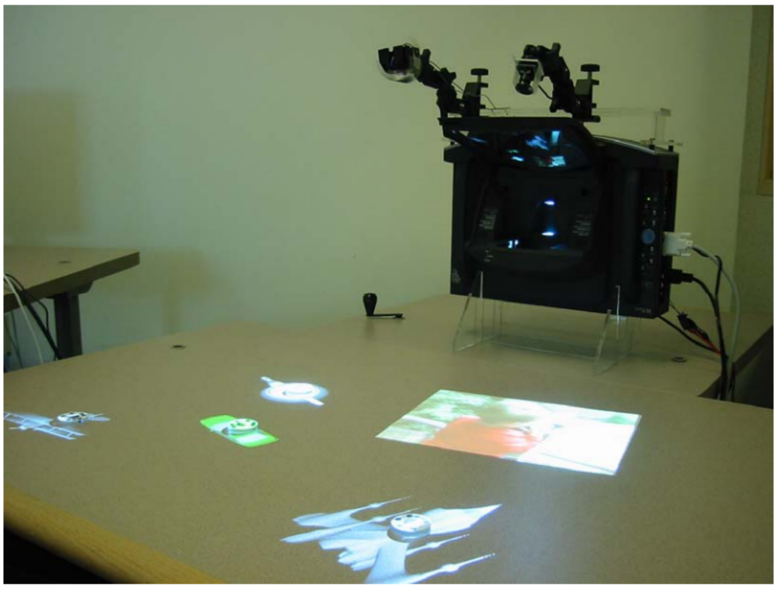


Figure 2.11: The PlayAnywhere system in use with touch and tangible objects as input.

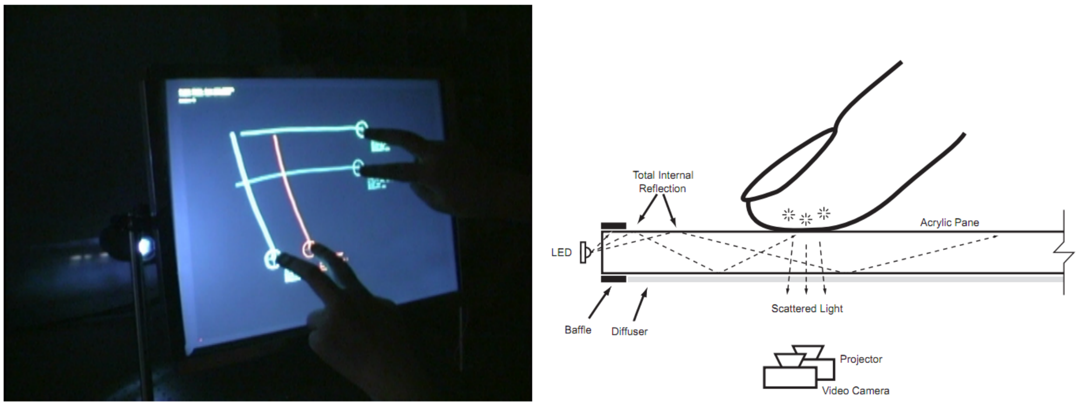
Bretzner et al., 2002; Letessier and Berard, 2004). There are several projects that detect finger and hand gestures by requiring users to wear colored gloves or markers, which is somewhat awkward for the users (McDonald et al., 2004; Holman et al., 2005).

Frustrated total internal reflection (FTIR) (Han, 2005) is an optical technique in which infrared lights are positioned along the edges of a sheet of glass. As a user touches the interactive surface, the light is reflected downward and detected by cameras positioned below the surface of the table. Figure 2.12 illustrates this system.

The detection of identity of the touch with vision based systems is difficult. The accuracy of touch detection using computer vision techniques also depends on lighting conditions, which may not be sustained in the face of sudden changes on the table. However, vision-based approaches are capable of recognizing other properties of hands and objects on the table such as size and color.

The other approach of detecting touch is *capacitive sensing*. It uses changes in electrical potentials to detect the position of our interactions. Capacitive systems alleviate some problems inherent in vision-based systems, since they integrate sensing technology into the surface of the touch device, which are not subject to interference through the occlusion of a sensor and have the potential to detect a much larger number of contact points.

Compared to computer vision techniques, capacitive systems are usually robust since they make use of electronical devices and elements that are reliable. The capacitive approach exploits special material or devices such as capacitive coupling (Dietz and Leigh, 2001), digitizing tablets (Leganchuk et al., 1998) or electromagnetic actuation (Pangaro et al., 2002; Weiss et al., 2010).



(a) (b)

Figure 2.12: FTIR multi-touch technology (Han, 2005): a) Multitouch interaction with an FTIR display. b) Schematic of FTIR sensing.

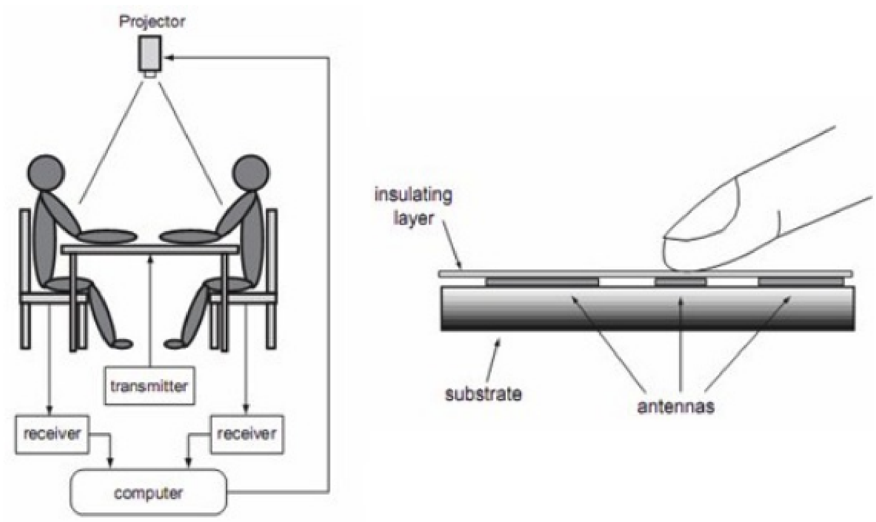
Two seminal works using this approach are DiamondTouch (Dietz and Leigh, 2001) and SmartSkin (Rekimoto, 2002) (Figure 2.13). The DiamondTouch table (Dietz and Leigh, 2001) relies on capacitive coupling technology. Users sit on conductive pads that are connected to the tabletop display. A uniquely identifiable current is transmitted through the conductive pads and then through each person's body. The sensing surface is an array of antennas that recognize these unique signals. The Diamond Touch provides high detection resolution and can identify which user is making each touch, but it cannot detect objects on or above the display.

SmartSkin (Rekimoto, 2002) can sense multiple hand positions and shapes as well as calculate how far hands and objects are from the surface, making it possible to track above-the-surface gestures. SmartSkin uses an antenna mesh to overcome the ambiguity of touch points, but offers lower resolution data and no user identification.

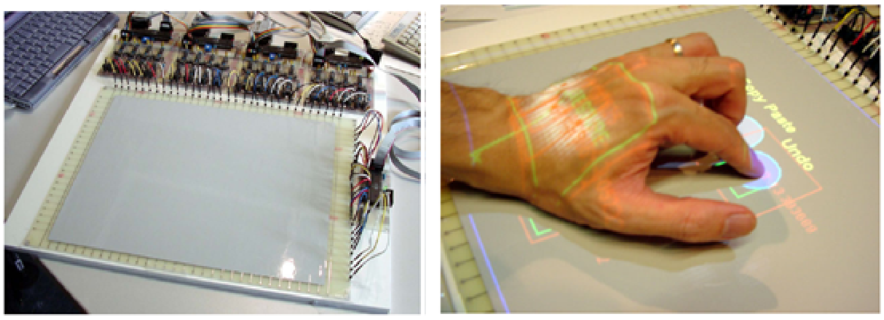
2.3.3 Stylus and pen-based interaction

Another common interaction technique for tabletop interfaces is stylus and pen-based input. The Escritoire system (Ashdown and Robinson, 2005) uses two overlapping projectors to display information on a large horizontal workspace. The low-resolution region fills an entire desk while the high resolution region accommodates the user's focus of attention. Two pens provide bimanual input over the entire desk area (Figure 2.14). To avoid interference between the two pens, a different technology is used for each pen: the first pen uses electromagnetism and the other uses ultrasound.

Coeno is a system that allows multiple people to simultaneously create pen-based annotations on a tabletop display (Haller et al., 2005). ConnectTables (Tandler et al., 2001) is a tabletop system supporting stylus-based interactions. This system involves tablet computers, and users are able to connect multiple tablets together to interact with other people and exchange



(a)



(b)

Figure 2.13: Capacitive systems: a) DiamondTouch (Dietz and Leigh, 2001); b)SmartSkin (Rekimoto, 2002)

content. The C-Slate system (Izadi et al., 2007) uses a horizontally mounted tablet that can recognize high resolution stylus input to support annotation. The interactions are augmented by multi-touch interaction and recognition of untagged physical objects using stereo cameras above the tabletop. Lee et al. (2004) presents the Haptic Pen, a pressure-sensitive stylus that provides tactile feedback for simultaneous users on large touch screens. A more recent example is work by Hinckley et al. (2010) involving multimodal commands that combine both pen and touch inputs.

2.3.4 Laptops and mobile devices

Devices such as laptops, mobile phones, and personal digital assistants (PDAs) were also used in combination with tabletop surfaces. An example of integrating laptops with a tabletop is the Augmented Surfaces project (Rekimoto and Saitoh, 1999). This tabletop surface allows multiple users to connect their laptops at the same time, letting users share with other people

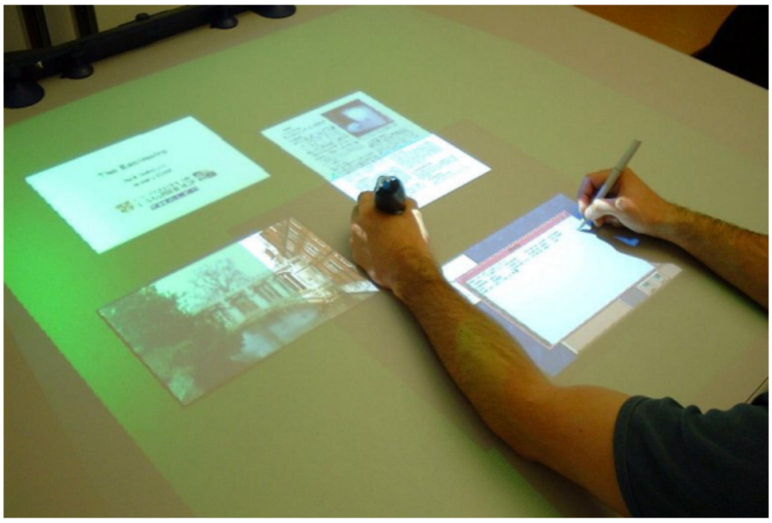


Figure 2.14: The Escritoire tabletop system in use with two pens (Ashdown and Robinson, 2005).

by dragging items from their own laptop onto the tabletop surface.

The well-known UbiTable (Shen et al., 2003a) supports a collaborative scenario when two users share and display their own content on the tabletop by dragging the desired information to a specified sharing region on their laptop. The Caretta system (Sugimoto et al., 2004) provides users with a shared map on a tabletop display and private information on connected PDAs. Similarly, the STARS system (Magerkurth et al., 2004) allows players to interact through a shared tabletop display while receiving private information through a PDA.

The SynergyNet project (AlAgha et al., 2010) presented the TablePortal, a system to help teachers manage and monitor collaborative learning on students' table from their multi-touch tabletop, or iPad (Figure 2.15). It provided a portal for all tabletops in the classroom to be connected to the teacher's multi-touch surface. The teacher could see and interact with the content produced within the entire classroom environment using multi-touch gestures. This system supported the teacher in managing the whole class activity from the teacher's table, issuing specific sets of artifacts to specific tables, monitoring the progress of the task, and giving assistance to students while they were working.

2.3.5 Tangible tabletops: using tangible as input for tabletop

Systems that use a tabletop surface as a shared workspace for multiple users and tangible objects as input are called tangible tabletops (Shaer and Hornecker, 2010). Using the taxonomy defined by Ullmer et al. (2005), these systems are called interactive surface TUIs, already mentioned in section 2.2.5. For clarity, in this review and throughout this thesis, we refer to these interfaces as *tangible tabletops*. Tangible tabletops combine interaction techniques and

Figure 2.15: The SynergyNet project (AlAgha et al., 2010): (left) A teacher is managing his class in real-time using iPad; (right) A teacher is using the TablePortal to interact with students' multi-touch tables.

technologies from both tabletop surfaces and Tangible User Interfaces.

The earliest works in the research domains of tabletop surfaces and TUIs were tangible tabletop systems (Figure 2.16). As described in section 2.2.2, the metaDESK (Ullmer and Ishii, 1997) is a back-projected interactive surface that allows users to manipulate a digital map using small-scale models of buildings. The DigitalDesk (Wellner, 1993) is a front-projected surface that enables pen and paper-based interactions.

There are a large variety of tangible tabletops developed using different approaches and technologies. For example, *acoustic systems* emit ultrasonic waves which are then received by objects that can determine their location on the table based on properties of this sound wave. Shen et al. (2003b) used Mimio [3], a commercially available acoustic tracker to enable users to share content on a tabletop. Mazalek et al. (2006) presented a system in which large pucks on the table surface can be tracked for positional and rotational information.

Storymat (Ryokai and Cassell, 1999) is a play carpet that can record and replay children's stories. It uses the *RFID* technology to detect tagged toys that are placed upon it. The system can record the story built by children and replay it by projecting an image of the moving toy onto the carpet.

The Flock of Birds from Ascension Inc [4] provides 3D *magnetic-based tracking* of small objects. Sensetable (Patten et al., 2001) is a system that electromagnetically tracks the positions of wireless objects on a tabletop surface. It is used to support applications in business supply chain management, urban planning, interactive visual art, and the performance and composition of electronic music. The tracked objects in this system have embedded functions such as dials and modifiers that are used to change the state of digital objects' parameters.

[3] http://www.mimio.com
[4] http://www.ascension-tech.com

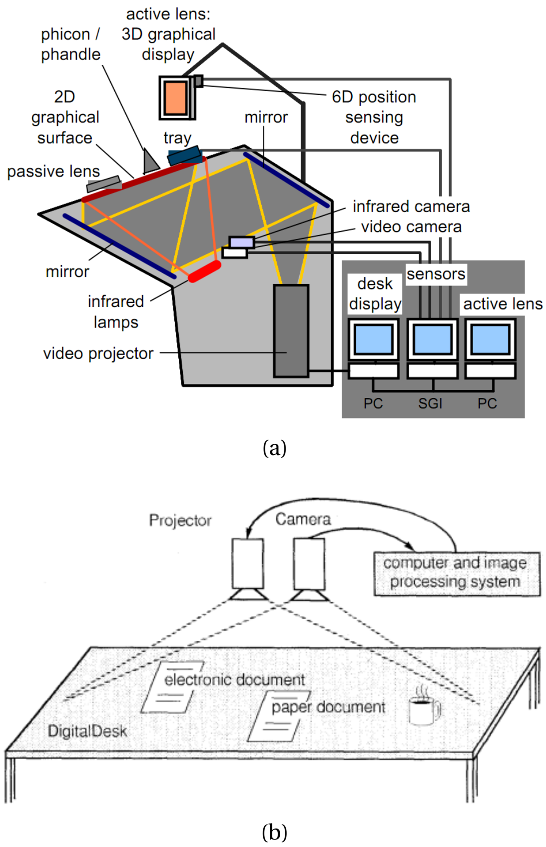


Figure 2.16: The setups of some earliest works: a) metaDesk (Ullmer and Ishii, 1997); b)DigitalDesk (Wellner, 1993)

However, *computer vision* is still the most common implementation method of tangible tabletops. Build-IT (Fjeld et al., 1998) is a brick-based application supporting engineers in the design of assembly lines and factories (Figure 2.17). It is composed of a table that is augmented with a projector and camera mounted on the ceiling. Users attach a brick to digital objects by placing it on top of them, releasing this link by covering the brick with their hands.

Slap widgets (Weiss et al., 2009) are transparent silicon widgets that can be visually tracked by the table and augmented with any type of digital data. The sample Slap widgets are used to interact with the tabletop underneath knobs, buttons, sliders, and a silicon keyboard, among others. Similarly, Kakehi et al. (2006) describe an enhancement to their Lumisight table in which objects transparent to IR light with an unique opaque pattern are placed on the surface. A camera beneath the table is used to track this pattern on each object.

Illuminating Clay (Piper et al., 2002) allows users to explore and analyze free form spatial models on a tabletop in the domain of landscape design (Figure 2.18a). Landscape models are constructed using a ductile clay support. A ceiling-mounted laser scanner captures, in real time, the shape of the landscape in three dimensions. From this information, simulations

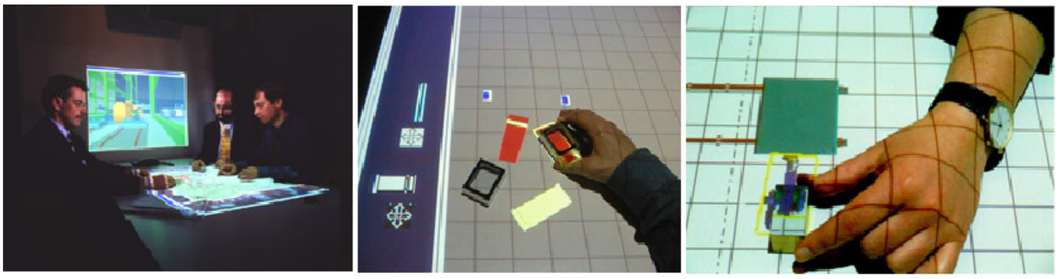


Figure 2.17: The BUILD-IT system (Fjeld et al., 1998) allows a design team to do model selection with a 'brick' and two-handed interaction.

such as shadow casting, land erosion, visibility, and travel time can be calculated. A projector displays digital information back onto the clay model.

Tabard et al. (2011) developed the eLabBench system to support biologists in their laboratory work (Figure 2.18b). The eLabBench allows biologists to organize their experiments around a tabletop interface with physical devices, such as racks of test tubes. It enables researchers to simultaneously work with the data and the equipment while documenting research. Users can pull digital resources, annotate these digital resources, place tubes on the tabletop to retrieve information, etc.

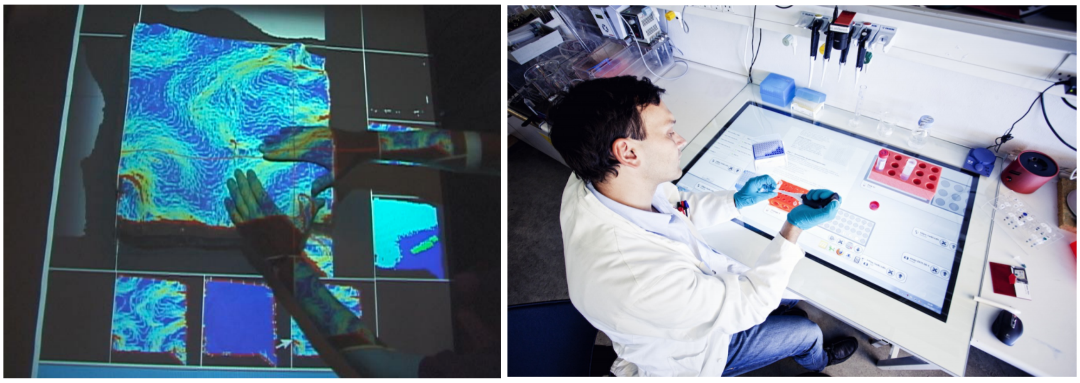


Figure 2.18: (left) A user modeling a landscape with IlluminatingClay (Piper et al., 2002); (right) A biologist doing a lab experiment on the eLabBench, a tabletop system supporting experimental research in the biology laboratory.

There have been several works trying to take advantage of the horizontal nature of tabletop surfaces to support users in working with paper documents. As already described, one very early work is the DigitalDesk (Wellner, 1993). There are also other works that recognize papers to control the interactive surface (Wilson, 2005; Klemmer et al., 2001; Hull et al., 2007; Kim et al., 2004). A common approach is to use markers printed on paper pieces, such as a barcode (Graham and Hull, 2003; Chand and Dey, 2006; Wu et al., 2008), visual tags (Brandl et al., 2008)(Figure 2.19), or infrared reflective markers (Holman et al., 2005).

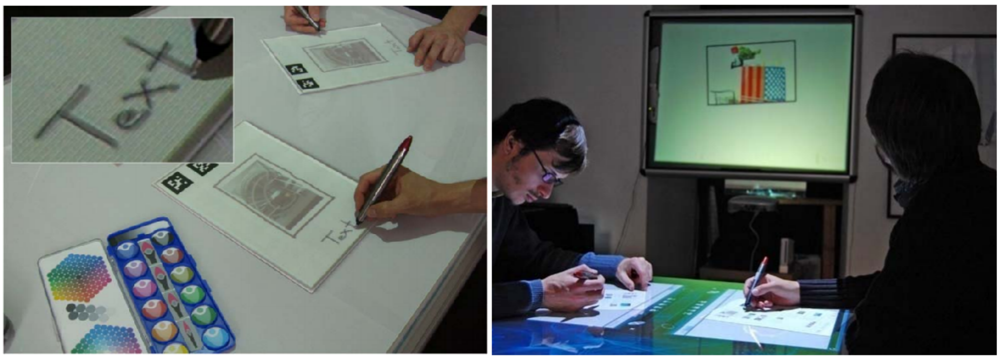


Figure 2.19: Tangible tabletops supporting paper-based interaction: b)Paper is used to interact with the tabletop and a vertical display (Brandl et al., 2008)

2.3.6 Evaluation

There have been several studies about the impact of tabletop usage on group process and performance. Ryall et al. (2004) reported on the effects of group size and table size on the task performance and how the work was distributed. Rogers and Lindley (2004) showed that small groups were more comfortable working around an interactive tabletop than in front of a PC or a vertical display. They proposed that tabletops invite people to reach out, and interact with it without feeling embarrassed of the consequences.

As proposed in (Rogers et al., 2009), group process and performance may depend to a large extent on the interaction modes. Interaction mode refers to the interaction means that one uses to interact with interactive systems. The effectiveness of an interaction mode is particularly important for educational activities. Inkpen (2001) conducted a study comparing drag-and-drop versus point-and-click interactions by children. The result demonstrated that a less effective technique like drag-and-drop can significantly influence children's performance in a task. Following this work, which is concerned with a traditional interactive application on PC, several studies investigated the impact of interaction modes with tabletops Ha et al. (2006); Forlines et al. (2007); Hornecker et al. (2008); Tan et al. (2008).

For example, multi-touch, physical object or mouse are different interaction input modes. Ha et al. (2006) investigated the effects of different input devices on users' behaviours and concluded that direct input methods (stylus, touch) support a greater awareness of intention and action than the indirect method (mouse). This is confirmed by a study comparing groups of three people using three mice against using a multi-touch table (Hornecker et al., 2008) in which the affordances of touch input and body movements resulted in a better awareness about (but also more interferences with) other group members. In terms of task performance, a single user may benefit from using a mouse in unimanual tasks and from fingers for bimanual input (Forlines et al., 2007). Direct drag-and-drop is considered the best all-around technique in a puzzle completion game, compared to indirect interaction methods on tabletop (Nacenta et al., 2007).

However, to date, there has been a lack of evidence about the effects of tabletop on learning tasks with a realistic setup. Most tasks used in previous research were layout design or physical performance tasks and required mainly physical manipulations (e.g. pointing, moving): puzzle-like games (Müller-Tomfelde and Schremmer, 2008; Nacenta et al., 2007), home, office, or garden layout (Tse et al., 2007; Rogers et al., 2009; Marshall et al., 2008). Only a few of them involved a higher abstract level task, such as tasks of scheduling (Tan et al., 2008), cognitive conflict, basic negotiation (Setlock et al., 2004; Rogers et al., 2009) or memory retention (Pawar et al., 2007).

Although it is clear that to evaluate educational outcomes is complex and still open to debate, knowing the effects of tabletop on a higher level learning task such as comprehension or synthesis is beneficial for the community.

2.4 Computer-Supported Collaborative Learning

2.4.1 Overview

Research on Computer-Supported Collaborative Learning (CSCL) emerged as a field during the 1980s. Collaborative learning is widely defined as an activity in which peers try to construct a shared knowledge through their interactions with each other and their environment (Roschelle and Teasley, 1995; Dillenbourg, 1999a). It is a continued and synchronous attempt to construct and maintain a shared representation of the problem to be solved.

In the field of collaborative learning, there have been different perspectives, both in theory and in practice, about how to satisfy this need for a synchronous shared representation. Research themes have evolved from considering the individual as the unit of analysis to focusing on the social activity and the group in which the individuals collaborate.

Dillenbourg et al. (1996) provided an overview of the development of research, and discussed three theoretical views: socio-constructivist, socio-cultural, and distributed (shared) cognition in CSCL. They argued that one viewpoint was not necessarily better than another but revealed that the socio-cultural and distributed cognition recently received more attention from researchers.

The socio-cultural and distributed cognition view has great implications and influences on CSCL and HCI research, as these two communities are concerned with developing technologies and encouraging social interactions around technologies to enhance learning.

It has been argued that HCI tools have mostly failed when researchers and designers adopted the individual isolated tasks as the primary unit of analysis. Rogers and Ellis (1994) claimed that the lack of consideration about how the tasks are performed in situ has led to the design of many computer-based systems that are unable to support the very tasks that they were built to support. This is because the technologies did not take into account the complex work practices around which they work and hence become inappropriate when in use.

2.4.2 From scripting to classroom orchestration

Scripting

Collaborative learning is not a mechanism per se. Learners do not benefit from collaboration simply because they are in a group rather than alone. Instead, according to Dillenbourg (1999a), collaborative learning provides an environment for learners to engage in potentially useful activities such as exploration, explanation, elaboration, knowledge elicitation, and conflict resolution.

Consequently, a main concern for CSCL has been to design tools that directly or indirectly support those kind of useful activities. The 'script' concept has been used to describe methods that structure face-to-face collaborative learning. Many researchers (O'Donnell et al., 1992; Aronson and Patnoe, 1997; Dillenbourg, 2002) realized this 'scripting' approach as a way to enhance computer-supported collaborative learning by structuring productive interactions. A collaborative script is a set of instructions specifying how the group members should interact, collaborate, and solve the problem. It is a detailed and explicit contract between the teacher and a group of students regarding their mode of collaboration.

There have been two main categories of CSCL tools designed to foster effective collaborative learning using collaborative script: structuring tools and regulating tools. *Structuring tools* tend to be anticipatory and usually designed to provide an explicit structure to foster some specific, positive, interaction process among learners and/or prevent some specific, negative, interaction process from occurring before the activity. For example, ArgueGraph (Jermann and Dillenbourg, 1999) is a so-called "macro-script", i.e. its core principle is to set up pairs in a special way to favor argumentation. The script is based on a simple multiple-choice questionnaire produced by the teacher. The system produces a graph in which all students are positioned according to their answers. The system or the tutor forms pairs of students by selecting peers with the largest distance on the graph (i.e. that are most different). The purpose is to increase the chance that pairs have to argue before answering the same questions again, but together.

Regulating tools facilitate the self-regulation process and on-the-fly changes of the teachers and learners' behaviours during the activity, as opposed to before the activity, as with structuring tools. To this end, regulating tools strive to capture the state of the collaborative activity as it unfolds and rely on this information to provide awareness, feedback, guidance, or even intervention. Awareness or mirroring tools are a common type of regulating tools.

For example, Jermann (2004) has developed a system that displays participation levels to the learners as they are solving problems. The indicators on the display represent the number of messages each learner has sent with respect to the number of problem-solving actions he and his teammates have taken. The system displays a color-coded model of desired interactions next to the observed interaction state. The students use this information to assess the quality of their interaction. They can decide whether or not to regulate their actions. The result of the study was that that this metacognitive display encourages students to participate more.

The Second Messenger (DiMicco et al., 2007) is a group mirror visualization that aimed to influence speaker behavior in collaborating groups. Sound was captured using head-mounted microphones. The system displays information about the group in real time on some shared surface. The authors built and tested different versions of this group mirror tool, concluding that the group mirror had certain effects on self-regulation.

Bachour et al. (2010) presented an interactive table, called Reflect (Figure 2.20), to help users regulate their face-to-face conversations. Reflect monitors the conversation taking place around it via embedded microphones and displays relevant information about member participation on its surface in a discreet and unobtrusive manner. The lab studies of Reflect showed that the table can be used to promote balanced partcipation with over-participators more likely to reduce their participation levels in order to achieve balance with the others.

Figure 2.20: The ReflectTable: a realtime visualization display projected on the table to support self-regulation (Bachour et al., 2010).

Orchestration

Recently, research on integrated pedagogical scripts has emerged. It is concerned with the integration of activities at multiple social planes such as individual reading, team argumentation, and plenary sessions (Dillenbourg and Jermann, 2007). Instead of focusing on scripting the activities for group collaboration, this approach proposes considering learning activities on different social planes of the classroom (individual, dyadic, group, and plenary activities).

This integrative scripting approach, together with the technological evolution in schools, has given rise to a new trend in CSCL research about orchestration (Dillenbourg et al., 2009; Kollar et al., 2011; Dillenbourg et al., 2011). Orchestration refers to the real time classroom management of multiple activities and multiple constraints conducted by teachers. It emphasizes the classroom constraints and the role of teachers in managing these technology-enhanced classrooms.

This relationship between orchestration and integration is related to what some authors called the "classroom as a complex technological ecosystem" (Luckin, 2008). This ecosystem also includes a physical environment, a content structure (the curriculum), and a rigid time structure. This orchestration movement calls for a shift from "designing and scripting for conversations" (understanding how design choices may trigger productive interactions) to "design for orchestration" (understanding how design choices may facilitate productive learning in a class ecosystem).

Orchestration can be seen as a movement towards a new blended version of teacher- and student-centric designs that promotes the need of empowering teachers by integrating new technologies in real classrooms (with all of their contextual restrictions).

Some early examples of technologies designed to support orchestration have started to emerge. The One Mouse Per Child project Alcoholado et al. (2011) proposed a visualization tool that shows simplified aggregated data about each of the 40 children in the classroom. Each student is represented by an icon on the display area. This information is displayed permanently without a need for the teacher to make queries, facilitating his/her awareness of the class progress and individual statuses (Figure 2.21).

Figure 2.21: The One Mouse Per Child project (Alcoholado et al., 2011): left) Up to 40 students working simultaneously on the system for a basic math lesson. right) A central display shows personal feedback for the whole classroom.

A similar work to One Mouse Per Child is the Mischief system by Moraveji et al. (2008). Mischief is a teaching system designed to use single-display groupware to enhance social awareness between collocated students and support classroom-wide interactions. Mischief enables up to 18 students in the classroom to interact simultaneously with a large shared display by placing a mouse on each student's desk. However, this work focuses on supporting a remote teacher, teaching via video communication. It would be interesting to see how the technology can be adopted for traditional co-located classrooms, which is the constraint of classroom orchestration.

Recent studies have shown the benefits of considering orchestration in the classroom (Prieto et al., 2011; Kollar et al., 2011). For example, Kollar et al. (2011) ran a study with a number of eighth-grade high school classrooms studying Biology. The results of this study demonstrated that alternating plenary, small group, and dyadic learning phases led to higher levels of learning competence than having all activities at only one level. The authors argued for the importance of orchestration, namely the sequencing of activities on the different social planes of the classroom.

2.5 Tangible tabletop and learning

2.5.1 Educational tangible tabletop applications

In terms of applications, tangible tabletops have been developed to facilitate learning abstract structures (Zuckerman et al., 2005b); numbers, sorting, and patterns (Manches et al., 2009); programming (Fernaeus and Tholander, 2006; Horn et al., 2009); and physics concepts (Parkes et al., 2008; Fjeld et al., 2007; Price et al., 2009), among other things. For example, Price et al. (2009) developed a tangible tabletop to support children learning about the behaviour of light (Figure 2.22). Visual effects, e.g. light reflection, absorption, transmission, and refraction, were projected on the table surface when users manipulated the torch and the blocks on the table surface. By simulating the real-world behaviours of all of the objects, e.g., the torch shining light, and the blocks reflecting light, etc., the system supports the abstraction of physical concepts.

Tangible Viewpoints (Mazalek et al., 2002) is a tangible tabletop system that explores how physical objects and augmented surfaces can be used as tangible embodiments of different character perspectives on an interactive table. Children navigate through multiple viewpoint stories by placing physical characters in the form of pawns on an interactive surface (Figure 2.23). Narratives corresponding to this character and position are displayed on the tabletop and a nearby screen.

The Flow of Electrons system (Conradi et al., 2011) provides a physical prototyping workspace for novices to learn about computing hardware (Figure 2.24). The workspace consists of a back-projected horizontal surface that tracks physical components like sensors, actuators, and microcontroller boards and augments them with additional digital information. By digitally experimenting with how to correctly wire physical components, users can experientially learn how to build a functioning circuit and then transition directly to building it physically.

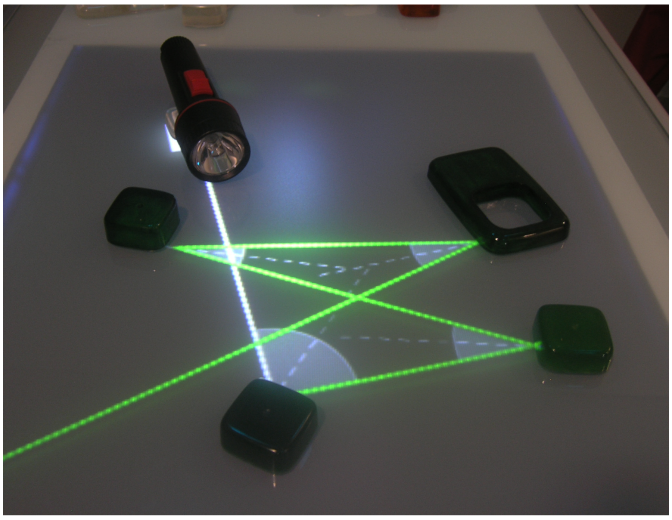


Figure 2.22: Learning about the behaviour of light with tangible tabletop (Price et al., 2009).

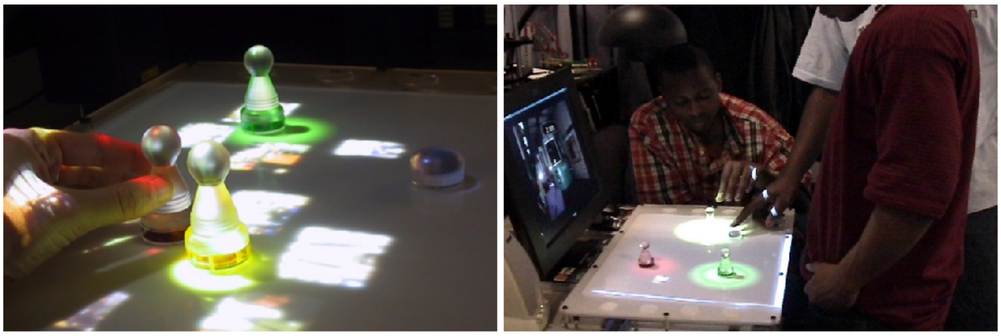


Figure 2.23: A group of kids interacting with Tangible Viewpoint, an tangible tabletop for multimedia storytelling (Mazalek et al., 2002).

2.5.2 Benefits for learning

Several studies comparing tangible tabletops versus other traditional methods have been conducted. Tangible tabletops have been shown to be more accessible to young children, increasing engagement and time-on-task factors (Horn et al., 2009; Fjeld et al., 2007). For example, Horn et al. (2009) showed that a tangible tabletop for programming was more inviting and more supportive of active collaboration than the mouse-based interface in an informal educational context. Similarly, pairs of children had more difficulty completing puzzles with a GUI than with a tangible tabletop due to the single user access (Xie et al., 2008).

Tabletops have a specific educational flavour since they are suited for co-located teamwork. However, Dillenbourg and Evans (2011) proposed that this benefit should not be over-emphasized. As they put it, "interactive tabletops are novel, original, and exciting. Yet, they will not alone radically change educational practice." What Dillenbourg and Evans (2011) argued is that, tangible tabletops have a set of specific affordances, and the duty of researchers

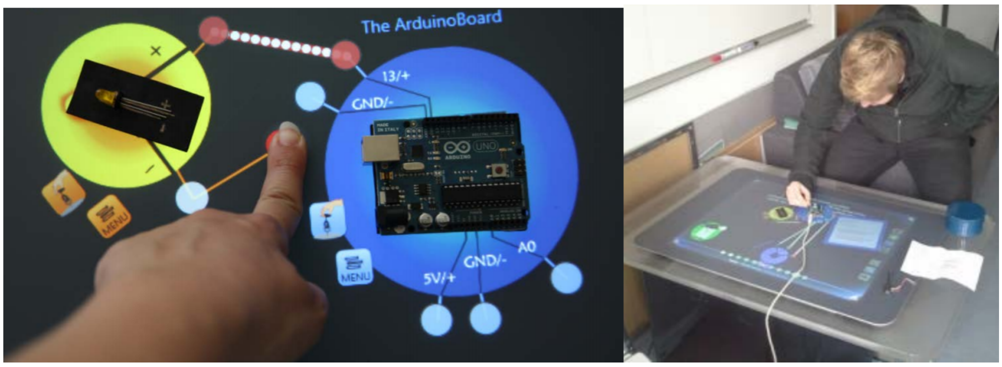


Figure 2.24: Physical components on the FlowofElectrons (Conradi et al., 2011) are augmented with digital information explaining pin functionality. It depicts intangible electronics and provides a safe test environment for digital experimentation of learners.

is to explore how these affordances can be exploited in different tasks and contexts, rather than over-expecting and over-generalizing a specific successful instance to every other contexts.

Indeed, the unique physical features of tangible tabletops offer the potential to facilitate learning in many ways.

Co-located learning. Tangible tabletops can be effective in supporting co-located teamwork and learning. Tangible tabletops provide a large shared worksplace area and help group members be better aware of each other's actions as well as exchange objects more freely.

This benefit has been confirmed by several studies (Ha et al., 2006; Hornecker et al., 2008). For example, through a study comparing groups of three people using mice versus a tabletop, Hornecker et al. (2008) showed that the affordances of direct touch input and body movements in the tabletop condition resulted in a better awareness of intention and action than the mouse condition. Rogers and Lindley (2004) also showed that small groups were more comfortable collaborating around an interactive tabletop than in front of a PC or a vertical display.

Participation and simultaneous interactions. Tangible tabletops can enable more participation and active learning thanks to their simultaneous interactions. Learning outcomes are generally dependent on the students' levels of participation in the activity and can be impaired when some group members dominate the whole activity (Slavin, 1995).

Tangible tabletops hence play an important role in bringing about more equitable participation thanks to simultaneous inputs (Stanton et al., 2002; Price and Rogers, 2004). Stanton et al. (2002) concluded that simultaneous inputs can promote more equitable interactions between children. Price and Rogers (2004) also discussed how digitally augmented physical spaces promoted active learning. A question arises concerning the comparison between tangible interface and multi-touch interface. Schneider et al. (2011) confirmed in a controlled experiment that a tangible tabletop interface led to better learning gain in a problem-solving task than a multi-touch interface with the same application. They explained that the tangible interface resulted in more exploration, which in turn contributed to the learning score.

Hands-on activities. Tangible tabletops support building learning activities in which groups of learners can interact directly with their hands by touching and manipulating objects. This sensori-motor experience that tangible tabletops offer has been described as beneficial for learning (Price and Rogers, 2004), relying on the idea that they support an enactive mode of reasoning (Bruner., 1966), and that they enable empirical abstractions of sensori-motor schemes (Piaget, 1974).

In addition, tangible tabletops are largely believed to be beneficial to learning outcomes because they leverage metaphors of object usage and take advantage of the close inter-relation between cognition and perception of the physical world (Klahr et al., 2006; Price, 2008; Hornecker and Buur, 2006).

Multiple modes of communication and representation. With the computer diffused into the background of physical environment, presenting a barrier-free, face-to-face style of collaboration, tangible tabletops have much to offer in terms of multiple modes of communication, such as speech, gesture, gaze, manipulation, etc. that provide a richer discourse for teaching and learning (Evans et al., 2009; Fleck et al., 2009).

Moreover, tangible tabletops with the integration of external concrete inputs and the abstract augmented information may be an excellent means to present Multiple External Representation (Ainsworth, 2006). The arguments put forward by this learning approach are that presenting learners with several instances of the same information at different levels of abstraction will act as a scaffold, allowing them to understand the more abstract representation by observing how it is related to the more concrete one.

2.5.3 Open issues

While it seems evident that the affordances of tangible tabletops provide new possibilities and enable many exciting activities, there are currently a few gaps in the literature.

Lack of studies on high-level thinking tasks

The evaluations of educational tangible tabletops have mostly emphasized the motivating and engaging nature of the interface, e.g. Price and Rogers (2004); Xie et al. (2008); Horn et al. (2009). Learner performance, if present, was mostly determined through task-based criteria such as speed, number, and quality of final designs, e.g. O'Hara and Payne (1998); Manches et al. (2009). There has been a lack of experimental studies with tasks at a higher level of abstraction, such as comprehension or synthesis. In this regard, little evidence has been provided that tangible tabletops offer more positive learning outcomes compared to more conventional interaction techniques (Marshall, 2007).

One of the reasons for this neglect is that the studies have mainly been designed for younger children such as works by Cao et al. (2010); Manches et al. (2009); Fernaeus and Tholander (2006); Horn et al. (2009); Parkes et al. (2008). The tasks used in these studies hence had to be adapted to their level of thinking. The systems that have been created focus almost exclusively on younger populations, mainly children aged 4 to 14 (Manches et al., 2009; Fernaeus and Tholander, 2006; Horn et al., 2009; Parkes et al., 2008). Researchers have paid little attention as to how TUIs may benefit other student populations, such as adolescents or university students (though, see (Fjeld et al., 2007)).

Lack of guidelines in developing for authentic settings and orchestration

The classroom is an environment with particular needs and constraints. While some studies reported on how tangible tabletop technologies are adopted by school communities (Cao et al., 2010; Piper and Hollan, 2009; Price and Rogers, 2004; Zuckerman and Resnick, 2003; Stanton et al., 2001), there has been little prior work that explores the requirements and guidelines for the design of such technologies in a real classroom. Appropriately designed technologies may play a crucial role in improving learning and teaching experiences.

Dillenbourg et al. (2011) argued that research has neglected the existence of classes and their teachers. While some early technologies have started to emerge to support the classroom and teacher orchestration (AlAgha et al., 2010; Alcoholado et al., 2011), we need to further investigate how to build technologies in general, and tangible tabletops in specific, to support this special setting.

3 DockLamp and ConceptMap study: A Tangible Tabletop in the Lab

3.1 Introduction

This chapter presents the design and studies about the DockLamp, a system we developed to explore the idea of turning any horizontal surface into an interactive tangible tabletop. We used the DockLamp to investigate the extent to which a tangible tabletop interface affects students' learning outcomes, learning processes and reflection.

The chapter first describes the motivation of the DockLamp, how its design evolved over time and the final learning scenario. The DockLamp features a novel interaction method called HandPaper+, enabling multiple users to use both physical papers and fingertips as mediums for interaction. It is a portable projector-camera system that is small enough to be easily carried around and deployed in real-world settings.

We then detail the ConceptMap study which examines how the DockLamp can benefit collaborative learning. The goal of this study is to deepen the understanding of tangible tabletop environments' impacts on learning and reflection in a high-level task, using a traditional, single mouse interface as the baseline condition.

3.2 Motivation

3.2.1 DockLamp's Portable form factor

A main issue of tabletop research is that, even though the research community has been active, few systems have really been used consistently in real settings. Apart from the lack of useful realistic applications, one of the main difficulties lies in the bulky form factor. Big tables are difficult to move, and hard to integrate into existing settings, such as classrooms. Moreover, considering that a traditional classroom has 15-20 students or more, HCI researchers and practitioners would probably like to have more than one unit for different groups working concurrently in the same class.

As described in chapter 2, the PlayAnywhere system (Wilson, 2005) represented a different approach in designing tangible tabletop. As opposed to existing bulky setups, it is a compact self-contained system, placed on one side of the table, which projects a large enough image. Though PlayAnywhere is much smaller than the other systems we have considered so far, it is still not easily portable.

We aim to extend the design space of projector-camera systems by presenting the DockLamp which is portable and foldable. Equiped with a small projector and a commodity webcam, the DockLamp enables natural interactions with any horizontal surface and can be easily deployed in existing physical spaces.

3.2.2 DockLamp's HandPaper+ Interactions

The DockLamp is implemented with an interaction method called HandPaper+. The design rationale is that migrating the simplicity of tangible paper manipulations and the naturalness of finger-based interactions may allow greater flexibility in the way information is manipulated, with a richer set of interaction techniques.

Consequently, HandPaper+ uses computer vision techniques to detect multiple fingertips both hovering over and touching the surface in real-time, regardless of their orientations. Fingertip and touch positions are then used in combination with paper tracking to provide new interaction gestures that users can perform in collaborative scenarios.

Compared to related works, the HandPaper+ interaction is different in one or more of the following points.

First, this method supports simultaneous multiple "bare" fingertip interactions regardless of their orientation and background. The easy rotation or movement of the lamp to fit it in the most adapted space on the table also resulted in a novel algorithm thats adapts to background changes in real-time.

Second, as opposed to other vision-based tabletop systems, the DockLamp is capable of detecting touch, thanks to a small simple diffuse laser source embedded in the base.

Third, despite a large body of literature, since the DigitalDesk(Wellner, 1993), there is surprisingly little work proposing interfaces that take advantage of fingertip gestures in combination with real physical papers (a few examples, though, are (Koike et al., 2000; Holman et al., 2005; Wu et al., 2008)). Our aim is to support both finger- and paper-based interactions, and allow cross references between the two, i.e. doing some gestures with hands has implications on the way papers react and vice versa.

3.3 Design of DockLamp and its interaction techniques

3.3.1 Evolution of DockLamp

The DockLamp was first designed to function as a projector to support screen sharing in collaborative learning scenarios. Later, we decided to make it more interactive with the vision of "interaction everywhere".

Figure 3.1 shows the evolution of the DockLamp's design over time. One of the first softwares we developed for this system permits display sharing by pressing a physical button on the lamp's base. In a prototypical situation, up to six students work together on a common project sitting around a table, each having his/her own laptop. They actively discuss a particular plan for the project presented by one of them. Instead of using a standard video projector, they use the lamp to project the images from presenter's laptop. The image of the presentation is projected on the table and its orientation can easily be changed by turning the head of the lamp.

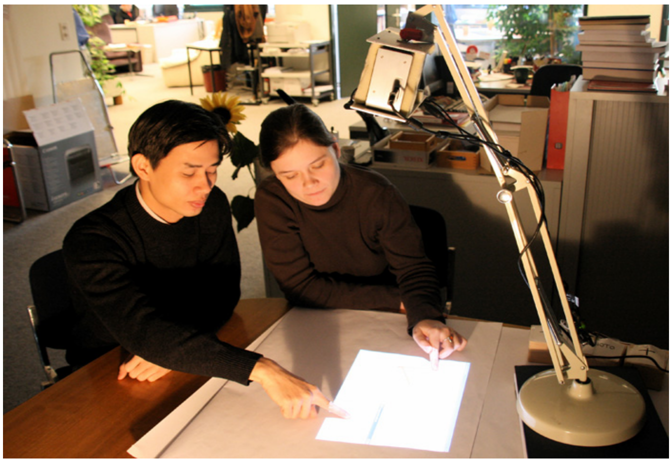
Our next iteration presented several changes to the initial DockLamp and its purpose. First, we embeded a color camera in the head of the lamp, providing it with the capability of capturing and recognizing objects in real-time. Second, we transformed it into a "portable" tangible tabletop system. The initial "in-house" prototype was replaced by an industrial design (designed by Martino d'Esposito, realized by Frédéric Kaplan).

The purpose of the final DockLamp design was to support students in interacting with shared virtual content on their workspace. The scenario we had in mind was a collaborative learning task, in which multiple learners read documents, discuss them, and collaboratively build a concept map about concepts in the documents. Their interaction with the DockLamp was facilitated by fingertip- and paper-based manipulations.

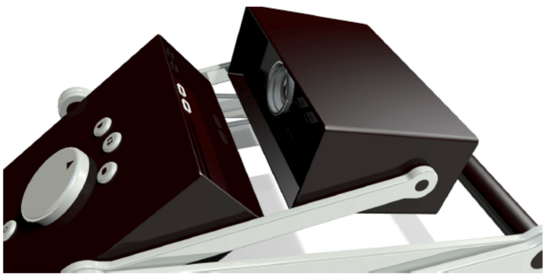
(a)

(b)

(c)



(d)



(e)

(f)

Figure 3.1: (a,b) The first prototype of the DockLamp as a screen sharing device with only a projector in its head, (c,d) The first design of DockLamp as an interactive tangible tabletop system, (e) A Docklamp's industrial design sketch, (f) The final design in use by students.

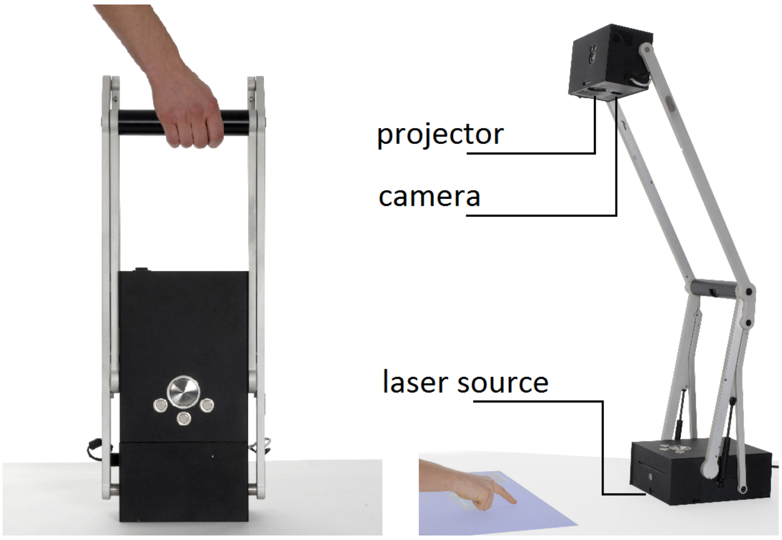


Figure 3.2: DockLamp consists of a projector, a camera on top, and a laser source at the bottom.

3.3.2 Final design of DockLamp

Configuration

The DockLamp is organized in two separate parts (Figure 3.2). The first part contains a projector and a color camera, while the second, at the bottom base, contains a mini-PC and a mechanical system that permits an easy rotation of the whole lamp. There are 4 physical buttons on top of the base which are directly connected to a circuit board on the PC. These buttons give access to very basic functionalities which can be re-defined, e.g. shutdown, or take a snapshot of the table. The base also includes a small laser source that can emit diffused beams on top of the table to enable touch detection. Since the projector and the camera are rigidly fixed with respect to each other, the calibration between them needs to be done only once and remains the same even when the system is moved.

Folding and rotation mechanisms

When closed, the DockLamp looks like a suitcase that can be carried around using a handle (507 x 215 x 63 mm). In this configuration, the projector lens and the camera are placed in a secured position. The suitcase can be easily opened and transformed into a lamp. When opened, the projector-camera module is automatically positioned in an appropriate vertical position, facing down at 70 cm of height, resulting in an interaction area of roughly 45 x 35 cm (approximately a 21-inch monitor). It supports simulatenous multi-user interactions using bare fingers and paper materials.

One of the advantages of the DockLamp is the ability to flexibly turn and rotate the device. The whole lamp can be rotated in order to project onto the most adapted space on the table. This functionality gives the DockLamp the ability to easily fit into any existing physical environment.

3.3.3 HandPaper+ interaction and Concept-mapping scenario

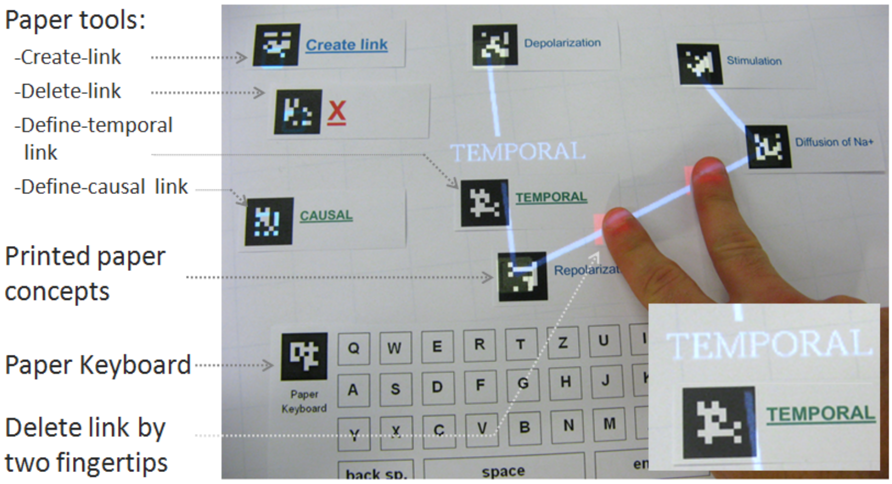


Figure 3.3: Paper concepts, some paper tools and the Paper Keyboard. The close-up shows the link definition projected on the table.

As presented above, the DockLamp aimed to support a collaborative concept-mapping scenario. In this scenario, multiple learners work together to visualize the relationships among different concepts, constructing a diagram called a concept map. Concepts, usually represented as boxes or circles, are connected with labeled links (e.g. "results in", "is required by", or "is a type of") representing the relationships between these concepts.

Figure 3.3 shows a close-up of a concept map being built with the DockLamp.

Paper concepts and paper tools

Paper concept: With the DockLamp, concepts are printed on small pieces of papers. The current prototype of our method uses normal pieces of papers with ARTag markers (Fiala, 2005). A region of 2x2cm on each paper is needed for printing a two-dimensional visual marker.

Paper tools include several special pieces of tagged papers, each of which represents a specific command to the system, such as creating or deleting a link between concepts.

Paper Keyboard is a keyboard layout that is printed on a paper. Since the objective of the Paper Keyboard is not for intensive typing but to enrich user interactions and to complement the HandPaper+ interaction, the typing speed is not a real concern.

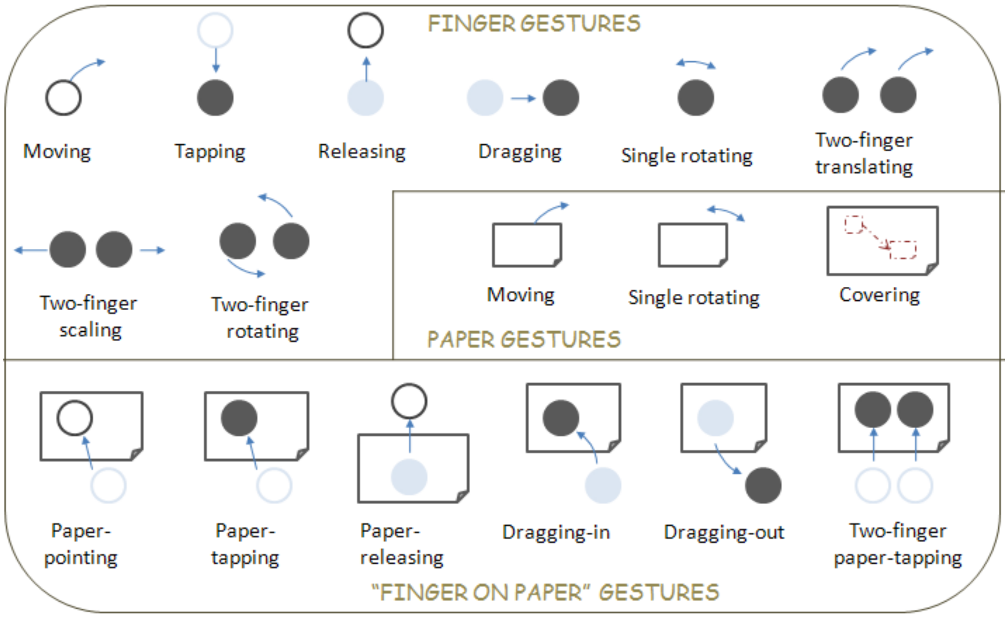


Figure 3.4: The basic gestures supported by our approach. A hollow circle shows a fingertip hovering the surface. A solid circle shows a fingertip touching the surface. A rectangle represents a paper.

Interactions with concept map

The DockLamp supports the concept-mapping scenario by combining finger and touch gestures with real paper to open a wide variety of interaction techniques with the concept map in a simple way. Figure 3.5 and 3.4 depicts a basic set of gestures supported by the DockLamp. They can be used separately (i.e. finger *or* paper interaction), or in combination (finger *alongside* paper interaction, or fingertip interaction *on* paper) to support the creation, manipulation, deletion of concepts and links. These gestures are used for different purposes in the scenario, which is elaborated in the next sections.

Concept creation and manipulations

Concepts can be created in two ways. First, a concept label can be directly printed on paper. These are *printed paper concepts*. As concepts are paper pieces and hence graspable, users can manipulate them easily with hands.

Second, a virtual concept label can also be assigned to a blank piece of paper. To begin, users move their finger over the table (*moving* gesture) and aim at a specific key on the keyboard (*paper-pointing* gesture). The key below their finger will be highlighted with visual feedback from the projector as a confirmation. The typing action is done by performing a sequence of a *paper-tapping* gesture and *paper-releasing* gesture.

As one is typing, a line of text will appear on the table, right next to the Paper Keyboard showing

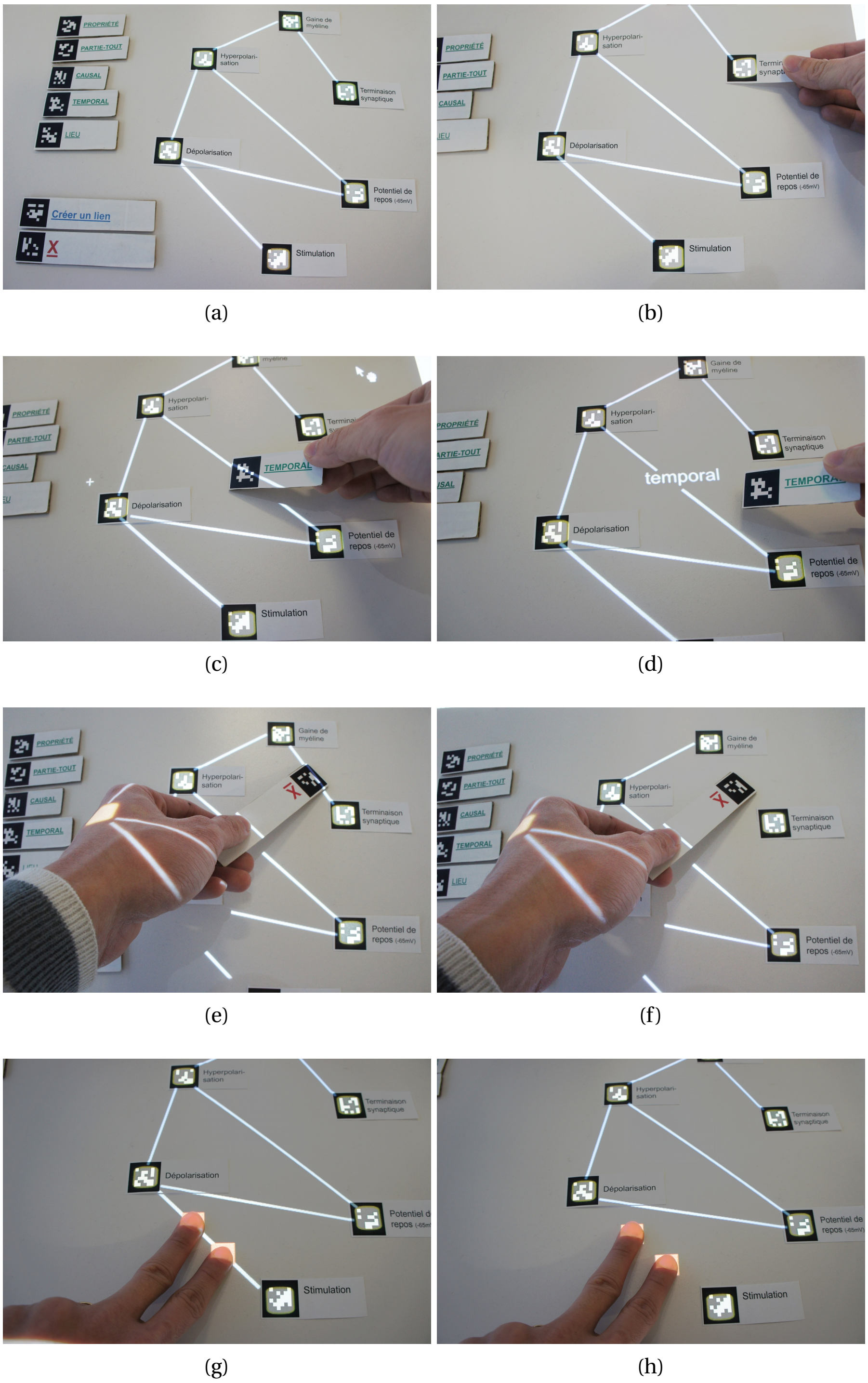


Figure 3.5: Interacting with a concept map using paper-based interface and finger-based interaction. (a,b) The concept map, 7 paper tools lined up to the left, and some printed paper concepts connected to each other to the right; (c,d) Defining a link type (e.g. 'temporal') using a paper tool; (e,f) Deleting a link between two concepts using a paper tool; (g,h) Deleting a link using two fingers.

what is being typed. *Single rotating* the Paper Keyboard will rotate the text accordingly. Users can do this gesture to better orient the text for their partners to read.

After typing the text, users press a key on the Paper Keyboard to assign this text to the blank piece of paper. Users interact with this paper like the other printed concepts, except that digital text is now projected on the paper. Alternatively, the text can be moved from the table to the blank paper by a *dragging-in* gesture: users simply move their finger over the text, tap on it, drag it onto the paper, and release the finger to complete the action. In much the same way, users can 'un-assign' a defined blank paper concept by a *dragging-out* gesture. Dragging the digital text that is projected on the paper out of it, leaving the paper blank as it was initially.

Link creation, definition and deletion

There are two options to create a link. First, users can bring two paper concepts closer until they touch one another to create a link between them, projected by the projector. Second, users can use a "create-link" paper tool: put the paper tool close to a concept and then move it close to another.

To define a link description, users use one of the five paper tools. Each of the tools bears a predefined specific text representing the relationship, e.g. causal, temporal, whole/part, etc. Users place this paper tool in the middle of the link, causing the text printed on the tool to stick to the link.

Users have two possibilities to delete a link: either by using the "delete-link" paper tool, or by performing an "erasing" gesture. To perform this erasing gesture, one stretches two fingers, e.g. the index and the middle finger, moves them into the middle of a link, and maintains them on the link for two seconds to delete it. This gesture can be thought of as doing a tapping gesture with two fingertips.

Map saving and loading

Users can save a concept map by pressing a designated key on the Paper Keyboard. When loaded the next time the system is in use, a digital graph representation will be reconstructed. Users may continue to alter the digital map by using their fingers with typical bimanual gestures as on other multi-touch systems, (e.g scaling, rotating or zooming). For example, *scaling* the view is accomplished by moving two fingers in opposite directions: bringing them together to zoom out and pulling them apart to zoom in. Changing the angle of the line segment created by two fingertips will *rotate* the view.

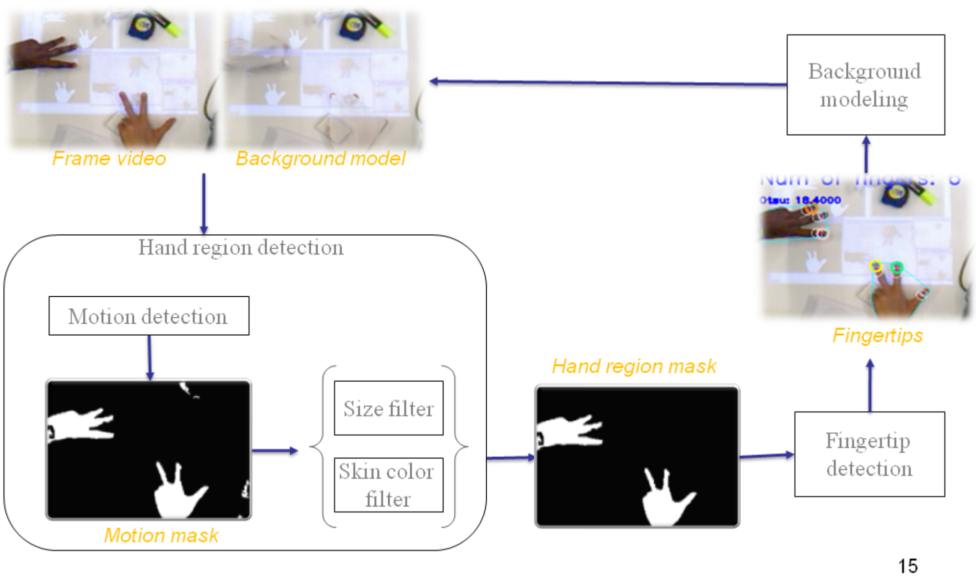


Figure 3.6: The DockLamp vision pipeline for any frame captured from the camera to detect fingertip and paper.

3.4 Implementation

The portability and rotational flexibility of the DockLamp presents considerable challenges for implementation. These features lead to sudden background changes during the interaction when the camera moves. Moreover, we wanted to support both touch and paper interactions on the DockLamp. These challenging requirements had a strong influence on the approach we chose.

We have developed an original vision-based method to cope with the above constraints. Our method consists of three key components: fingertip detection, touch detection and touch on paper detection, each of which serves as a building block to the whole system (Fig.3.6).

Our vision framework is written in C/C++ on top of the OpenCV (Pisarevsky et al., 2008), a highly optimized library for computer vision and image processing primitives. Paper tracking with visual markers is run at the resolution of 1280x960 with ARTag library (Fiala, 2005). Fingertip detection is performed at 640x480. The video is captured at 7 frames per second (fps) although both algorithms can run up to 15fps.

There are several processing steps that we perform with each new image from the camera. The algorithm is fast, running in real-time. It proves effective at a certain level of over-exposure of the camera, even when captured images are distorted by visual feedback from the projector.

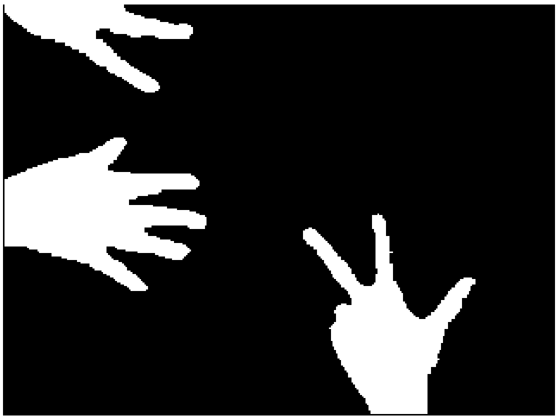


Figure 3.7: A hand mask which was the result of background subtraction, auto-thresholding and skin validation. The white part shows detected hand regions.

The full algorithm is elaborated in Appendix A. Here we only briefly describe each building block.

3.4.1 Hand region detection

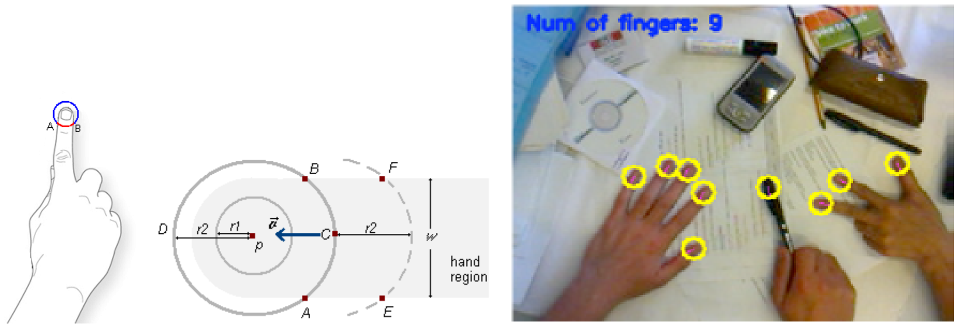
Moving hands are extracted from video frames using a background subtraction technique. The technique involves a subtraction between the current video frame recorded by camera and the estimated background (an image including only static objects on the table) to gain a *difference image*. This difference image is thresholded, yielding a binary mask, showing the moving objects in the frame. We then use a size filter to eliminate all of the moving blobs that are smaller than the size of a normal hand (defined by a threshold). This helps alleviate problems due to noise, small moving objects, and lighting changes.

To make hand extraction more reliable, we apply a skin filter to the resulting mask. Now, only moving blobs that have a color similar to skin color (defined in Appendix A) will be marked as a hand. After this step, we obtain a so-called *hand mask* whose pixels have a value of 1 (or white) if they are inside the hand regions and 0 (or black) if outside (Figure 3.7).

3.4.2 Fingertip detection

We apply a geometric model (Figure 3.8) on the hand mask to identify the *fingertip pixels*. This model specifies that a fingertip has to be at the end of a long- and- thin- enough cylinder (the finger). This model is applied on every pixel in the hand mask. A pixel is marked as a fingertip pixel if it satisfies the set of rules implied in this geometric model (Appendix A).

A connected component of several fingertip pixels represents a fingertip. A fingertip's position is computed as the average coordinates of these fingertip pixels. The finger orientation can also be easily achieved from the model. Figure 3.8 illustrates this step.

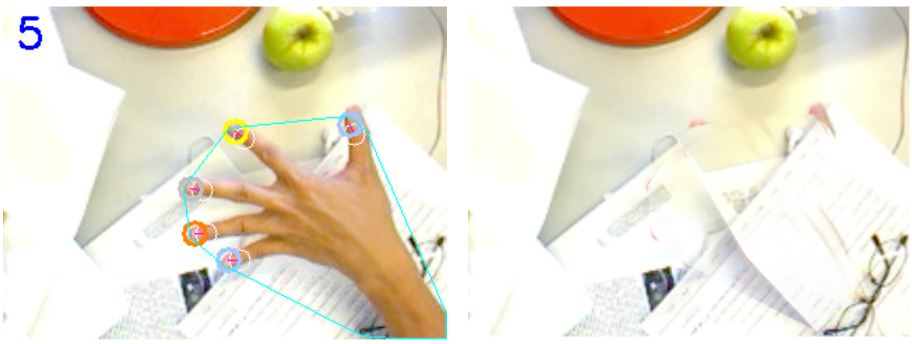


(a) (b) (c)

Figure 3.8: The template used for fingertip detection and its result. a) Observation: a circle drawn on any fingertip is divided into two parts b) Our geometrical template is checked against every pixel p in the image c) Result of fingertip detection. Pens that are held in hand can also be detected (but not the static pens on the table).

3.4.3 Background modeling

As a final step, we need to estimate the static background of the table based on the frame grabbed by the camera. The DockLamp, unlike traditional designs, enables users to rotate the whole lamp, causing sudden changes in the video scene. This requires a new solution to update the background using statistical information from the pixels in conjunction with information at the object level, namely fingertips and moving hands. We compute the background model as a weighted sum of its previous value and its value in the current video frame, besides hand regions including at least one fingertip. Figure 3.9 shows an example for our approach.



(a) (b)

Figure 3.9: We use convex hulls of detected hands and fingertips to support background estimation. (a) Video frame and detected fingertips (b) Estimated background, computed as a weighted sum of its previous value and its value in the current frame, besides hand regions including at least one fingertip.

3.4.4 Touch detection

As previously mentioned, other systems implement clicking behaviour by using dwelling, i.e. keeping the finger still for a certain amount of time, or with multiple cameras. Integrating a small laser source in the DockLamp's base enables us to detect touch using only one color camera. Our laser source spreads a very thin sheet of harmless diffused laser just above the table. The finger touching the surface will result in a red-colored dot in the video frame (Figure 3.10). We group these red pixels into a connected cluster. The average coordinate of a cluster represents a touch. In practice, we also check touch validity by ensuring that it is close to one of the fingertips detected in the previous step. This is to avoid mis-detection of the arm or other objects on the table.

(a) (b)

Figure 3.10: Touch detection: a) The red dots appear on fingers when they touch the table b) Detected touches.

3.4.5 Touch on paper detection

We use the ARTag library (Fiala, 2005) to track real paper in real-time. Each paper within the workspace contains a visual marker at a corner that helps the system detect its position and orientation. For example, each paper concept in Figure 3.3 has a region of 2x2cm at the top-left corner. A piece of paper can have multiple control regions which accept fingertip touching, each of which can send a specific command to the computer. The Paper Keyboard presented above is an example of this type of interaction.

A matrix mapping of the real world measurement system (in centimeters) to the camera's measurement system (in pixels) is obtained by initially calibrating the camera. This helps the system to project visual feedback correctly on top of the physical paper and hands.

3.5 Evaluation of DockLamp's interactions

To explore the usability and effects of the DockLamp, we undertook a series of evaluation studies at different scales. This section reports informal evaluations about the final design of the DockLamp. Section 3.6 details a controlled experiment about the DockLamp with a learning task.

3.5.1 Informal evaluations and public responses

First, we evaluated the usability of the DockLamp design and interaction techniques in the concept-mapping scenario using informal interviews and observations of potential users. These informal evaluations took place at various demo sessions for the public, both at our lab and in-the-wild settings including scientific conferences in the US and UK, classrooms and technological fairs in Switzerland.

Here are some prominent findings summarized from observations of real users interactions and informal interviews.

Form factor. The public response to the form factor was quite positive. They highly appreciated the fact that the DockLamp is portable and lightweight to carry around. From our own experiences, we saw strong evidence that this portable form factor is critical for deployment. It not only faciliates a more straightforward preparation and setup, but can potentially have a positive impact on the adoption rate of the technology in real settings.

Even though the design of DockLamp still left space for improvements (for example, not really stable due to the folding mechanical devices), our public demo sessions in real settings were prepared quite easily and quickly thanks to the little time needed to install the system. We could just bring the DockLamp to schools, put it on any table, unfold it, plug in the electricity, and it was ready for use.

Deployment and observations of the DockLamp gave us insights as to how to design similar systems for real use. The design of our portable TinkerLamp for logistics apprentices was partly inspired by these findings. The TinkerLamp will be described in detail later in chapter 4.

HandPaper+ interactions. All subjects noted that it took very little effort and time to learn and build concept maps using our technique. The most common positive comments were “fun, easy to use”, “better for team”, “faster than using PC”.

We observed that the subjects used both deletion methods equally: erasing gesture by hand and using a paper. Although it took more waiting time for the link to be deleted by fingers, some people said that fingertip deletion was more natural for them since they did not have to think and look for the special tagged paper among a lot of other papers. The others, meanwhile, claimed that they used two fingers to delete links at the beginning of the task, but prefered to use paper to delete in later stages as it is small and therefore more suitable in cramped space.

Speed. Our informal experiment has shown that the computer vision algorithm is fast enough and computationally independent of the number of fingertips. The latency of the method is about 20ms - 30ms with anywhere between 5 and 20 simultaneous fingers. Users reported a satisfaction regarding the speed of interaction. They reported no significant lag when interacting. However, in theory, the speed of the system differs according to the number of foreground pixels, i.e. the amount of moving objects in the scene, which is not a real concern in our interaction scenarios.

Correctness and responsiveness. Since our model exploits object-based knowledge and the fusion of skin color and motion, the system performed well in most settings, especially in situations where hands start motion after appearing in scene for a long time. It is, however, assumed that fingers move at normal speed, i.e. 2.5-3m/s.

The algorithm adapts almost immediately to sudden background changes produced by the rotation of the DockLamp or noisy projected images and texts on the table. However, as with other vision-based systems, this adaptivity varies according to a threshold which is predetermined by the lighting condition and the physical room ambiance. In particular, the touch detection feature did not react very well to lighting changes. Further complement schemes, such as making use of an infrared camera, might be necessary to increase correctness. The fixed threshold of hand size also caused some false negatives for kids. Their small hands were sometimes not detected by the system.

3.6 ConceptMap Study: examining tangible tabletop in the lab

3.6.1 Overview of the study

The main research question of this study is the following: *"To what extent does a tangible tabletop interface affect the collaboration between students and their learning outcomes when compared to a traditional PC?"* More specifically, we explore the relative educational values of tabletop settings compared to single-mouse configurations. DockLamp is used in one condition and is compared to a traditional single mouse interface as a baseline condition.

3.6.2 Task description

We adopted a collaborative learning task in which groups of three people studied a three-page document and built a concept map about a neurophysiologic phenomenon of "neural transmission". This experimental task and its materials were developed and tested intensively at our lab in several experiments (Sangin et al., 2008; Molinari et al., 2008).

The content of the document (detailed in Appendix B) described chemical interactions inside neurons, consisting of information that requires the learners to understand the logical order of neurons' processes.

Prior to collaboration, the document was divided into three parts of one page with equal length. Each group member was handed a different section, reading and understanding it individually. Then, the group was asked to collaborate in order to comprehend the document as a whole. This task required the students to access different but complementary parts of information about the learning topic. This collaboration mode is known as knowledge interdependence which supports sharing learning resources among partners, and is believed to encourage students to have productive interaction activities such as explanation, or conflict resolution Buchs et al. (2004); Dillenbourg (1999b).

The group was then asked to externalize their common knowledge into a concept map (a map that represents relations among 23 important concepts, 7 or 8 concepts for each part). The relations are of five types: causal, temporal, whole/part, place and property. These five relations correspond to the five pre-created boxes (in the computer condition) or the five“define-link” paper tools (in the tabletop condition).

The actions that a group had to perform during the task include visually searching the workspace (or the monitor in the computer condtion) for concepts, repositioning concepts on the table (or screen), passing on objects (mouse, paper concepts, text documents) to other group members, and manipulating the objects (creating links among concepts, deleting links).

3.6.3 Participants and conditions

Forty-eight university students were solicited and renumerated to participate in the study. They may or may not have had some knowledge about the topic. 23% of the volunteers were female (11 people) and 77% male (37 people). 16 groups of three students were randomly formed based on their availability time. The participants did not know each other before the study. The groups consisted of one female and two male participants in 11 of the groups, and three male participants in each of the remaining five groups.

The two experimental conditions were: (1) the tabletop condition, in which the participants used the DockLamp (hereafter called tabletop groups) and (2) the computer condition, in which they built concept maps using a traditional computer with a single mouse and keyboard (computer groups). Eight of the groups were assigned to one condition and the remaining eight to the other condition.

3.6.4 Procedure

After a brief introduction of the purpose of the study, each of the experiments lasted 90 minutes, consisting of seven phases as follows (Figure 3.11).

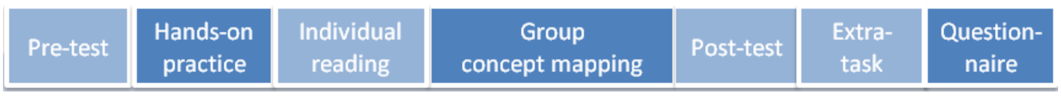


Figure 3.11: The 7 phases of the ConceptMap study.

Pre-test. Each participant individually completed a 30-question test: six multiple-choice questions and 24 inference verification questions. A multiple-choice question included four possibilities with one or more possible correct answers. The inference verification questions included true or false assertions of a statement. The pre-test consisted of three parts, each part with two multiple-choice and eight inference verification questions, related according to the three parts of the document. All questions were validated by domain experts (a neurobiology researcher and a biology teacher) and tested with students in another experiment.

Hands-on practice. The participants were then given instructions on how the system worked and allowed to create sample concept maps until they were familiar with the technology.

Individual reading. 7 mins. Each member of the group was given a different page of the document and asked to read it individually. They were allowed to take notes on these pages or in other separate notebooks.

Main task: Collaborative concept-mapping. 28 mins. The group was given 23 important concepts in the document. In the computer condition, those concepts had already been created in the CmapTools program[1] prior to the study. In the tabletop condition, those concepts were printed on pieces of paper. The group was asked to collaborate the way they wanted, given that the ultimate goal was to understand the concepts and their relationships and to be able to externalize their knowledge onto a concept map. There was no reward for finishing early.

Post-test. 7 mins. The participants individually did an identical test to the pre-test.

Extra-task. 12 mins. The groups then switched interface (computer interface if they had used tabletop during the concept-mapping phase and vice versa) to re-build the concept map that they had created in the main task.

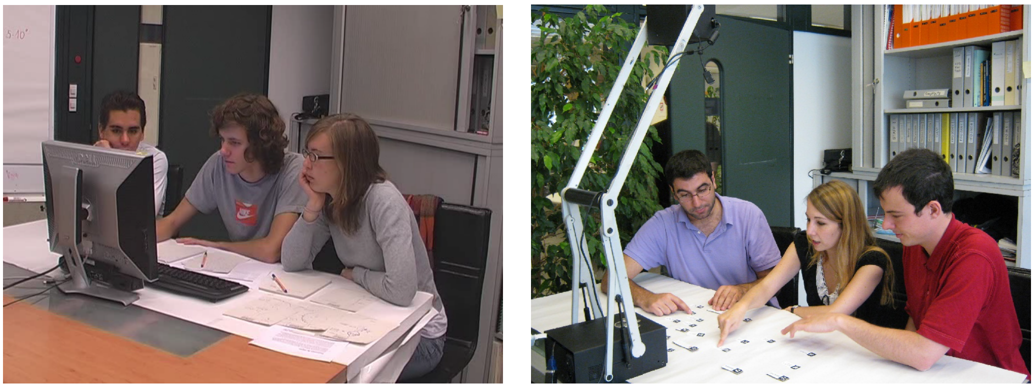
Usability questionnaire. Each participant filled out a 7-point Likert-style questionnaire customized from the IBM's CUSQ questionnaire (Lewis, 1995). The participants were also asked to list the top 3 negative and positive aspects of both interfaces according to their experience. An unstructured interview with the groups ended the study.

Materials for this experiment, including the reading document, the tests, and usability questionnaire can be found in the Appendix B.

3.6.5 Technical setup

The computers used in Computer Condition and inside the DockLamp were identical: Intel CoreDuo, 2.4Ghz, 2Gb RAM. Seats were positioned in a side-by-side setup with three chairs next to each other across the long side of a table whose size is 1.6m x 1m (Figure 3.12). This position setting was used to prevent any bias against the computer condition as this is the only setting that can allow participants to perceive all visual cues from the monitor. Visual display sizes remain similar across the two conditions: the projection (tabletop condition) is

[1] http://cmap.ihmc.us



(a) (b)

Figure 3.12: The ConceptMap experiment: Three subjects using a) Computer b) DockLamp interface.

45cm by 35cm and the monitor real estate (computer condition) is 40cm x 35cm, both with a resolution of 1024 x 768.

Specific setup for the computer condition

Besides an LCD monitor, a wireless standard keyboard and 3-button mouse were used, which allowed group members to share and pass the tools between one another without any obtrusive limitation. The computer program used to build a concept map in this condition was IHMC CmapTools version 4.18. It had also been previously used by about 100 students during our other experiments without any usability problems.

Specific setup for the tabletop condition

In this condition, participants manipulated (moved and rotated) concepts printed on small pieces of paper, collaborating under the DockLamp. The interface used for the study was a partial implementation of the whole scenario presented in section 3.3.3. The functionalities provided in this implementation are as follows. Subjects can use only pre-printed paper concepts, and the “create-link”, “delete-link” and “define-link” paper tools (without typing concepts or linking definitions on-the-fly). The reason we did not support the “bring-close” option to create a link is because, we saw in the pilot study that it created lots of accidental links due to the density of physical paper concepts on the table. The two ways of deleting a link, with paper and finger were both provided. That is, besides using a “delete-link” paper tool, another way to delete links was to use two fingers. Participants simply tapped two fingers on a link, kept them still for two seconds, and the link was deleted. No typing, saving, or loading actions were included.

The paper concept pieces were printed in black and white. The paper tools (used for creating/defining/deleting link) were printed in color. Each paper is stuck to a small piece of cardboard 2mm thick for easy manipulation.

Usability and pilot studies

Usability problems reported during five pilot studies with 15 participants were corrected prior to the ConceptMap study. All subjects stated that they were not bothered by the speed of the program during our pilot studies. The experiments were conducted under controlled lighting conditions (indoor, no direct sunlight, illumination varying from 600 to 800 lux).

3.6.6 Dependent measures

We gathered multiple sources of data: (1) direct observations of group interactions, (2) recorded logs of concept maps created by the groups, (3) pre- and post-study scores for learning performance, (4) satisfaction questionnaires and (5) video recordings of group interactions. We used five dependent measures, three at the individual level and two at the group level.

Individual measures

Individual Learning Gain Total (denoted as IGT). This variable is computed for each participant by taking the difference between the post-test score and the pre-test score. The students having a certain amount of knowledge about the topic before the experiment would normally score high on the pre-test and hereafter are called the high-expertise students.

Individual Learning Gain from Partners (IGP). This variable reflects the number of questions for which students provided correct answers despite the fact that the corresponding information was not included in their partial text. This variable shows how much knowledge was shared to this individual by his/her partners.

Self-Reported Interface Preferences. We report here the analysis of participants' agreements on two items in the satisfaction questionnaire: "I like using the interface of this system" and "Overall, I am satisfied with this system".

Group measures

Group Learning Gain Total (GGT). The sum of all three IGTs in the group.

Group Learning Gain from Partners (GGP). The sum of all three IGPs in the group.

We expected that the support of tangibility and simultaneous actions and the nature of tangible tabletop interfaces would facilitate collaboration among group members and hence lead to more positive learning outcomes. Specifically, we expected that groups using tabletop interfaces will have a higher result than those of groups using the computer interface in each of the five dependent measures.

3.7 Findings

3.7.1 Learning gain

The interface had no significant effect on the Group Learning Gain Total. A t-test found no difference between GGT in two conditions, $t(14) = 1.24, p > .05$, two-tailed, though computer groups gained higher on average ($M = 25.63$ vs $M = 21.88$ for computer and tabletop groups respectively).

To look for an explanation of this non-significance, we looked at the work in (Sangin et al., 2008), in which the authors used the same experiment task in a study about knowledge awareness tool, and found an effect of the heterogeneity in learners' prior knowledge on learning performance. This "group heterogeneity" factor is computed as the standard deviation of the pre-test scores from all three group members.

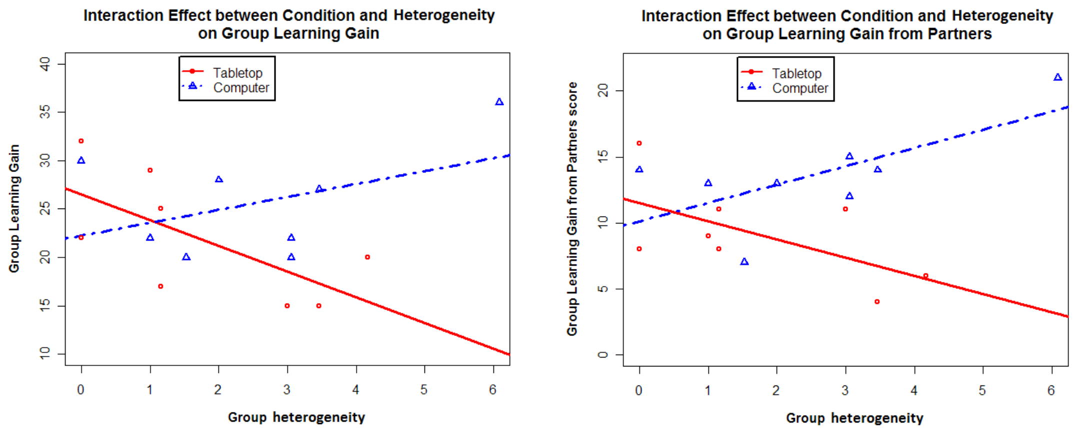
We used this group heterogeneity factor and the condition factor in a multiple linear regression with the Group Learning Gain Total GGT as the response variable. The two explanatory variables used for the regression were the condition factor and the group heterogeneity. The results showed that *there was an interaction effect between condition and group heterogeneity*, $F(1,12) = 5.74, p =< .05$.

Figure 3.13a shows that when group heterogeneity increases, the group learning gain increases for groups using the computer interface (dashed blue line), and decreases for groups using the tabletop interface (solid red line). This indicates that the condition impacted the group learning gain differently according to the members variance in pre-test scores.

Computer interface groups had significantly greater scores in Group Learning Gain from Partners (GGP) than tabletop interface groups. This surprising finding states that, in the computer condition, the GGP averaged 13.63 points, compared to 9.13 points in the tabletop condition, a significant difference confirmed by t-test, $t(14) = 2.40, p < .05$, two-tailed.

An interesting explanation for this difference was found when we fit a multiple linear regression model with GGP being the response variable and the condition factor and group heterogeneity being the two predictor terms. The result showed that the interaction between group heterogeneity and condition is a significant predictor of GGP, explaining 57% of total variance in GGP ($R^2 = .57, F(2,13) = 8.59, p < .005$). As shown in the visualization of the interaction effect (Figure 3.13b), when the variance in pre-test scores among three group members increases, groups in the computer condition learned more from their partners (dashed blue line), whereas this outcome decreased for groups in the tabletop condition (solid red line).

The interface used by groups had no significant effect on the Individual Learning Gain To-



(a) (b)

Figure 3.13: Interaction effect between condition and group heterogeneity: (a) Heterogeneous groups scored less in Group Learning Gain Total in the tabletop condition compared to those in the computer condition. (b) Heterogeneous groups learned less from their partners in the tabletop condition compared to those in the computer condition.

tal (IGT) that each participant achieved. When using computer and tabletop interfaces, each individual scored on average 8.54 points and 7.29 points respectively in the IGT. This is not a significant difference: $F(1,45) = 1.12, p > .05$.

The interface had a marginally significant effect on the Individual Learning Gain from Partners (IGP) that each participant achieved. Participants who used the computer interface achieved an IGP score of 4.54 on average, which is higher than those who used tabletop interface, averaging 3.04 points. However, this divergence in IGP was only marginally significant, $F(1,45) = 3.29, p < .07$.

These results are summarized in Table 3.1.

Measure	Condition		Statistical test
	Computer	Tabletop	
Group Learning Gain Total (GGT)	$m = 25.63$	$m = 21.88$	t-test, $t(14) = 1.24, p > .05$
Group Learning Gain From Partners (GGP)	$m = 13.63$	$m = 9.13$	t-test, $t(14) = 2.40, p < .05$
Individual Learning Gain Total (IGT)	$m = 8.54$	$m = 7.29$	ANOVA, $F(1,45) = 1.12, p > .05$
Individual Learning Gain From Partners (IGP)	$m = 4.54$	$m = 3.04$	ANOVA, $F(1,45) = 3.29, p < .07$

Table 3.1: Summary of the difference in learning outcomes between two conditions: Computer and Tabletop.

3.7.2 Amount of speech

Participants spoke slightly more about concept maps in the computer condition than in the tabletop condition, $t(46) = 1.78$, $p = .08$. This result was achieved by coding all of the videos to count the time spent speaking about the content of the texts and concept map-related issues. Since each group member read a different part of the document, it was crucial that they explain their text to the partners in order to build the whole concept map. *This difference in speaking time in part may explain the higher score of learning from partners (GGP) in the tabletop condition.*

We looked further at the video recordings of the three groups that had the best and worst learning gain. The best group was in the computer condition, which spoke for a total amount of 1004 seconds (60% of the total time of the main task). The amount of speech contributed by each member was 208 seconds (11% total time of the main task), 488 seconds (24.8%) and 308 seconds (15.7%), respectively.

As predicted, we found that the worst group (which happened to be in the tabletop condition) did not talk much. The amount of speech from this group was so low that we decided not to analyze their data. We rather chose the second worst group (also from the tabletop condition) for more useful information. The members of the second worst group spoke more than two times less than the best group, for a total time of 496 seconds. Each member contributed 240 seconds (14.1%), 151 seconds(8.9%) and 105 seconds (6.2%), respectively.

3.7.3 Collaboration process

Mode of collaboration

We observed that groups in the computer condition worked closely together from the beginning until the end of the experiment. At the beginning of the experiment, five of the eight groups in the computer condition started the concept-mapping phase by explaining their own texts to their partners. After that, they would go on to build the concept map collaboratively. The other three groups started by working together right away with on-screen manipulations intertwined with explanation along the way.

On the other hand, in the tabletop condition, the strategies seemed to be richer. Groups in the tabletop condition shifted back and forth between a parallel mode, i.e. people working individually, and a collaborative mode, i.e. people working in collaboration. Their strategies involved a mix of explanation, individual work and group work. Only three out of eight groups started off by taking turns to explain their texts. Five groups started without explanation. These groups all did parallel physical manipulations individually right from the beginning.

The problem of manipulation temptation

We noticed several instances of what we coined *"manipulation temptation"* in the tabletop condition. This term refers to the fact that the tabletop interface seemed very tempting, and led the students to manipulate too much without much discussion or reflection.

The first example is described above, when most groups in this condition started to manipulate concepts right at the begining without discussing or explaining the texts to each other.

Other examples could be found during simultaneous manipulations. Although these parallel working periods helped group members to be able to be independent in creating, defining or deleting links separately, they may not necessarily be considered productive: sometimes groups spent too much time working individually rather than communicating and thinking with their partners, like in the following extract:

1 S3: ''Channels opening''. Is that what you have?
2 S1: What? (S1 is busy building her own links and did not pay attention)
3 S3: ''Channels opening''. I think there is a way to create a link.
4 S2: With the channels opening? (S2 is also more concentrated on building his links, asking without looking up)
5 (S3 stops asking in frustration.)

In the computer condition, these concurrent actions happened occasionally, but since there was only a mouse and a keyboard, participants generally worked together. For example, the group that scored the highest scores in both measurements (*GGT* and *GGP*) started the main task by taking turns to explain their own texts, and then collaborating to build the concept map. In the course of collaborating, all questions were addressed to the group as a whole. They also asked their partners to confirm every time a link was created.

3.7.4 Roles assignment

While participants were assigned to specific contents, explicit roles for executing the task were not assigned. However, video analysis showed that people assigned roles implicitly. In the computer condition, this was clearly the case. Very often, the person who sat closest to the keyboard or mouse would be the one to use it. Generally, the subjects who sat to the right of the monitor were the ones who used the mouse; the subjects who sat in front of the monitor were the ones who used the keyboard. Any group member who wanted to do something would propose an action out loud and then wait for the members controlling the devices to carry out the real action. These implicit roles were not changed throughout the activity.

In six out of the eight computer groups, there was a "leader" who emerged. They were high-expertise students who suggested to the two others what to do and guided the whole conversation. Quantitative analysis showed that there is a strong correlation between expertise and speaking time (Pearson's $r = .28, df = 46, p < .05$).

In the tabletop condition, there was less evidence of role distribution. All members participated quite equally in the task. However, in cases where there was a high-expertise student in the group, that person would lead the conversation at the beginning of the experiment when the group members were explaining the texts to each other and *would fade out gradually towards the end.* This fading was likely because all members had something in front of them to do with the tabletop interface and did not pay attention to the "leaders" like in the computer condition.

3.7.5 Concept maps

We analyzed the impact of the type of interface on the concept maps that participants created during the task. In the computer condition, participants created concept maps with an average of 23.88 links, while in the tabletop condition, concept maps had an average of 24.88 links, not a significant difference by t-test, $t(14) = -.52, p > .05$.

The numbers of "interlinks", i.e. links connecting two different concepts initially given to two different group members, do not differ statistically across conditions ($t(14) = .7, p > .05$), although groups using the computer created more interlinks ($M = 8.12$), compared to $M = 7.00$ in the tabletop condition.

3.7.6 Usability aspects

Satisfaction and preference

Overall, in the usability questionaires, the tabletop was rated with a mean of 5.16 out of 7 points, compared to a 5.36 for the traditional computer interface. This means that they are fairly satisfied with the tabletop despite being completely new to the interface.

We are interested in the satisfaction level of the users, and hence analyzed question 8 ("I like using the interface of this system") and 9 ("Overall, I am satisfied with this system") more closely. We expected that participants would prefer to use the tabletop interface (H5) but be more satisfied with the computer interface due to their familiarity with it.

The results show that participants agreed significantly more with the statement "I like using the interface of this system" for tabletop interface (5.78 in average) than for computer interface (4.96 in average). This was confirmed by a Wilcoxon sign-ranked test, $W = 372.5, p < .05$. On the other hand, there was no statistical difference in the agreement level for two conditions with the statement "Overall, I am satisfied with this system" ($W = 219, p > .05$). Participants in the computer condition had an average rating of 5.65, compared to that of 5.44 in the tabletop condition.

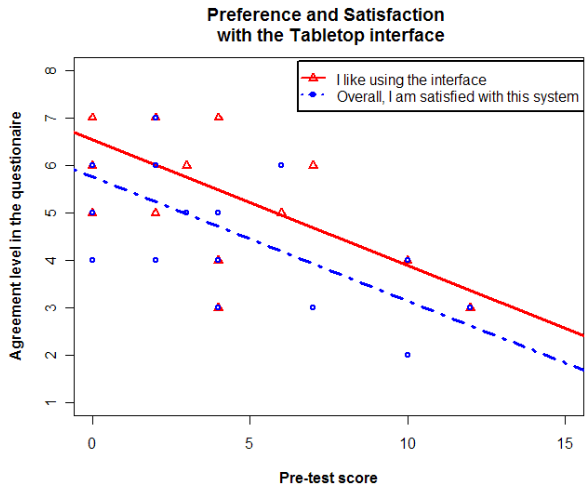


Figure 3.14: The low-performing students were more satisfied and preferred using the tabletop interface than the high-performing ones.

Performance-preference paradox

When exploring the data in the tabletop condition, we found a quantitative result similar to the so-called Performance-preference paradox (Oviatt et al., 2006), which was described as a negative correlation between knowledge and preference for high-tech interfaces. Our result indicates that participants who scored low in the pre-test agreed more with the statement "I like using the interface of this system" than those who scored high (mixed linear regression, $F(1,14) = 22.34, p < .0005$). In other words, the high-expertise students did not seem to like the tabletop interface as much as the low-expertise ones, probably in part because they did not feel able to influence their peers. In contrast, the low-expertise students who were able to easily participate and manipulate their own concepts showed a high interest in the interface. Figure 3.14 illustrates this issue.

This finding was replicated when we checked the pre-test score against the agreement level on the statement "Overall, I am satisfied with this system". The fewer correct answers the subjects made during the pre-test, the more they were satisfied with the tabletop interface ($F(1,15) = 9.18, p < .01$). We did not find the same effect with the computer interface.

Comments on negative and positive aspects

We asked the participants to report their comments on the most negative and positive aspects for the other condition. The top 3 negative aspects for the tabletop interface are: (1) mis-detection, (2) small workplace and messy visualization, (3) less speaking. The top 3 positive aspects are: (1) concurrent interactions and collaboration, (2) intuitive interaction, (3) tangible interaction.

The unstructured interview with the groups after the study revealed reasons for those preferences.

Mis-detection. Although there was no serious error caused by the computer vision algorithm, several detection errors occurred in the tabletop condition, namely the paper or finger not being detected properly. Subjects noted that they were distracted from the learning task when those errors happened. This was mostly the case when the background model of the table did not adapt fast enough to the interactions.

Small workplace and messy visualization. Subjects had several complaints about the tabletop system since there were so many concepts in the task. They stated "it is hard when I have to look for a concept among the others". Some said "the projection is too small and the links are everywhere in this dense space"(the projection size is 35x45 cm, similar to that of a 21-inch monitor, a paper concept size is 2x7 cm). These responses explain the second negative aspect. While the small workplace is unavoidable to retain the DockLamp's mobility, the messy visualizations could be overcome with another task that does not require so many pieces of paper on the table.

Less speaking. The participants commented that sometimes the ease of manipulation made them "play" with the papers and fingers more than they should have. This led to the "less speaking" aspect reported in the top 3 negative aspects for the tabletop condition. As a participant put it: *"this is nice but there is a problem of mutual and shared understanding when everybody is working individually".*

Positive aspects. On the positive side, all participants appreciated the affordances that the tabletop interface provided. The most positive aspect was concurrency of interactions and collaboration. The participants liked the fact that they could interact simulataneously. The second most positive aspect was that the interface was intuitive and easy to use. The third aspect was the tangibility of paper pieces, which enabled fast and concrete manipulations.

3.8 Discussion on the ConceptMap study

3.8.1 Effects on collaborative learning

The results show that, at the group level, there was a significant effect on "Learning Gain from Partners" in favor of the computer condition. Groups using the computer interface had statistically higher scores in this measure than groups using the tabletop interface. There was no significant benefit of using the tabletop interface compared to using the traditional computer interface in every other measures.

There are several possible explanations for these results.

Negative effect of tangible tabletop on heterogeneous groups

There was an interaction effect between condition and group heterogeneity. Groups with more variance in initial knowledge among members learned more in the computer condition but struggled in the tabletop condition. In other words, the tabletop interface is considered harmful, to some extent, for groups whose members do not have equivalent knowledge about the topic. One might speculate that this effect might be because, with the tabletop setting, the high-expertise students failed to lead the conversation as much as with the computer setting. Other group members were sometimes too busy manipulating and did not pay attention to what they had to say. That is probably why they were not satisfied with the tabletop interface as much as the low-performing students (the performance-preference paradox).

Less discussion in tabletop condition

Participants in our study spoke slightly more in the computer condition and the qualitative analysis shows that speaking might have some effect on learning outcomes. This is somewhat in line with the studies (Rogers et al., 2009; Birnholtz et al., 2007) in which the authors found that the single access point with mouse and keyboard in some way forces more verbal interaction between group members. It can be argued that the best group's members who were in the computer condition scored higher in the learning gain measure since they had a higher amount of speech, questioning and confirming the new knowledge from their partners.

Problem of manipulation temptation

Another possible explanation for the higher scores in the computer condition is that the tabletop interface provides a two-fold effect. On one hand, as also suggested in (Marshall et al., 2008), it allows more freedom and equity in interaction(i.e. simultaneous manipulations with the system from multiple users). On the other hand, the *manipulation temptation* problem contributes to a lack of verbal collaboration which is considered beneficial for learning activities (Webb, 1989; Dillenbourg, 1999b) or even decreases the quality of discussion. Each group member focused on his own actions, looking down to the table, instead of discussing with the group. Group members may have misunderstood or learned information incorrectly without having a chance to confirm with their partners since they were busy doing their own manipulations on the tabletop.

We learned from the post-study questionnaires that participants preferred to use the tabletop than computer. While they clearly had fun with the interface, the tabletop is not so "collaborative" in terms of speaking and thinking together. This playfulness, which is still a good factor, caused problems in terms of lack of reflection. Sometimes the students spent too much time "playing" individually with the interface (i.e. "manipulation temptation" problem) rather than really communicating and reflecting with their partners.

All these issues discussed above were in fact closely related. They all centered around the notion of lacking of discussion and reflection, which later became a key issue in the rest of this thesis.

3.8.2 Limitations of the study

We took a holistic approach: our study compared the DockLamp with the traditional computer as an ecologically valid complete unit. We were interested in how high-level tasks are performed with the traditional computer as a whole and with the multi-user tangible interface as a whole. The limitation of this approach is that it is difficult to associate the effects to a specific factor. There is no simple and certain answer to an effect as all the variables may interact with one another and contribute in a complex way. While some of the factors such as the display orientation, the input methods, and the input entry points have been controlled in other experiments (Rogers and Lindley, 2004; Rogers et al., 2009; Marshall et al., 2008; Ha et al., 2006), it is difficult to separate them in our study which is more observational.

In this study, we used measures at two levels, i.e. individual and group learning gains. These two measures, and hence the respective statistical tests are not independent. For this reason, the results at the two levels are quite consistent, even though the 'individual learning gain from others' only resulted in a marginal signficance, as opposed to the statistical significance of the 'group learning gain from partners' measure (this discrepancy may have to do with the group heterogeneity that was described in the qualitative analyses). While only individual measures may have sufficed, we included both levels because we wanted to take advantage of the group measure to explore the effect of group heterogeneity on group learning gain as proposed by Sangin et al. (2008).

As we stated, evaluating educational outcomes is a complex and still open issue. Hence, the results of our study should be interpreted with the particular focus of the study in mind: expressive task type, tangible input, and short-term knowledge comprehension testing. Other factors include the specific knowledge domain, projection size, and group size.

3.9 General discussion on the DockLamp

3.9.1 Benefits of hand and paper interactions

The satisfaction questionnaires suggested that the use of these new interaction styles (finger and paper) extends the types of actions that people can perform under augmented tabletop environments. These interaction styles led to a richer quality in the collaboration process. Both the paper tools and fingertip interaction were appreciated by our participants and hold promising potential in other learning scenarios.

Although the participants used both paper tools and fingers to interact with the system, it seemed that paper tools are a more general method. Paper tools offer greater flexibilities for the users. As one participant said: *"I used fingers to delete links at the beginning but prefered to use paper to delete in the later stage because it is small and therefore more suitable in cramped space"*. The reason users used fingertip deletion was mainly that they do not have to think and look for the particular piece among a lot of other papers. These findings imply that paper interfaces, or tangible interface in general, are probably best utilized when the distribution of paper pieces on the table is not too dense.

3.9.2 Benefits of portability in real settings

We use our experience with the DockLamp to argue that the portability of a tangible tabletop system are more suited for classroom use than traditional setups. The DockLamp itself was not cheap and not really solid because the integration of folding mechanical devices makes it tall and fragile. Nevertheless, it presents an interesting example of how a portable tangible tabletop can facilitate its deployment significantly. This is very crucial in designing systems for classroom settings for two reasons.

First, the portability helps the researchers easily setup their system in real classrooms, reducing time and effort. More importantly, the portable and small system can fit into existing classrooms. We can simply arrange classroom furnitures and objects to accommodate the systems, and later put them back in their previous arrangement after the learning session.

Second, they occupy equal or less real estate than fixed big systems. Due to their small size, multiple units in the classroom can be setup and allow more (if not all) students and groups to interact and learn at the same time. This will likely increase the adoption rate of the technology in real settings.

These reasons partly inspired the design of our portable TinkerLamp, which is a tangible tabletop system developed to support collaborative learning of logistics apprentices. It will be described in detail later in the next chapters.

3.9.3 Learning and tangible tabletop systems

The literature has neglected to examine the effects of tangible tabletop interface on a learning task of a higher level abstraction such as comprehension or synthesis. We conducted an empirical comparison between a tabletop interface, the DockLamp, and a traditional computer to contribute to our understanding of this issue.

It is worth remembering that the study had some limitations, including a small sample size, and a combination of these limitations affected the learning outcomes in our study.

The most important findings we found are summarized as follows.

Support for simultaneous and equal participation. On the positive side, the tabletop afforded more concurrent physical manipulations, and resulted in a variety of interaction styles, and more equity in interaction, similar to (Marshall et al., 2008; Rogers et al., 2009).

Problem of manipulation temptation and lack of discussion. On the negative side, tabletop systems need further thought and consideration when it comes to learning outcomes. First, there is a *"manipulation temptation"* during the interaction. Participants seemed to have too many individual manipulations which sometimes led to unproductive collaboration and less discussion. The collaboration strategy also seemed to be affected because students were tempted to manipulate right away without much discussion. Second, the high-expertise students failed to transfer their knowledge to their peers, probably due to the effect of multiple points of access and parallel working. These problems implied that similar systems should consider reducing these negative effects to let students focus more on reflection and discussion.

In chapter 4, we show similar findings from another experiment using a different task and in a real setting. Together, they bring more insights as to how to maximize the positive effects of tabletop systems in terms of students' learning.

3.10 Summary

We presented the design and evaluations of the DockLamp and its interaction techniques. Our goal however, was not only to design a tool. We were also interested in studying its implications on users' activities and on the way they learned collaboratively. The work presented in this chapter is only a first step in our effort to explore the effect of tangible tabletop interfaces on collaborative learning tasks. We showed our analyses that provide more insights with regard to how these innovative interfaces affect verbal interaction processes, interaction quality, strategy, and collaboration processes.

The implications of this chapter are:

- Future systems should consider portable design for easier setup, deployment and adoption.
- A tangible tabletop can potentially create a lack of students' reflection due to the negative effect of the *manipulation temptation* problem. Future systems should take care of the trade-off between individual manipulations versus group reflection and discussion.

4 TinkerLamp and Warehouse Study: a Tangible Tabletop in the Classroom

4.1 Introduction

This chapter presents the TinkerLamp, a tangible tabletop environment we developed for logistics apprentices, and the Warehouse study, a study that investigated the effects of this environment on learning in a classroom setting.

The TinkerLamp helps apprentices and teachers engage in interactive learning activities via the use of tangible objects and augmented paper. Several TinkerLamps were installed and used in three professional schools in Switzerland. These deployments enabled us to examine how groups of apprentices, typically aged 16-20, study around multiple TinkerLamps in parallel and how the teacher interacts with them.

We compared the task performance, understanding, and problem solving scores of 61 apprentices studying in one of two conditions: either around the TinkerLamp or using paper and pen. Then, by focusing on the quantitative and qualitative data in the TinkerLamp condition, we provide evidence that, similar to chapter 3, tangible tabletops have both positive and negative effects on student collaboration, learning and reflection. We also show that supporting teacher's classroom orchestration is crucial in order to alleviate this negative effect.

4.2 Research context

4.2.1 Dual model, logistics training and the abstraction gap

(a) (b)

Figure 4.1: There is an abstraction gap between what is taught at school and what the apprentices do at work. a) Learning at school is usually abstract. b) Working in warehouse is limited to simple and basic tasks.

In Switzerland, the prevailing organization of vocational training follows a dual approach: apprentices work three to four days per week in a company and spend one day per week in a vocational school (Figure 4.1).

The dual model promises a close relation between concepts taught at school and working experience. The work presented here is part of the DUAL-T project funded by the Swiss Federal Office for Professional Education and Technology. DUAL-T explores the potential of learning technologies in vocational training, focusing on learning activities that merge the school and workplace.

The domain of our interest is logistics, a profession that involves the storage and transportation of goods, the design of warehouses and transportation routes, as well as the management of inventories and information. It appears that besides its advantages, the frequent context switching of the dual model also presents several problems for logistics apprentices. Observations and interviews led us to identify a central problem in the training of apprentices which we refer to as the "abstraction gap", i.e. a gap between the level of abstraction taught at school and at work.

On the one hand, school is too theoretical. Our field observations show that what is taught in school is unspecific and inauthentic compared to the apprentices' daily practice. The teachings are usually abstract and often illustrated through mathematical exercises (e.g. compute the storage surface using a warehouse blueprint). Apprentices usually find it difficult to understand this abstract knowledge, or the relevance of the exercises to their practical experience.

On the other hand, at the workplace, apprentices do not have opportunities to reflect on and practice what is taught in school. The types of tasks they perform at the workplace are relatively simple and basic. For example, they are usually limited to moving boxes with a forklift between two locations chosen by a computer, rather than having a chance to apply the higher-level management strategies they are taught at school.

In summary, the switching of context from the company (involving action) to the classroom (involving theory) requires special consideration. The central research question is to find out how educational technologies can be used to bridge the abstraction gap, i.e. to enable the integration of theoretical concepts in concrete experience.

4.3 The TinkerLamp

4.3.1 Design goals of TinkerLamp

The objective of the TinkerLamp system is to create a stronger link between the theory taught at school and the experience acquired at the workplace, aiming to bridge the abstraction gap. More specifically, it aims at helping logistics apprentices understand theoretical concepts presented at schools by letting logistics apprentices experiment these concepts on an augmented small-scale model of a warehouse.

Our goals are for the TinkerLamp to

- act as a bridge to facilitate understanding of high-level concepts through embodied interaction and physical objects that are similar to those they normally find in their workplace.
- support more exploration from the students, helping them have multiple perspectives by trying out different warehouse models.

The TinkerLamp design goals are rooted from several theoretical frameworks.

Practice field

The practice field (Barab and Duffy, 2000) framework provides a conceptual guide to design authentic learning environments. It promotes the design of authentic contexts that reflect the way the knowledge will be used in real life and provide learners with authentic activities. It follows the principles outlined by situated learning (authenticity of the learning situation, complex problem-solving, and expertise modeling) within the context of schools.

To realize this goal, we went on field trips to real warehouses and worked closely with the teachers at vocational schools throughout the project to ensure a real-world perspective when designing the environment. We performed field observations and evaluations to capture the complexity of authentic settings, as opposed to lab experiments.

Embodiment

Embodiment (Fishkin, 2004) is a central notion to our design. It refers to how closely the input focus is tied to the output focus. As embodiment increases, the “cognitive distance” between the input mechanism and the result of that mechanism decreases. This can be useful in our context since we would like to leverage both the apprentices’ practical experience and manual manipulation to support their own learning.

However, as partly informed by our ConceptMap study (chapter 3), embodiment, which brings about concrete manipulation and engagement, may lead to unproductive collaboration and less discussion (the “manipulation temptation” problem). Marshall et al. (2003) argued that too strong embodiment may be counterproductive if the goal of the activity is to foster reflection.

Multiple External Representations

As the concrete representation offered by the small-scale model may not be enough for knowledge abstraction, we applied the principle of Multiple External Representations (MERs) (Ainsworth, 2006). MERs is a learning approach which proposes that presenting learners with the same information several times at different levels of abstraction will act as a scaffold, allowing them to understand more deeply.

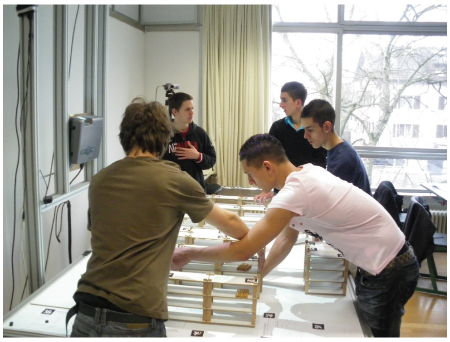
Working with a tangible augmented simulation involves the coordination of multiple external representations of varying levels of abstraction (Scaife et al., 1996; Blackwell and Green, 2003) which in turn support different levels of reasoning (Bruner, 1966). We aim to provide a bridge between tangible concreteness and abstract notions by having other representation types, such as virtual graphs, numbers and visualizations that are projected on the table.

4.3.2 Design of TinkerLamp

The TinkerLamp enables apprentices to perform problem-solving activities in an immersive environment like a real warehouse (Figure 4.2a), and hence relate them to their practical working experience (Jermann et al., 2008; Zufferey et al., 2009).

Sharing some characteristics with the DockLamp presented in chapter 3, the TinkerLamp is a portable tangible tabletop system. A projector and a camera are mounted in a metal box suspended by an aluminum body which is 1.2m high. The size of the projected interactive surface is approximately an A3 paper (50 x 37 cm). The projector and the camera are connected to a computer. This computer recognizes tagged objects on the table via images captured by the camera and commands the projector to project corresponding visual feedback.

(a)



(b)

Figure 4.2: a) TinkerLamp, a tangible tabletop system for logistics training. b)TinkerTable, the initial design which lead to the current TinkerLamp.

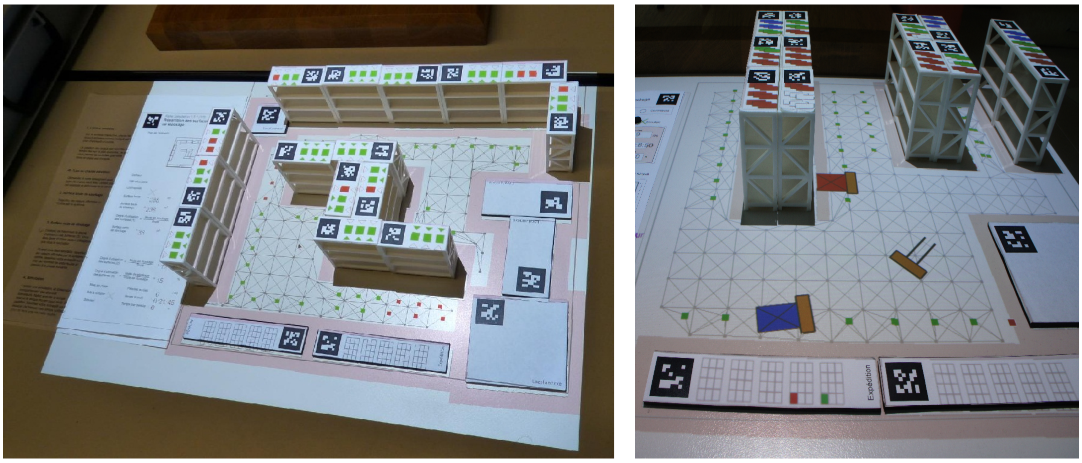
The TinkerLamp's design was the result of an iterative process. It evolved from being a big table (2.5 x 1.5 m) as illustrated in Figure 4.2b to the current smaller size (Figure 4.2a). This evolution was partly informed by our experience with the DockLamp's portability (chapter 3, section 3.9.2), and partly by our observations of the TinkerTable in the classroom. This replacement of the big TinkerTable by multiple small TinkerLamps are for several practical and pedagogical reasons.

In terms of practicality, the advantage of the TinkerLamps is that they do not need a reserved space in the classroom. They can be put away when not in use and brought out when necessary. This factor allows them to fit into existing environments easily.

In terms of pedagogy, having multiple TinkerLamps in a classroom allows the teacher to have every student involved in an activity with the same task. When TinkerLamp was still a big table (TinkerTable), only one unit could be placed in the classroom. This setup complicated the task of the teacher. Since only 4 to 6 apprentices could work around it at the same time, another task had to be assigned to the rest of the class. Consequently, it posed certain difficulties for the teacher, namely monitoring several groups working on different tasks in parallel. Using multiple TinkerLamps reduced this stress by enabling the whole class to work on the same task.

Apprentices and teachers interact with the TinkerLamp through a user interface, involving two interaction modalities: a tangible warehouse model and a paper-based interface, called TinkerSheet. The warehouse small-scale model is our realization of the practice field goal and the embodiment design goal. The TinkerSheet is our realization of the Multiple External Representations design goal. The idea is to present apprentices with the same information projected both on the warehouse small-scale model and on the TinkerSheets, allowing them to relate one representation to the other and progressively build a valid model about the logistics concepts.

4.3.3 Warehouse small-scale model: tangible interface



(a) (b)

Figure 4.3: Tinker systems: (a) Small-scale model with a TinkerSheet to the left. The red navigation nodes projected on the floor of the warehouse model specify that there is not enough space for forklifts to work with the corresponding shelf. The green ones specify a good situation with enough space for forklifts. (b) A simulation is being run with the warehouse model.

The small-scale model enables hands-on activities which are closer to the real context of a warehouse to help apprentices overcome the lack of abstraction skills. It aims to provide a figurative representation of a warehouse which is easy for apprentices to relate to their own experience.

Users interact with the warehouse model using miniature plastic shelves, docks, and offices (Figure 4.3a). Each element of this small-scale warehouse is tagged with a fiducial marker that enables automatic camera object recognition.

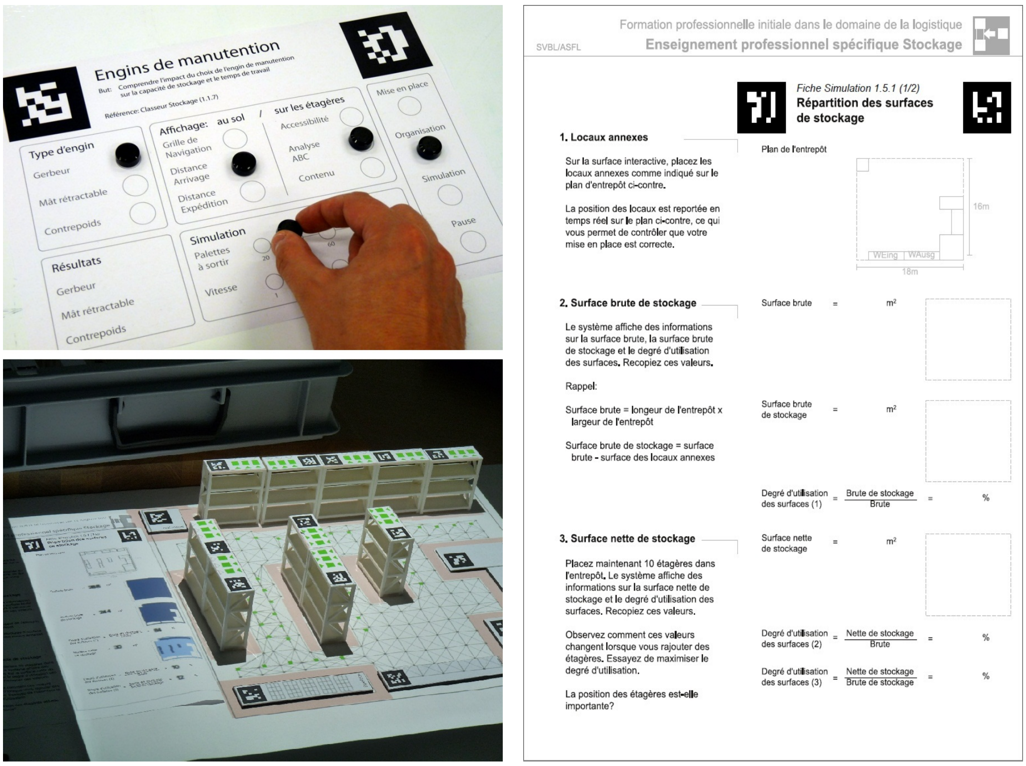
The model is augmented with visual feedback and information through a projector in the lamp's head. Figure 4.3a shows an example of these augmentations: the drawing of navigation nodes around each shelf. When two shelves are placed too close together, the navigation nodes turn red, indicating that there is not enough space for a forklift to work in the alley between these shelves.

4.3.4 Simulation of warehouse models

The apprentices can also run a simulation on the models (Figure 4.3b). The apprentices can choose among three types of forklifts which differ in terms of size and maximum driving speed using the TinkerSheet interface (described below). This choice of forklifts allows apprentices to experiment with the trade-offs between the forklift types and warehouse storage. For example, they can see that forklift types have an influence on both the work efficiency (a faster forklift moves more pallets in a given time) and the storage capacity (faster forklifts are bigger, need larger alleys and thus reduce the capacity of the warehouse).

The simulation computes statistics related to the physical structure of the warehouse such as the areas used for storing goods, the distance between shelves, etc. It then uses simple models of customers and suppliers that generate a flow of goods entering and leaving the warehouse in real-time. This real-time simulated information is displayed directly on top of the model and on the TinkerSheet, e.g. animation of how forklifts approach the shelves, the statistics about the warehouse inventory, or storage management strategies.

4.3.5 TinkerSheet: paper interface



(a) (b)

Figure 4.4: Different types of TinkerSheets: (a,top) The initial design of TinkerSheet, (a,bottom) The final design of TinkerSheet in use, (b) The final design of TinkerSheet with more details

TinkerSheet is a paper-based interface, aimed to address the Multiple External Representations design goal (Figure 4.4). We aimed to complement the concrete representation offered by the small-scale model with less embodied, more abstract representations given on TinkerSheets. TinkerSheets offer a generic container for information at any level of representation, figurative or symbolic, such as warehouse blueprints or numerical data. This information on the TinkerSheets can help apprentices to have multiple perspectives on the warehouse they are building. According to Ainsworth (2006), these representations can facilitate the transition from one level of abstraction to another and result in deeper learning.

TinkerSheet also targets to alleviate the "manipulation temptation" and too strong embodiment problem, encouraging the students to step back from the concrete manipulation and practice more reflection.

A TinkerSheet is a piece of paper automatically tracked in real-time by fiducial markers that allow users to control the system, e.g. setting parameters for the simulation, changing the size of the forklift, etc. It also serves as a visual feedback space on which textual or graphical summary information from the simulation are projected (i.e. the warehouse statistics such as surface areas, degree of utilisation of the warehouse, etc.).

Interaction with a TinkerSheet is primarily performed by using a physical token. Users can just grasp the token, place it in an input area to trigger an action. Alternatively, in case the token is lost, users can also interact with the TinkerSheet by using a pen to draw a filled circle on the input area.

4.3.6 Implementation

The TinkerLamp environment was initially designed by Patrick Jermann and Guillaume Zufferey in the scope of the DUAL-T project. The environment consists of two main components at the implementation level.

The first component is the *Tinker Programming Framework*, which was co-developed by Guillaume Zufferey, Aurelien Lucchi and myself. This framework provides a task-independent base for the development of applications for the Tinker environment. It includes low-level functions such as camera frames grabbing, computer vision detection algorithms, tangible artifacts detection, fiducial marker detection, data flow operations, graphics rendering, coordinate mapping between camera and screen spaces, etc. This framework serves as a basis for all the interactions that the TinkerLamp has to support.

The second component is the *TinkerWare* application, which concerns all aspects related to the logistics domain, (managing tangible shelves, warehouse models, warehouse simulations, etc) provides both back-end and front-end sides to illustrate the concepts addressed in the curriculum of logistic apprentices. The implementation of the TinkerWare component was mainly developed by Guillaume Zufferey in his thesis (Zufferey, 2010). The thesis focused on the complementarity of tangible and paper interfaces and how they can be used to support learning in the logistics domain.

Within the context of the DUAL-T project, I participated in and continued his work, conducting studies of the TinkerLamp and then iterating the design. One of those studies is the Warehouse study, reported in this chapter. The findings of these studies motivated the design of TinkerLamp v2.0 to support more reflection and orchestration (chapter 5).

4.4 Method

4.4.1 Procedure

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

Figure 4.5: Two conditions in the Warehouse study: a) and b) Tangible Condition. c) and d) Paper condition

Four classes with a total of 61 apprentices (56 males and 5 females, ranging from 16-20 years old) participated in the study. The study took place in a classroom during two full days. To simulate the use of the technology in a classroom as close as possible to the reality, the teachers were involved in the study. The students had been using the system in their class for at least one year before the study took place, so they already had an introduction to the TinkerLamp and how it works.

The study used a between-subject design. Figure 4.5 shows the setup of the two experimental conditions: (1) the TinkerLamp condition (two classes of 15 students), in which groups of about 4 apprentices collaborated around the TinkerLamp; (2) the paper/pencil condition (one class of 15 students and another of 16 students), in which the activity involved students doing the same exercises but with paper and pen, without any technological support. There were two teachers, each managing a different class in each of the conditions.

4.4.2 Experiment task

Task description

The experimental task was derived from a typical exercise in the curriculum and hence resembled a school task. The structure of the activity was the result of a participatory design process between researchers and the teachers participating in the study.

The objective of the learning task was to teach different types of surfaces that are used to design a warehouse, e.g. raw surface, raw storage surface, net storage surface, etc. For example, the *raw surface* is simply the surface of the whole warehouse. The *raw storage surface* is the raw surface minus annex rooms (offices, technical rooms, docks, etc.)

The apprentices were required to understand what constitutes each type of surface and its impact on work effciency by building and exploring the physical models. They were expected to explore the warehouse surfaces and figure out the placement of different warehouse elements (docks, storage shelves, administration offices, etc.) by taking into account various constraints, namely the influence of different forklift types on alley width and the transportation speed in the warehouse.

Task structure

The study consisted of three phases: introduction lecture (30 mins), group activity (60 mins) and class debriefing (30 mins) (Figure 4.6). During the lecture, the teacher gave the apprentices an introduction to the concepts of surfaces that they were to learn. The class was then split into four groups of three or four apprentices for a group activity. There were two phases: 1) building warehouse models using only 10 shelves, and 2) building warehouse models using as many shelves as possible. A more detailed description of the task structure can be found on the left side of the two TinkerSheets used for this study (Appendix C, section C.1).

Figure 4.6: The phases of the Warehouse study.

Each group was asked to collaboratively build models, to compare the layouts, and to reflect on what they had built to understand the different types of surfaces. In the paper/pencil condition, they drew warehouse models on paper using pens, erasers, and rulers. In the tangible condition, the group built the warehouse layouts using the TinkerLamp.

In both conditions, the teacher toured around the room to respond to help requests. At the end of the exercise session, the teacher organized a debriefing session where the conclusions of each group were discussed.

4.4.3 Technical setup

TinkerLamp's software

In the tangible condition, there were four TinkerLamps set up at the four corners of the room, leaving empty space at the center of the room for the teacher. The activity took place around the small-scale model and two TinkerSheets. The two TinkerSheets were used one after another, according to the phase of the activities. The first sheet was composed of feedback zones, displaying the different types of surfaces of a warehouse both in graphical and numerical forms . The second sheet let apprentices select the type of forklifts to be used in the warehouse. It contained interactional elements that could be marked with a physical token that allowed the students to run simulations and displays associated feedbacks. The design of these two sheets can be found in Appendix C, section C.1.

Usability and pilot studies

A pilot study was run with the same teachers in two classes (not the classses in this study) several months in advance which resulted in appropriate enhancements in terms of the task structure, setup, and timing. All participants reported in the feedback session that they encountered no difficulty learning and using the TinkerLamp interface.

4.4.4 Measures and analysis approach

The main goal of the Warehouse study was to assess how a tangible tabletop is used in an authentic setting. The analysis focuses on the TinkerLamp interface. We aimed to understand how learning activities take place around this interface and highlight opportunities for the design of similar systems. The paper/pencil condition is included as a baseline condition only for the purpose of quantitatively comparing task performance and learning outcomes.

Quantitative analysis

Since the apprentices did not know anything about the topic prior to the study, there was no pre-test. An individual post-test (Appendix C) was distributed at the end of the study to measure learning gain. Four primary dependent variables were used in the comparison between the two conditions: (1) number of alternative solutions explored; (2) number of shelves in the final layouts; (3) understanding score; and (4) problem-solving score. These measures are described in more detail later in sections 4.5.1 and 4.5.2.

Qualitative analysis

We followed the approach described in (Jordan and Henderson, 1995) for qualitative analysis, relying on different sources of data: field notes, audio/video recordings, and the analysis of resulting artifacts. Among other sources, we analyzed audio/video logs of the groups' conversations and the classroom interactions as a whole, along with the recorded images of warehouse layouts built by the groups throughout the study. Field notes were used to suggest interesting episodes in the recordings. First a content log was created, consisting of a very rough summary listing of events and conversations as they occur on the recordings. The recordings were then analyzed using an open coding approach to allow prominent themes to emerge. When necessary, some coding categories were quantified and content logs were expanded into transcriptions.

Hypotheses

We expected the following results with respect to quantitative measures.

1. Tangible interfaces lead to better task performance (more alternative solutions, and more shelves in the final designs) than the traditional paper-and-pen approach. We assume that apprentices will benefit from the physical and tangible nature of TinkerLamp. This interface should lead to faster manipulation, more concurrent actions and consequently, a greater number of alternative solutions and more shelves in their warehouse layouts.

2. Tangible interfaces lead to more positive learning outcomes (understanding and applying concepts in other situations better) than the traditional paper-and-pen approach. We assume that a small-scale model of the warehouse is better for learning thanks to its concrete representation and embodiment mechanism. Moreover, the multiple representations provided by the TinkerSheets and the warehouse model should also result in more positive learning.

4.5 Findings

4.5.1 Task performance

Task performance was determined by two measures: (1) the number of alternative solutions and (2) the number of shelves in the final layouts.

Number of alternative solutions.

The number of alternative solutions is the number of warehouse layouts that the group tried out during the activity, counted based on logs and recordings. In the tangible condition, it was the number of layouts that were chosen to be simulated. In the paper/pencil condition, it was represented by the warehouse models drawn on paper.

It is evident that in the course of collaboration, apprentices in the TinkerLamp condition explored more alternative layouts than those in the paper/pencil condition. Over the activity, groups who used the tangible interface completed 4.6 layouts on average, and groups in the paper/pencil condition completed only 2.5 on average. This divergence in number of alternative layouts was significant, confirmed by a Wilcoxon sign-ranked test, $W(14) = 8.0, p < .01$.

Number of shelves in final solutions.

The number of shelves in the final layouts was computed based on the number of shelves that the apprentices succesfully placed in the warehouse. The greater this variable is, the better the warehouse is in terms of storage capacity.

The apprentices in the TinkerLamp condition designed final solutions with a greater storage capacity compared to the paper/pencil condition. A t-test revealed a significantly higher number of shelves being placed in the final layout in the tangible condition ($t(14) = 2.36, p < .05$). The students managed to use more space in the warehouse, successfully placing 18.0 shelves on average in the final warehouse, compared to 15.1 shelves by those using paper and pens.

Table 4.1 summarizes these results.

Measures	Paper/pen	TinkerLamp	Statistical test
Alternative solutions	$m = 2.5$	$m = 4.6$	Wilcoxon, $W(14) = 8.0, p < .01$
Number of shelves in final solutions	$m = 15.1$	$m = 18.0$	t-test, $t(14) = 2.36, p < .05$

Table 4.1: Difference between two conditions in terms of task performance.

4.5.2 Learning outcomes

Learning performance was determined by two variables, both through the post-test (Appendix C): (1) understanding score and (2) problem-solving score.

Understanding score.

The understanding score was computed from the first part of the post-test. It represented the understanding of the concepts of surfaces, which the students were supposed to comprehend after the activity. This part consisted of 12 multiple-choice questions, each with four options and only one correct answer worth one point.

The maximum understanding score is 12 (all 12 answers being correct). Analysis revealed that the apprentices in both conditions did learn after the activity. Since there was no pre-test, we compared their mean score with purely random answering. The result showed that their score is significantly higher than that resulted by random answering. A student randomly choosing answers has a probability of only 0.05 of getting 6 correct answers or more (according to a binomial distribution B(12 questions, 0.25 chance of being correct)), while the average understanding scores of both conditions were higher than 7 (mean = 7.84 vs mean = 7.43 for paper and tangible groups respectively). However, the relative difference between the two conditions is not significant, ANOVA test, $F(1,14) = .25, p > .05$.

Problem-solving score.

The problem-solving score was computed from the second part of the post-test. In this part, the apprentices had to answer an open-ended question concerning a realistic warehouse problem. They were asked to maximize the efficiency of an existing warehouse layout. This question does not have one single correct answer but rather involves a trade-off between several constraints (e.g. having as many shelves as possible but still maintaining enough corridor space for forklifts to move around) that the apprentices have to take into account. The problem-solving score was evaluated as the average of several aspects: whether the apprentices successfully augmented the net storage surface in the warehouse, how detailed and correct their propositions were, whether their propositions ensured enough alley space for forklifts' movements and manipulations, etc.

Apprentices in the paper/pencil condition had an average of 5.16, as opposed to 5.15 in the tangible condition (over a maximum of 8), not a significant difference confirmed by a ANOVA test, $F(1,14) = .06, p > .05$. None of the statistical tests on each partial aspect yielded a significant difference between the two conditions.

Table 4.2 summarizes these results.

Measures	Paper/pen	TinkerLamp	Statistical test
Understanding score	$m = 7.84$	$m = 7.43$	ANOVA, $F(1,14) = .25, p > .05$
Problem-solving score	$m = 5.16$	$m = 5.15$	ANOVA, $F(1,14) = .06, p > .05$

Table 4.2: Difference between two conditions in terms of learning outcomes.

4.5.3 Use of tangible shelves and model building activity

As stated, the focus of the analysis is to examine how the TUI affected study practices. Consequently, from this part on, we present the findings concerning the behaviors specific to the TUI condition.

The interaction with tangible shelves appeared to be very engaging and intuitive for the apprentices. They continuously added shelves on the table and tested small variations of their layout. In total, 37 unique warehouse layouts were created and simulated during the study in the TUI condition. As part of this process, many alternative layouts were experimented with by the apprentices but were not considered a final solution. These many layouts illustrate the bigger design space the apprentices had for their exploration. Figure 4.7 shows the number of models each group managed to build during the session.

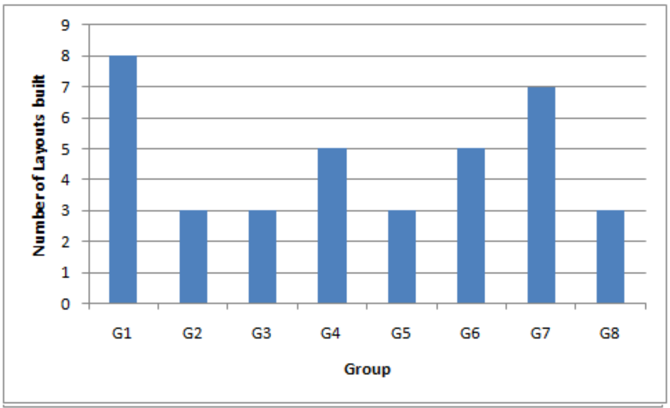


Figure 4.7: Number of layouts completely built and simulated by each group.

We performed a correlation test between the apprentices' manipulation level and their learning outcomes. Results showed that there was no significant correlation between the physical manipulation level and the learning test scores (Pearson's correlation $R^2 = .14, p > .05$).

To understand how the warehouse building process took place, we computed the time to complete a warehouse layout based on video timestamps according to when students started and stopped constructing each layout. We did not include time spent in off-task behavior. Our analysis (Figure 4.8) showed that the time to complete a layout varied from 1 minute to 14 minutes (3-5 minutes on average for any given group). This variation in length was mainly due to the following factors.

- First, it depended on the activity the teacher asked the students to perform. Maximizing the net surface with as many shelves as possible took more time to complete than building the warehouse using only a few shelves, for example.
- Second, it depended on the length of discussion that the students had along the building process. Some models were built very quickly with apprentices only focusing on manipulation and not talking much along the way. Some models were discussed extensively among group members, which strengthened the time to complete.
- Third, discussion with the teacher also extended the building time. The discussion between the groups and teachers usually were at a higher level, i.e. reflection about the surface concepts, and how these concepts were related with the model being built.

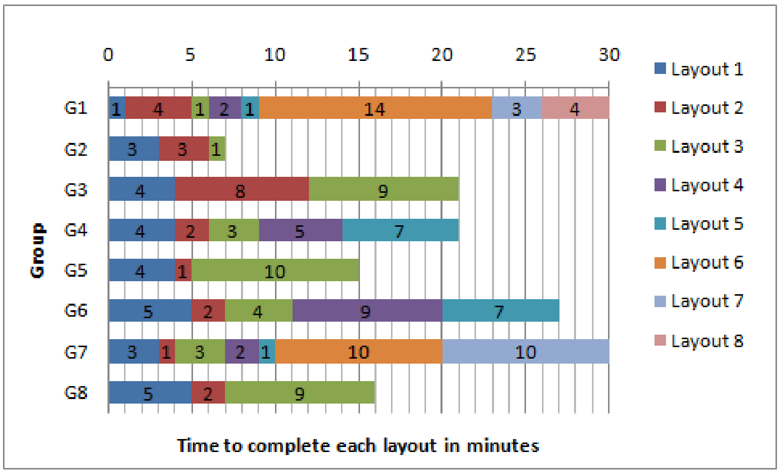


Figure 4.8: Time to build layouts for each group.

We noticed instances where the students missed potential opportunities for comparing similar layouts to each other. Specifically, they were afraid of not having the model available for subsequent reflection, and hence stopped exploring. For example, when group G6 finished building a layout that they were content with, the apprentices were reluctant to explore new variations to understand more about the differences between these variations. There was no means to "save" the current tangible model and they were afraid of losing the current "perfect" layout, as in the transcript below.

1 (11:00 minutes into the activity)
2 A: But we can put two! (suggesting to modify the current model in a good way)
3 B: What do you mean? Like one that comes on this side? But you didn't like it before?
4 A: If we put it like this, it can work! (pointing to the model)
5 B: No, because you have to be able to pass in the middle
6 A: Yes, but you don't have to pass on both sides!
7 B: It's complicated! No, let's leave it how it was! (A agrees and they give up on the idea because they think it will require breaking down the current model)

The apprentices were strongly dependent on the teacher during the class. Therefore, when situations like this occurred, they tended to wait for the teacher to come back to their group. Given the amount of time the teacher had to spend managing the class and each individual group, this waiting time caused an abrupt pause in the flow of their group.

The teacher was also sometimes hindered by this problem during his discussion with the groups. At many points, he asked the students to compare and reason about the differences between the current layout and previous models (which had been broken down). The discussions were difficult for both parties as they had no concrete layout to refer to. The teacher sometimes asked the apprentices to write the statistics down, or to sketch the current model on paper before breaking it down to make room for another one.

However, the tangible models proved to be very useful for the teachers, facilitating the discussion between the students and them. The models were perceived by the teachers as a teaching resource. They provided external representations and concrete examples for the discussion.

4.5.4 Discussion activity

A collection of recordings from four groups (out of eight) in the tangible condition was chosen for a more detailed conversation analysis. Material for this analysis was selected by the following criteria:

- one group whose members all had a very low score (group G6);
- one group whose members all had a very high or perfect score (G1);
- two groups with 1 or 2 members who scored very high but the other members scored low or very low (G5 and G8).

The purpose for this sampling was to explore what factors during the activity affected the learning outcomes of these groups.

Each group was rated according to two categories: discussion type and collaboration quality.

Discussion type focuses on the content of the collaboration. It emerged as a very important theme after a bottom-up exploration of the data. It is further classified into two dimensions:

- manipulation discussion: discussion about how to manipulate physical shelves
- reflection discussion: discussion about the logistic concepts

Collaboration quality focuses more on meta aspects of collaboration, i.e. how users manage and regulate their collaboration. Collaboration quality was determined from our examination of literature to see how collaborative tasks can be affected. It is considered a crucial measure and has been used extensively in Computer-Supported Collaborative Learning research. We adopted the approach introduced by Meier et al. (Meier et al., 2007). Of the 9 rating dimensions in (Meier et al., 2007), we selected five most relevant dimensions to our task: mutual understanding, dialogue management, information pooling, reaching consensus, and reciprocal interaction. The collaboration quality score is computed as the average of these five dimensions. The Appendix C defines each dimension used for our conversation analysis and provides examples of each from the transcript.

We rated the conversations using a 3-point scale (0, 1 and 2) that informed both about quality and duration with a 0 translating to a low quality, short conversation, and a 2 translating to a high quality, long conversation. This 3-point scale aims to avoid over-emphasizing the qualitative difference and simplify the rating process. We did not use a second coder for the conversation analysis, since the small number of samples (only 4 groups) makes any statistical test on the agreement level unreliable. We were aware of this bias but the rating nevertheless had some valuable insights.

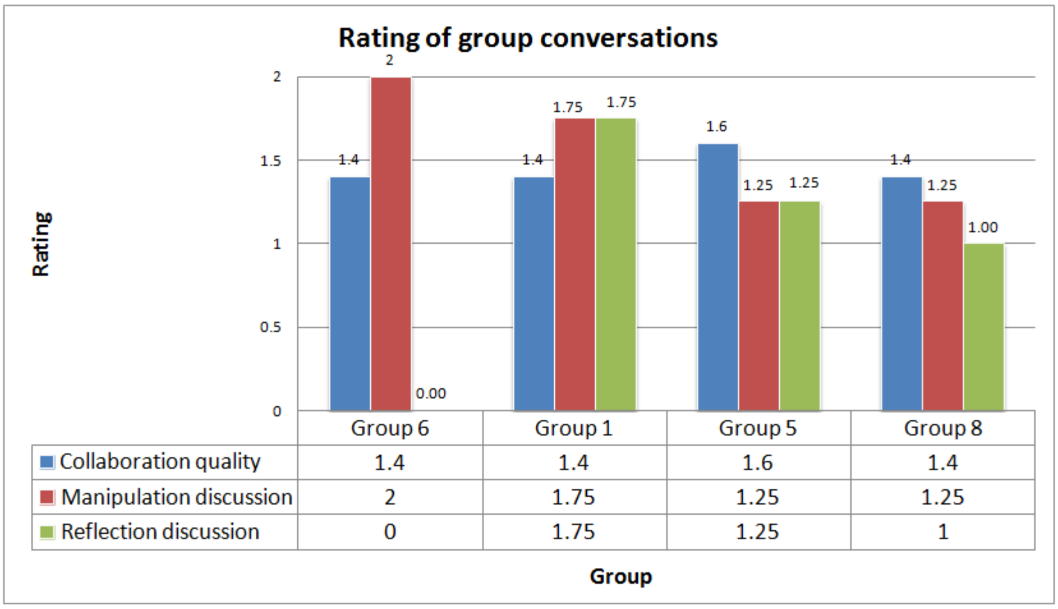


Figure 4.9: Conversation analysis for the four chosen groups. Group 6 is the group with low scores, Group 1 is the group with high scores, Group 5 and Group 8 are the groups with mixed scores.

Figure 4.9 shows the results of this conversation analysis. It reveals that there is no big difference across the groups in terms of collaboration quality. Every group had a moderate rating in the collaboration quality rating ($score = 1.4$ for Group 6, Group 1, Group 8 and $score = 1.6$ for Group 5).

However, we observed a considerable difference when it comes to manipulation discussion vs. reflection discussion. Consider group G6 as an example. This was the worst group in terms of test score. Group G6 did not have a balance between manipulation discussion ($score = 2.0$) and reflection discussion ($score = 0.0$). A majority of their discussion time was task-focused, being at the manipulation level with nearly none at the high level. They only cared about manipulation and placement of shelves. Manipulation discussion alone is arguably not very useful for comprehending concepts of interest and in turn, learning.

Throughout the whole activity, their discussion typically remained at the manipulation level. This led to a very low score in the post-test for all group members (ranging from 3/12 to 6/12). The apprentices did not seem to be able to step back, and explore, for instance, the relation between the number of shelves in the layouts and their corresponding space utilization degree, a process which is central in understanding the lesson. We illustrate this in the excerpts below.

Eleven minutes into the activity, the apprentices were concerned about where to put the shelves to make the warehouse look nice and maximize the number of shelves in a warehouse.

1 A: Put them at the back. (A proposes how to place the shelves)
2 B: No it doesnt work there anymore.
3 A: Yes it does, look... stop, here is ok, you can leave this one here. (A tries to convince the others and manipulates the shelves himself to show his strategy)
4 C: We have to put 5 shelves.
5 A: No, we have to put 10.
6 B: Hum 10, that's right.
7 (They keep discussing about how to manipulate the objects. A mix of fast pace voices and shelf manipulation in parallel)
8 A,B,C: Can you put some back there again? No, it doesn't work. Push, push. If I put them more in this direction, then... You can't put 2 there? Yes, I can. Yes it works. Ah, no. Like this!

Fifty-eight minutes into the activity; they were still discussing about these low-level issues:

1 A: How could we do it? (A wonders about where to put the shelves)
2 B: First we should do a path in the middle.
3 A: It was already hard enough to put them like that!
4 C: We could put one in the middle. (C points to a shelf, and proposes another way of placing shelves)
5 B: Yes, that's what I thought too. If we do all like that? (B agrees and manipulates some shelves right away)
6 A: No, it's not the same!
7 C: So we just do a little space in the middle. (C talks about another way of putting shelves)
8 A: Yeah and then we can take the 4 shelves there and do this way. (A agrees and starts manipulating some shelves)

The best group (G1), in contrast, spent equal time discussing about how to manipulate the physical objects ($score = 1.75$) and about the surface concepts ($score = 1.75$). Not only interacting with the shelves and discussing about them, they also had high-level reflection episodes throughout the session. One example occurred 27 minutes into the activity:

1 A: Is it good? (A points to the model)
2 B: What is raw storage surface? (B tries to answer the question)

3 A: It's the raw surface minus the working paths. (A answers after thinking)
4 (They were thinking about the concepts of surfaces and trying to relate them to the information augmented on the table at the same time)
5 B: How do we count the working paths, where is it?
6 C: Here, the working paths. How do we do this? OK, I move it.(pointing to the model)
7 B: Yeah, it's 30!

This finding is considerable when taking the time spent building the models into account (Figure 4.8). This group G1 built 8 layouts, spending a total of 30 minutes. They took full advantage of this exploration opportunity, discussing and making sense of the layouts. Conversely, although spending nearly as much time building models as G1 (5 layouts in 27 minutes), the worst group G6 seemed trapped into only focusing on the manipulation level and failed to step back and reflect.

This insight was confirmed in the other two groups. The analysis revealed that both of these two groups neglected high-level reflection to some extent. At least 2 out of 4 members in each group were more interested in the placement of the shelves, and less motivated about talking and discussing high-level concepts. This was very likely the reason that their test scores were low. On the contrary, group members who had a high rating in reflection discussion also scored high in the post-test.

4.5.5 Use of TinkerSheets

As expected, we observed that the two TinkerSheets, combined with the small-scale model, offered multiple sources of information for the apprentices. For example, the degree of utilization of the warehouse is represented by different types of representations and feedback: the placement of shelves on the table, the 2D representation on the TinkerSheet, and the textual numerical value on the TinkerSheet.

These augmentations allowed the students and teachers to discuss the relation between different elements included in the interface. For instance, we saw that the teacher asked the students to try putting more shelves in the table and look at the textual numbers on TinkerSheets to see how the degree of utilization varies. It proved that this paper-based interface is a promising means to support the Multiple External Representations approach with tangible, provide more abstract visualizations to support learning, besides the concrete manipulation given by the small-scale model.

However, the two TinkerSheets used in this study did not seem to adequately fulfill its design goal of preventing too strong embodiment and manipulation temptation. We had expected the TinkerSheet to support students to step back from manipulating and reflecting. Even though apprentices did use the TinkerSheets for this purpose, i.e. to look at the visualizations of different surfaces, read the statistics, and discuss high-level concepts, these moments did not occur very often. With the teachers being busy with other groups, the apprentices often neglected this reflection step, and were often stuck at manipulating shelves.

4.5.6 Teacher, reflection and the problem of class awareness

The teachers spent the majority of their time going around the room to observe and help the groups. A common strategy they used was to start at the group closest to them, then go on to the next group in a clockwise (or counterclockwise) direction. Once with the group, the teacher either observed how the group performed from a distance or asked a short question as a way to catch up with what they had been doing while he was away.

The time the teachers spent with their students was very beneficial for reflection. As we showed above, some of the groups were better than the others at self-regulating and doing reflection on their own. However, all of them were given opportunities and “forced” to think when the teachers came to their group. The teachers always asked reflective questions that relate what the students were doing (i.e. manipulating most of the times) and the logistics concepts, or asked them to discuss with each other rather than just working individually.

(a) (b)

Figure 4.10: The class-level activities and issues: a) Simultaneous requests for help from the groups. b) Teacher discussing with the whole class during an activity. There was no mechanism to support a class discussion about the arrangement of layouts constructed by each group.

However, the time the teacher spent with each group was not optimal. We observed that that the pattern of the teachers’ movements, and hence the classroom dynamics, was fairly spontaneous and subject to frequent changes. A help request or an interruption by a group may well divert a teacher’s pre-defined itinerary. Working with four TinkerLamps at the same time posed certain difficulties regarding the teacher’s classroom management (Figure 4.10a).

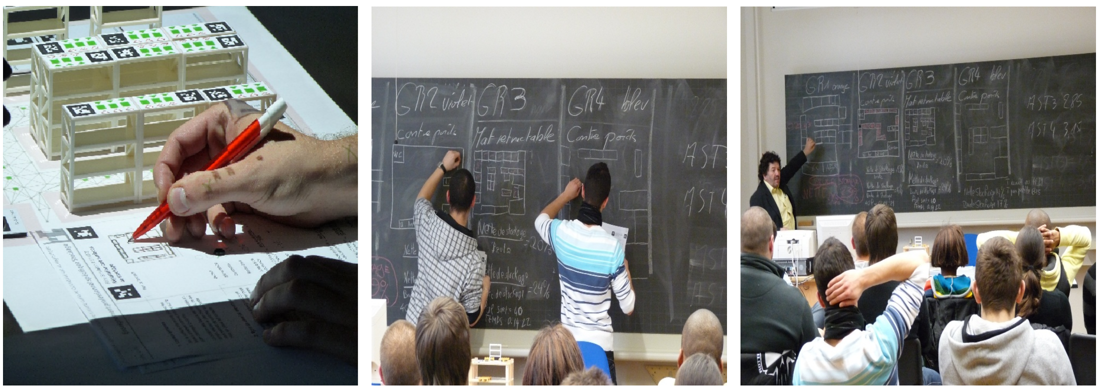
For example, there were several occassions where two or more groups made requests simultanously. He went to one group to help them but forgot about the other group when finished with the first one, instead proceeding to a different group. It was also difficult for the teacher to keep track of the progress of all the groups. It usually took him some time before he could fully assess what the apprentices had been doing without him in order to give an appropriate intervention.

4.5.7 Spontaneous class-level activities

The teachers switched between helping the apprentices at the group level, and discussing with the whole class (Figure 4.10b). The move from “group-level” activities to “class-level” discussion often took place when the teacher wanted to talk to the whole class and make them reflect about interesting layouts during his tour of the room, to discuss the relation between the layouts, or to make sure every group had understood the concepts correctly.

These activities led to different extents of success. A negative example occurred 35 minutes into the activity of class 1. At this point, the teacher was trying to debrief the consequences of the number of shelves, their placement and the net surface concept with the class. He was asking each group to read the number of shelves they had placed on the table and the net surface area out loud. However, since there was *no means for the group to demonstrate how they had placed the shelves* in the warehouse, it was difficult for the teacher to explain the values obtained and re-interpret them for the whole class. Consequently, this “class-level” activity turned out to be an interaction between the teacher and each group sequentially, with the other groups not paying attention. In other instances, gaining the attention of the whole class was sometimes challenging for the teacher when everybody was concentrating and working on their own group model.

On the other hand, a positive example occurred 40 minutes into the activity of class 2. The teacher asked each group to read the number of shelves they were able to fit on the table and the amount of time their simulation took to complete. The class became very lively with everybody excited about trying to prove that their group was the best, which encouraged a lot of between-group discussions.



(a) (b) (c)

Figure 4.11: The continuity of activities: a) Tracing the virtual graphics on TinkerSheet. b) Transfer the traced layout on blackboard. c) Teacher debriefing with the whole class.

4.5.8 Final debriefing session

The debriefing session at the end of the class took place on the blackboard (Figure 4.11c). The teacher asked apprentices to trace their solution on the TinkerSheet and reproduce both the numerical values and the warehouse layout on the blackboard. The teacher then discussed the different solutions proposed by each group. This session was particularly important for learning outcomes, because it involved reflective activities that were enforced by the teacher to the whole class. During this time, the teacher encouraged apprentices to reflect about the practical actions that had been performed during the group activity.

During this session, however, we noticed an open issue for the teacher. It was impossible for him to refer to solutions previously built by the students or the problem-solving steps taken by the apprentices. This issue limited the debriefing to only the layouts that were drawn on the blackboard. In addition, while one could argue that the manual transfer of layouts from TinkerSheet to the blackboard could be useful in terms of reflection, we felt that the continuity of the activities was not very smooth.

4.6 Discussion

4.6.1 Task performance: Direct and concrete manipulations

Our findings showed that the task performances (number of alternative solutions explored and number of shelves in the final solution) in the tangible condition are higher than those in the paper/pencil condition. This can be explained by the direct interaction mechanism. Obviously, grasping a tangible shelf and placing it on the table to create a model is faster. Modifying the model is also facilitated by the fact that tangibles leave no traces behind. Apprentices could simply move shelves to another position, as opposed to erasing and re-drawing the layout with paper and pens. Simultanous actions also speed up the process. Design iterations were therefore done quickly which saved time for apprentices to try out other possible options. This finding about better task performances are consistent with what have been found in the literature, e.g. (Pawar et al., 2007; Rogers et al., 2009; Marshall et al., 2008).

4.6.2 Learning benefits: Effects of too much manipulation

Despite the success in terms of task performance, the tangible condition did not seem to have more positive effects than the paper/pencil condition on either the understanding or the problem-solving score. In other words, the task outcomes and the learning outcomes are not tightly connected. The learning task used in this study was inspired from a traditional school task, but also from the theoretical perspective, where Cohen (1994) found a loosely structured task is more beneficial for collaborative learning and problem-solving than a tightly structured one. For this reason, the task had been designed so as to give the apprentices some freedom in terms of what, when and how to discuss during the activity. Our hope had been that the more familiar representation to the apprentices' work experience and the embodied cognition implied in tangible manipulations would encourage more fruitful and free collaboration, and eventually more understanding and problem-solving. However, there was no evidence from our findings suggesting that these factors lead to more abstract reasoning.

Importantly, we found that the *balance between manipulation and high-level discussion played a critical role in the learning process with the system.* The right combination of these two factors resulted in effective exploration, and hence understanding. Manipulating tangible objects and discussing low-level aspects of the activity (e.g. where to place shelves) is necessary. If exploited properly, these two factors help the apprentices be more efficient, build more layouts, and learn more (as was the case for group G1).

Nevertheless, neither too much manipulation without discussion nor too much discussion at the low level is good (as was the case of group G6). The interface sometimes led the apprentices to manipulate too much. It led to less detailed and insightful discussions during the building process, which would have been good for learning. Another consequence is the apprentices not having enough high-level reflection, and hence using less intensive cognitive effort to make sense of the solutions.

We had expected the TinkerSheets to help alleviate this problem. However, we found that only providing the students with a complementary representation of the small-scale model on TinkerSheets is not enough to trigger reflection. Work on manipulatives used in mathematical education has shown that focusing on the manipulative rather than on what it represents is detrimental to learning (Uttal, 1997). (de Jong, 2006) also reported the negative effects of running too many simulations on learning. In light of these works, we believe that the TinkerLamp at this point suffered from a "double" negative effect, i.e. it provided users with two features, running simulation and manipulating objects directly, and each being potentially harmful to learning. This problem we saw here is another example of the "manipulation temptation" problem observed in chapter 3.

4.6.3 The need to support classroom orchestration

During the Warehouse study, we identified many interesting phenomena that would have been hard to observe in lab settings because they arise uniquely in classroom setting. The most important, but unsurprising, insight was that a teacher, can notably affect the reflection level of his student. He can ask reflective questions to individuals, encourage the group to discuss, and have class-wide comparisons. These activities are crucial to the learning outcomes. In other words, a way to alleviate the negative effect of manipulation temptation is to facilitate these activities by the teacher. This brings up the need to support teacher's classroom orchestration (Dillenbourg and Jermann, 2010) since teaching in a classroom equiped with multiple TinkerLamps is not an easy task.

For example, although the task was the same for all of the groups, each group moved at own pace of exploration when working with the tabletops. Different groups also had different results and understanding about the concepts (e.g. how to make sense of different warehouse layouts with the same statistics). The teacher needs to be aware of the current state of the class and properly acts to facilitate a more coherent understanding of all students by contrasting the differences between groups and propagating the best solution throughout the class.

Among others, there is a need for an awareness or monitoring tool to support orchestration. This tool may be needed for the teacher to quickly examine the status of different groups in the class. It can be beneficial to mediate simultaneous help requests in that the teacher knows who needs help the most (as opposed to being spontaneous like in the current study).

4.6.4 The need to support the continuity of activities

One important aspect of the classroom use of the TinkerLamp, and supporting orchestration, is the importance of continuity of activities on reflection. Not only reflection at the group level was important, we saw that the final debriefing sessions and class-level discussions during the activity were also as crucial. These class-level activities were the moments where the whole class discussed and compared their different strategies, different solutions, and different perspectives with the guidance of teachers.

The current state of TinkerLamp did not provide enough support for the teachers to move from the group level to the class level. Since the warehouse layouts, the main topic for class discussion, have a strong spatial component, current class-level discussions were hindered because the teacher and students could not easily demonstrate their layouts to the class.

There is also a need to "save" layouts during the exploration with tangible objects for references in later phases of the activity (e.g. for comparison and reflection). One of the difficulties in saving tangible models has been due to its physicality. Does saving mean create a physical clone of the current model? Will we lose the benefits of immersive 3D perception it we save in 2D?

From our study, we believe that saving does not have to be "tangible saving", which requires the apprentices to have physical models as the "saved model". The type of saving (save in tangible 3D, 2.5D or 2D) very much depends on the task. We argue that 2D graphics or sketches are enough for this high-level task and this population. The apprentices and the teachers in fact did draw 2D sketches on paper to "save" the 3D models during the study.

The use of these sketches in complement to the tangible model to support learning is an important issue. It suggests a more thorough support for multiple activities and resources in the classroom and the continuity of these activities. It also marks a shift in perceiving the benefits of tangible tabletops which "provide a 3D and close coupling of interaction and perception" to "a shared resource to support discussion and exploration". In other words, we have empirical support for a focus shift from system functionality towards the physical and social context of interaction with and around the interface (Fernaeus and Tholander, 2006).

4.6.5 Limitations of the study.

Following the line of the ConceptMap study, this Warehouse study takes on a holistic approach: we examine the effects of tangible tabletops when they work as ecologically valid and complete units. To go a step further, this study takes place in a real classroom with a school task.

As a consequence, various factors in a classroom (which could not and should not be controlled) could contribute and affect the learning outcomes. The teacher factor is an important example. We could not and should not control how the teachers teach, but rather observe how they adopt the technology to improve their teaching practice and student learning. Furthermore, since the post-test is carried out with paper and pen, it can be argued that there is a bias towards the paper/pencil condition. Although the apprentices could have been asked to answer those same questions using a more neutral means, doing tests on paper with pen has been traditional in schools, and we wanted to use it as a legitimate device to judge the apprentices (ideally, we want to think of a way to integrate the TinkerLamp into this assessment phase). Another factor is that students in these real settings tend to have much more off-task conversations and sometimes attitude and motivational problems. These factors make the test scores, and hence the quantitative results, fragile. They could have been easily distorted. In this regard, we believe that the qualitative details offer more insightful findings to inform the design of similar systems.

4.7 Summary

This chapter presents the TinkerLamp, a tangible tabletop to support logistics training, and the findings of a study that investigated the effects of this system in a classroom setting. We believe that by having a real scenario, the effects of artificial experiment factors on observed behaviours are reduced.

Our study demonstrated that the TUI provides pedagogical values to support learning logistics and warehouse-related concepts. The apprentices in the tangible condition explored more, building significantly more layouts and layouts with more shelves, than those in the paper/pencil condition. This was most likely due to the tangibility and direct manipulation mechanism. This made the learning experience richer and more appealing to the students.

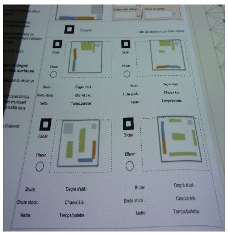
However, contrary to our expectations and the common assumption about the close coupling of 3D physical objects with perception, there were no significant effect of the tangible tabletop on either the understanding or the problem-solving score when compared to the paper/pencil condition. This result should be taken with caution given the authentic setting discussed in the limitation section. However, still, it was clear from our analysis that there are several design issues that have to be considered when using TUIs for learning tasks that focus on high-level understanding.

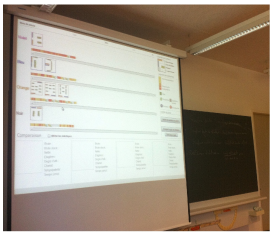
These issues include the problem of “manipulation temptation” and the need to balance low-level manipulation and discussion with high-level reflection. The authentic classroom setting with the involvement of teachers in the study also led to an important insight: the critical support needed for classroom orchestration and teacher's class-level activities.

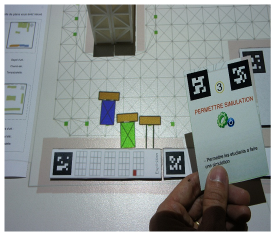
The implications of this chapter are:

- The importance of reflection and high-level thinking for learning with tangible tabletops. Tangible models and physical manipulations are not enough for more positive learning outcomes.
- A repeat of the problem of *manipulation temptation* in a classroom setting. Future systems should address this problem, i.e. address the trade-off between low-level manipulations vs. high-level reflection and discussion.
- The importance of supporting orchestration: 1) Supporting the teachers to better orchestrate the class and to intervene in student collaboration is a way to support student's reflection. 2) Having multiple tangible tabletops in the classroom requires an adequate level of support for teacher's orchestration in managing the class and keeping track of the groups' progress.

5 TinkerLamp 2.0: Supporting Reflection and Orchestration







5.1 Introduction

This chapter presents our effort in exploring how to build a tangible tabletop system that would provide explicit support for teachers' orchestration and students' reflection. It details the implementation and design iterations of TinkerLamp 2.0, the next generation of the TinkerLamp system described in chapter 4.

The design of TinkerLamp 2.0 was inspired from the two previous systems, the DockLamp and the TinkerLamp. Despite the range of different settings (lab and classroom), different tasks (concept-mapping and warehouse building), and samples (university students and vocational apprentices), we showed that these two previous systems had several problems in common. They highlighted the importance of two interrelated themes in learning with tangible tabletops: reflection and orchestration.

We designed and tested TinkerLamp 2.0 in collaboration with 3 teachers and more than 150 logistics apprentices. As we worked with them, TinkerLamp 2.0 progressively evolved from a stand-alone application to an ecology of tools that support different levels of interactions and different activities for both students and teachers.

5.2 Design implications from the last two studies

5.2.1 Explicit support for reflection

There are two common issues that we observed in both the ConceptMap (chapter 3) and the Warehouse study (chapter 4): the importance of discussion at a high level of abstraction (i.e. related to the learning concepts) and the problem of "manipulation temptation".

- High-level thinking and discussion: Learning outcomes are highly influenced by the amount of high-level thinking and discussion. In the ConceptMap study, the group discussion about the texts are necessary for the understanding of the concepts about neural transmission. In the Warehouse study, the discussion and comparison between the different warehouse models and their statistics affected how the students understood logistics concepts.
- "Manipulation temptation": Manipulation temptation refers to multiple instances where the physical manipulations and actions tended to interfere and prevent potential opportunities for learning to materialize. For example, in both studies, those who used the tangible tabletop tended to start implementing the solution right away without discussing. Furthermore, high-level reflection was neglected by many groups in the Warehouse study because they were only focused on building physical models.

These two issues centered around the notion of reflection. While there are several definitions of reflection in the literature, it is generally accepted that reflection requires students to use critical thinking to examine presented information and ponder on experiences, question their validity, and draw conclusions based on the resulting ideas (Hoyrup and Elkjaer, 2006). Reflection has been mentioned as important for learning by research in education and CSCL, (Ackermann, 1996; de Jong, 2010; Davis, 2003; Quintana et al., 2001). Studies with single mouse interfaces in these domains have suggested that, while effective learning does involve engaging task-focused activities, it also requires periods of reflection where knowledge is abstracted and more cognitive load is required (Ackermann, 1996; de Jong, 2010).

What we saw in both of our studies are the empirical evidence as to how these findings also hold true in the tangible tabletop context. One can argue that reflection is even more crucial in tangible tabletop environments and needs to be carefully addressed due to the following reasons.

- Tangible interfaces tend to result in more frequent and more simultaneous actions than traditional PCs due to their concreteness. These actions, in turn, can result in limited mutual understanding (Marshall et al., 2008; Harris et al., 2009).
- Students using tangible interfaces tend to solve the learning tasks through trial and error, and accomplish the tasks "too fast". This may have resulted in a less concentrated

> and intensive cognitive effort to make sense of the learning concepts and form a deeper understanding.

Current practice in interaction design with respect to explicit design for reflection in educational applications still leaves much to be desired. Consequently, the DockLamp and TinkerLamp initially did not address the reflection issue explicitly. Their designs up to this point assumed that the benefits from other affordances (namely more participation, faster manipulation in the DockLamp, or Multiple External Representations in the TinkerLamp) would improve learning or afford reflection. This was, however, not the case. For example, in the Warehouse study, most logistics apprentices did not reflect until their teachers explicitly told them to.

These findings led us to believe that *reflection needed to be explicitly considered and integrated into our learning environment*. We aimed to support both reflection-in-action and reflection-on-action in our design (Schön, 1983). Reflection-in-action refers to the reflection during actions which enables learners to carry out an experiment which serves to generate both a new understanding of the phenomenon and a change in the situation. The act of reflecting-on-action enables learners to spend time exploring why they acted as they did, what was happening in a group and so on. The boundary between in-action and on-action is vague, and the same reflection can be seen as in- or on-action depending on the context and the designer.

5.2.2 Support teachers for orchestration

The teacher was the deciding factor that determined the success of the class, and as we argued in chapter 4, determined the amount of reflection opportunities. In the Warehouse study, the teachers played a crucial role. They ran introduction lectures, toured the class to have discussions with each group, led class-wide reflections, and encouraged cross-table discussions and comparisons. This finding is hardly original, but it nevertheless is very important and insightful.

First, it suggests that orchestration and reflection is related. Supporting the teacher with his classroom orchestration is a way to support reflection. Providing the teacher with appropriate tools, enabling him to interact with the group and the class more effectively and efficiently is a way to balance between high-level discussion and physical manipulation, which is important for learning.

Second, it suggests that the teacher's role cannot be undermined despite the introduction of new technologies in the classroom. Even with the TinkerLamps, the teacher was the main driver and had an effect on almost every aspect of the learning session, including the reflection issue mentioned above.

Third, it shows the complexities of the many levels of activities that can take place in the class: individual learning, teamwork, and class-wide activities, and possibly outside of the class

Some of these activities are based on the TinkerLamps, some on the blackboard, some through discussion, etc. At the same time, the teachers have to deal with many students and groups studying in parallel.

These findings confirm the importance of *supporting orchestration and facilitating teachers in conducting class activities in real-time* (Dillenbourg and Jermann, 2010; Dillenbourg et al., 2011). It is both a solution to the reflection problem, and a problem by its own to be solved since there currently is little work that addresses the issue of designing technologies for classroom orchestration.

As we would like to develop technologies that can be used in real classrooms, an implication for us is that our TinkerLamp environment should empower teachers in the challenging task of orchestration. We also consider the continuity of activities a related concept when designing to support orchestration. Orchestration is very much about the management and switch between activites at different levels and contexts, e.g. from group to class, which requires a seamless transition between these levels.

5.3 Design goals for TinkerLamp 2.0

The ultimate goal for the TinkerLamp 2.0 was to improve learning and provide more reflection opportunities, besides its engagement and easy manipulation support. We specified four key design goals for TinkerLamp 2.0, all centered around two important themes: reflection and orchestration. These goals are not mutually exclusive, but rather related and complementary to each other.

- **Create explicit opportunities for reflection**: It should discourage the "manipulation temptation". It needs to be able to trigger reflection-in-action and reflection-on-action (during and after the manipulation of physical objects).
- **Support continuity**: It should connect and support a fluid transition between different learning phases: at different points in time and place, within and beyond the tangible tabletops, within and beyond the classroom, etc.
- **Empower the teacher**: It should provide the teacher with information and privileges necessary for his class management and orchestration. It should help the teacher deal with multiple groups in parallel and conduct and control activities in a subtle and appropriate way from the front of the classroom.
- **Facilitate class-wide activities**: It should facilitate the running of class-wide activities (e.g. debriefing by the teacher) as well as facilitate interactions among different groups in the class.

These design goals implied that the TinkerLamp 2.0 system would need to provide support for learning resources in the whole learning workflow in the classroom. The tangible models should not be the sole focus of the activity. Other representations, activities and tools can be produced based on the tangible models and used around them at various points to provide multiple perspectives about logistics concepts. In other words, to our intuition, *supporting both reflection and classroom orchestration requires the design and implementation of an ecology of tools*, not just a stand-alone application as is often the case in the literature.

We considered a design space with four dimensions to explore the most appropriate tools when designing TinkerLamp 2.0 (Figure 5.1). It is our further realization of the four design goals.

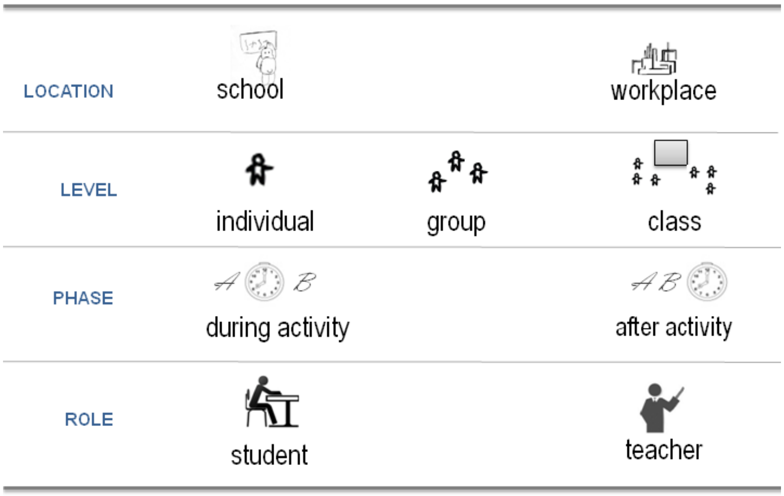


Figure 5.1: The design space for TinkerLamp 2.0 tools.

In the explanation of the design dimensions below, for simplicity, we refer to any representation, activities, and tool that can be designed for the TinkerLamp 2.0 system under the same term “tool”.

Location. The “location” dimension shows the context where the tool can be used. At this point, we considered two places where it can be used: at school or at the apprentices’ workplace. Of these two contexts, we put more focus on the school context.

Level. This dimension specifies the social plane at which the tool can be used. More specifically, it can be used at different levels: for individual, for group or for the whole class.

Phase. The “phase” dimension describes when the tool is used. For example, it can be used during the building phase, (i.e. the time apprentices are building warehouse models), or after the building phase. Tools used during the building phase are designed to support processes that take place while students are interacting with the system (e.g. manipulating tangible shelves) such as students’ reflection in-action or teachers’ intervention with a group on the spot. On the other hand, tools used after the building phase can be interpreted as designed to support processes that make use of the completed warehouse layouts such as student’s reflection on-action, or teachers’ orchestration actions with the whole class, *Role.* This dimension specifies the role that the tool is designed to support. The two roles that were considered in this design space are teacher and student.

Guided by our design goals, design space and influenced by our users, we progressively explored a variety of tools, each corresponding to a set of parameters in the design space. Three design iterations were completed, each iteration focusing on a subpart of the design space. As we will show in the rest of the thesis, the provision of a set of tools, instead of just one powerful tool, leads to an adequate intervention, supporting both teachers and students for their teaching and learning.

5.4 First iteration: during-activity support

5.4.1 LayoutBrowser: supporting reflection-in-action

Objective

The design goal of the LayoutBrowser is illustrated in Figure 5.2. It was designed to facilitate the capture and discussion of experiences achieved *during* manipulation activities with the TinkerLamp to provide opportunities for reflection-in-action in *group*, at *school*. It aimed to support both *teacher* and *students*.

Figure 5.2: The design objectives of the LayoutBrowser.

The reference to previously built warehouse layouts had been difficult with TinkerLamp 1.0 because the system did not keep external representations of these layouts. In this iteration, we aimed to create a tool that would help transform students' mental representations of warehouse layouts to external reprensentations visible on the table to create more opportunities for reflection-in-action.

We assumed that maintaining an internal state of warehouses poses difficulties on students. With difficulties in reasoning and abstraction skills, apprentices already encountered problems in expressing their ideas into drawings (Jermann et al., 2008). Few of them were correct in terms of scaling. Hence, the learning flow could be improved if the tangible interface could be saved and represented in another way. In addition, our Warehouse study showed that the 2D manually-sketched layouts could be used as a shared resource, around which the teacher and students could gesture to illustrate their ideas and reflect about the experiences they had while manipulating.

Design

We decided to design a new TinkerSheet with a layout-saving capability, called the Layout-Browser (Figure 5.3). Students can use this LayoutBrowser to control the interface and save 3D tangible models into 2D graphics, which allows for more comparison between the different layouts. It also allows students to further explore other alternatives without fear of ruining the current model. The teacher can also use it to keep a track of what the students have built so he can intervene more properly.

New interaction elements

To this end, we needed technical improvements on the TinkerSheet architecture, giving it the ability to detect one-time actions, e.g. putting a token on a button to save the current layout. The previous implementation only allowed the detection of continuous settings and the states of the system were constantly updated.

The implementation of LayoutBrowser introduced three new interaction widgets on Tinker-Sheet: click button, toggle button, and hover button. With these new interaction elements, the LayoutBrowser enables the students to activate a click button to save their physical models into 2D graphics, highlight a layout using a toggle button, or show the models' statistics using a hover button.

- A *click button* on a TinkerSheet is the equivalent to a normal button in a Graphical User Interface (GUI). It is represented on the sheet by a black hollow square. It is activated by a token placed on top of it. However, different to other existing widgets (e.g. radio button), when activated, the design of the click button enables it to trigger the associated action only once, even when the token remains on top of it afterwards. It can only be re-activated after the token is taken off and put back again.

  In Figure 5.3, the square "Sauver" (Save) button is a *click button*. Putting a token on it saves the current model in the list below, only once.

- A *toggle button* is similar to a checkbox in a GUI. It is designed and functions in the same way as a click button, except that everytime it is activated, it toggles the value of the associated parameter (e.g. from off to on or vice versa).

  In Figure 5.3, the 4 square "Choisir" (Select) buttons are 4 *toggle buttons*. Putting a token on each of them highlights/un-highlights the layout which has been saved in the rectangle next to it.

- A *hover button* is represented by a circle. The action associated with it is triggered as long as the button is activated. As soon as the token is taken away, the action is stopped. It is similar to a tooltip in a GUI, but instead of showing a tooltip, it calls an action.

In Figure 5.3, the 4 round "Afficher" (Show) buttons are 4 *hover buttons*. As long as a token is put on it, it shows the statistics of the corresponding saved layout.

5.4.2 Pen-based interaction: empowering the teacher

Objective

The design goal of the pen-based interaction is illustrated in Figure 5.4. This is designed as a way to empower the *teachers during* the building phase, giving them special rights when discussing with *groups*, such as showing solutions or changing parameters which should not be used by apprentices. We only let the teachers use this pen. This teacher-exclusive, pen-based interaction is also meant to support reflection. For example, the teacher can turn off the showing of warehouse statistics using his pen, and ask the students to predict or compare the warehouse layouts.

Design

Pen-based interactions were enabled by using a simple off-the-shelf light pen (Figure 5.5). The system works by detecting light spots created by the pen on the TinkerSheet using a thresholding algorithm. If the light spot detected is inside a control area (e.g. feedback zone, hover button, etc.), the control is activated. If the control is a feedback zone, a circular menu will be projected around the pen position. The teacher can interact with this menu by clicking again on the menu item he wants. This pen interaction is similar to interactions using a stylus on a touch-screen.

Interaction permission

The addition of the teacher's pen in the TinkerLamp system allowed a separation in terms of interaction rights. While the students could only interact with TinkerLamps through the plastic token, the teachers were equipped with a "magic" pen that could activate more features.

We enhanced the TinkerSheet architecture to allow the customization of access control for each element. An element (e.g. the hover button to show statistics of saved layouts) can be set to only activate with the teacher's pen, and not by the plastic tokens held by the students.

This "privileges" scheme empowers the teachers, giving them special rights when interacting with the system. Their job was not limited to just going around the class and discussing with students. They were now able to interact directly with the system in a way that the students could not, to make their discussion with students more interesting and insightful. An example is that the "simulation" button can be only activated by the teacher with his pen. This prevents

Figure 5.3: The LayoutBrowser. (top) The top part shows the layout currently being built and its statistics. Below this part, there is a “Save” (“Sauver”) button to save the current layout. (bottom) The bottom part contains the list of saved layouts, having four areas, each used for one layout and its statistics.

Figure 5.4: The design objectives of pen-based interaction.

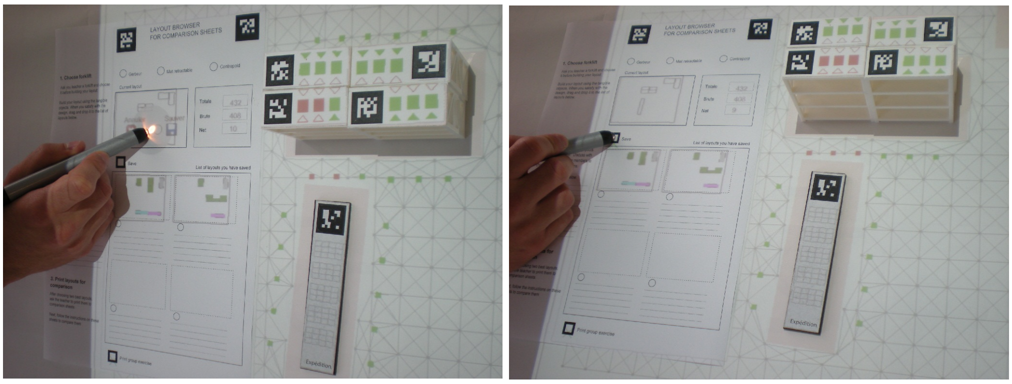


Figure 5.5: Teachers can have more power than their students when interacting with the system, enabled through pen-based interations.

the students from running too many simulations without reflecting on them.

5.4.3 Evaluations

Dissatisfaction of pen-based interactions

Interviews with the teachers suggested that the pen-based interaction was not necessarily a good means to support them in the classroom. They appreciated the idea of providing further opportunities for reflection and empowering the teacher but were concerned about the multiple steps involved with the pen and menu interaction. As one teacher said *"I would have to turn on the pen, click on the surface, choose the option on the page, and repeat these actions with every group."* The interaction was seen as cumbersome according to the teachers. From a design perspective, we also felt that the teacher and his "technologically magic pen" may become the focal point of attention from everybody in the group since it takes some time for the interaction to be finished. This put too much pressure on the teacher, and when the technology did not react properly to his action, it would create awkward moments. Consequently, we abandoned this pen-based interaction in the next iteration. The goal of equipping the teacher with special tools remained though, which led to the design of the "TinkerKey" in iteration 3.

Field trial

We conducted a field trial with two classes totalling 31 apprentices and two teachers. The scenario was similar to that described in chapter 4 but with the introduction of LayoutBrowser. At the end of each class, we distributed a questionnaire to collect feedback about the LayoutBrowser. This questionnaire was a customized, more succinct version of the USE questionnaire (Lund, 2001).

LayoutBrowser's teacher support

On the teacher side, the saving capability proved to facilitate his work and discussions. It made recent building results visible on the table, allowing quick over-the-shoulder assessment by the teacher. In the sessions that we observed, the teachers were clearly able to impose more questions that incited reflection on the students.

Both teachers reported that the LayoutBrowser provided them with a history of layouts built by apprentices throughout the activity, along with the warehouse statistics. This helped them be aware of what apprentices had achieved and therefore ask corresponding questions (Figure 5.6). As one teacher said, *"it (saving capability) has changed my strategy when approaching the groups. Instead of looking at the warehouse model, now I use it (the LayoutBrowser) as the entry point. Looking at it gives me some hints to ask questions."*

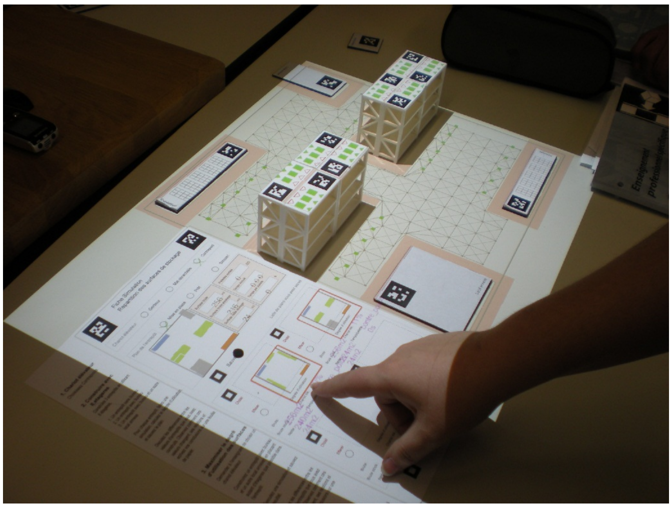


Figure 5.6: The LayoutBrowser enabled comparisons between different layouts saved during the activity. It also facilitated the discussion between the teacher and the students.

We observed that the LayoutBrowser also provided the teachers with an awareness of the class progress. Specifically, the teachers said they looked to see how many layouts each group saved to know if everybody was at the same stage in the activity in order to decide when to move on to the next phase.

Observations of students and questionnaire responses

We observed that the LayoutBrowser was useful for the students. Rather than referring to and discussing an implicit and internal warehouse representation, the apprentices could now build and save the layouts in visible forms. These external representations encouraged discussion and reflection. We saw that the apprentices engaged in discussions about comparing the different layouts they had built under the teacher's guidance.

The students' perceptions of the environment were positive. The ratings using a Likert scale of 1 to 7 (Table 5.1) suggest that the LayoutBrowser was a fairly usable interface. The full list of questions can be found in Appendix D.

	Usefulness	Ease of use	Ease of learning	Satisfaction
Rating	6.28(0.73)	5.80(1.32)	6.6(0.68)	6.14(1.10)
Overall average	6.05(1.23)			

Table 5.1: The rating means (and standard deviation) of usability dimensions for the Layout-Browser.

The most negative aspects mentioned in the open-ended evaluation part of the questionnaire were:

- The sensitivity of the sheet and the calibration problem (7 responses), referring to the fact that the 2D visual feedback and the plastic token detection was a few milimeters above the printed rectangle target. This was technically unavoidable due to the imperfect mapping between projector and camera parameters.
- The contrast of the 2D graphics being low due to the colors chosen (4 responses)

The most highly rated aspects of the system were:

- Its ease of use and learning (8 responses)
- The capability of saving models into small 2D layouts and delete them (6 responses)
- The statistics saved below the layout resulting in more concentration (4 responses).

These findings and observations confirmed that the LayoutBrowser and its functionalities were indeed appropriate for the task and appreciated by the students.

5.4.4 Summary of the first iteration

Table 5.2 summarizes the proposed features and the insights from our field evaluations.

New feature	Goal	Evaluation	
Saving with LayoutBrowser	Support reflection-in-action	Useful for discussion among teachers and students	✓
Pen-based interaction	Empower teachers	Cumbersome, interaction takes time to complete	✗

Open issues:

- Need another way of empowering teachers to replace the pen.

Table 5.2: Summary of the first iteration.

5.5 Second iteration: after-activity support

The second iteration sought to add more explicit opportunities for reflection-on-action. In the LayoutBrowser, we added a feature that enforced reflection at the end of the activity (Figure 5.7). By activating this function, the teacher could print out two paper-based exercises with closed- and open-ended questions, requiring the students to think and reflect after finishing the building of all of the warehouse models.

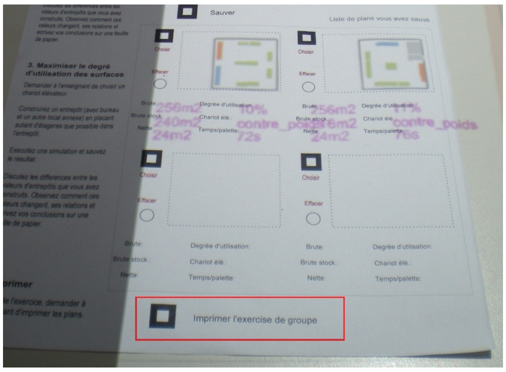


Figure 5.7: At the bottom of the LayoutBrowser, we introduced a button to print out paper exercises for group and to bring to the workplace.

5.5.1 Group reflection exercise sheet: printing for reflection-on-action

Objective

The first exercise was a *group* reflection exercise. This exercise was done at the end of the class (*after* the building phase). Its purpose was to have the *apprentices* think back and reflect on the models they built during the class. Figure 5.8 illustrates its design goals.

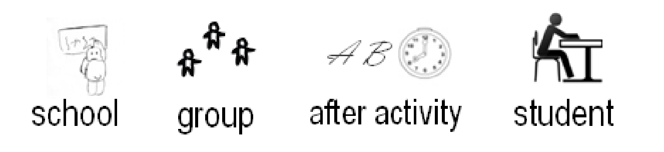


Figure 5.8: The design objectives of the Group Reflection Exercise Sheet.

Design

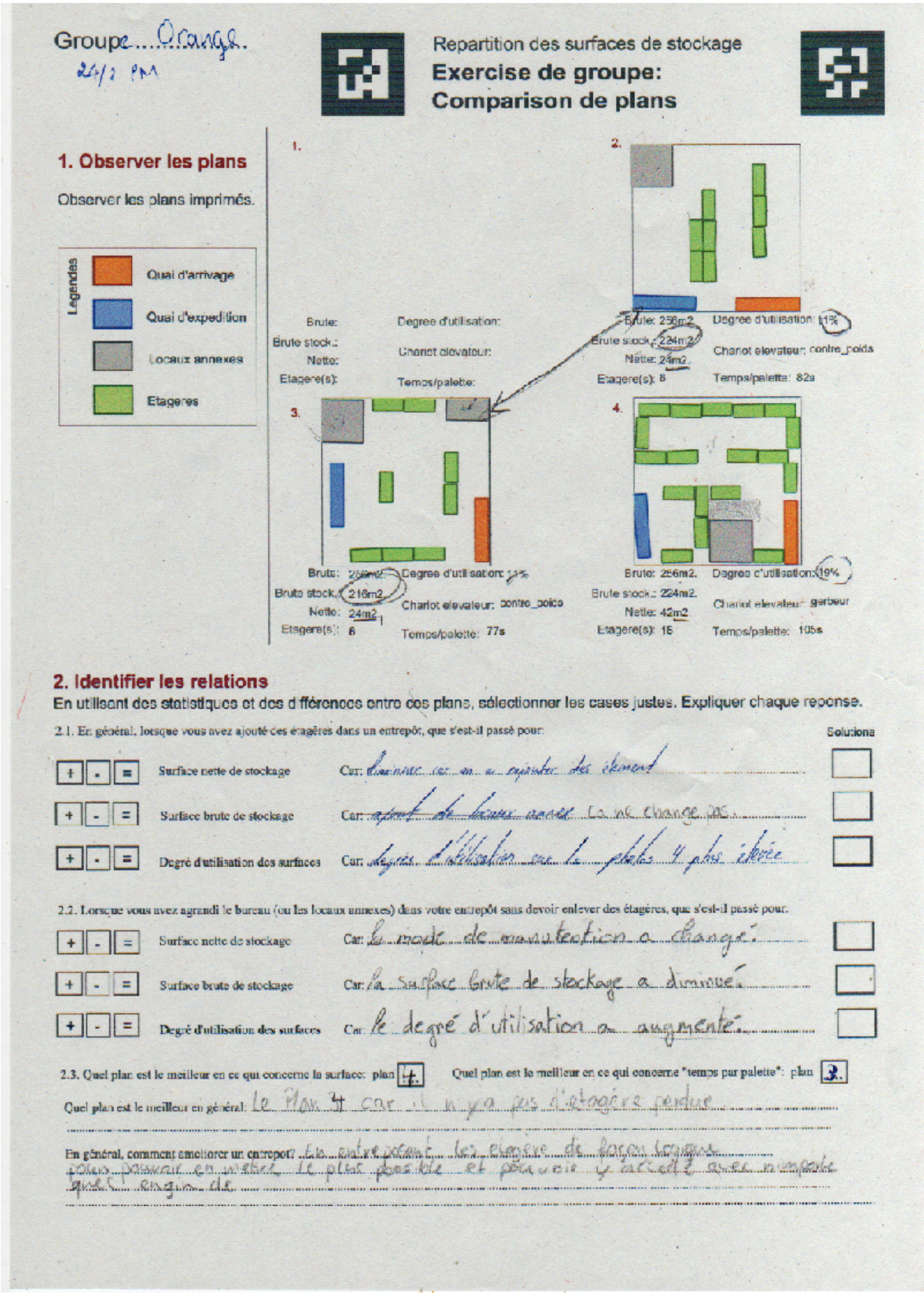
For each group, the teacher selected a few of the most interesting layouts the students had created from their LayoutBrowser. These layouts were sent over the network to the teacher's computer and printed out. This allowed each group to reflect on the personal layouts that they themselves had built during the class rather than a previously designed and printed exercise sheet with unfamiliar layouts.

The flow for this exercise was as follows:

- Groups of four receive a sheet, printed from their LayoutBrowser.
- The sheet comprises of 3 parts: 1) the four best layouts each group built during the manipulation phase. 2) Several multiple-choice questions (the same for all groups), asking them to compare the four layouts according to several criteria and explain their reasoning. 3) Several open-ended questions (the same for all groups), asking them to reflect on the overall best layout, and deduct the rule for designing productive warehouses.
- The groups discuss and agree on their responses, filling in the sheet.
- The teacher walks around the classroom to help with requests.
- The TinkerLamp shows the correct solutions for the multiple-choice questions.
- The teacher organizes a class debriefing session at the end, discussing the responses from all of the groups.

Figure 5.9 shows an example of this exercise.

This group reflection exercise is designed to be run under the supervision of the teacher. With this, we hoped to bring the teacher to the front of the class and explicitly elicit reflection and discussion between him and the groups.



Groupe ... Orange.
24/2 PM

Repartition des surfaces de stockage
Exercise de groupe:
Comparison de plans

1. Observer les plans

Observer les plans imprimés.

Legendes
- Quai d'arrivage
- Quai d'expedition
- Locaux annexes
- Etageres

1.
Brute:
Brute stock.:
Nette:
Etagere(s):
Degree d'utilisation:
Chariot elevateur:
Temps/palette:

2.
Brute: 256m2
Brute stock.: 224m2
Nette: 24m2
Etagere(s): 8
Degree d'utilisation: 11%
Chariot elevateur: contre_poids
Temps/palette: 82s

3.
Brute: 256m2
Brute stock.: 216m2
Nette: 24m2
Etagere(s): 8
Degree d'utilisation: 11%
Chariot elevateur: contre_poids
Temps/palette: 77s

4.
Brute: 256m2.
Brute stock.: 224m2.
Nette: 42m2
Etagere(s): 18
Degree d'utilisation: 19%
Chariot elevateur: gerbeur
Temps/palette: 105s

2. Identifier les relations

En utilisant des statistiques et des différences entre ces plans, sélectionner les cases justes. Expliquer chaque réponse.

2.1. En général, lorsque vous avez ajouté ces étagères dans un entrepôt, que s'est-il passé pour: Solutions

[+] [-] [=] Surface nette de stockage Car: diminue car on a rajouter des élément

[+] [-] [=] Surface brute de stockage Car: ~~ajout de bureaux annexe~~ ça ne change pas.

[+] [-] [=] Degré d'utilisation des surfaces Car: degrés d'utilisation sur le plan 4 plus élevée

2.2. Lorsque vous avez agrandi le bureau (ou les locaux annexes) dans votre entrepôt sans devoir enlever des étagères, que s'est-il passé pour:

[+] [-] [=] Surface nette de stockage Car: le mode de manutention a changé.

[+] [-] [=] Surface brute de stockage Car: la surface brute de stockage a diminué.

[+] [-] [=] Degré d'utilisation des surfaces Car: le degré d'utilisation a augmenté.

2.3. Quel plan est le meilleur en ce qui concerne la surface: plan 4. Quel plan est le meilleur en ce qui concerne "temps par palette": plan 3.

Quel plan est le meilleur en général: le Plan 4 car il n'y a pas d'étagère perdue

En général, comment ameliorer un entrepot? En entreposant les étagère de façon logique pour pouvoir en mettre le plus possible et pouvoir y accédé avec n'importe quel engin de

Figure 5.9: The design of the Group Reflection Exercise sheet completed by a student in our field study

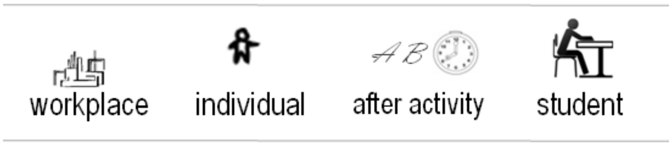


Figure 5.10: The design objectives of the Fieldwork exercise

5.5.2 Fieldwork sheet: learning outside the school

Objective

In this iteration, we began exploring how learning can be continued beyond the tangible tabletop and the classroom. The goal is for school knowledge and experience gained *after* working with TinkerLamps to be captured and re-used at the *apprentices' workplace*. This resulted in the design of the Fieldwork. Figure 5.10 illustrates its design goals.

Design

Similar to the group reflection exercise, the Fieldwork sheet is composed by the teacher of a selection of the most important layouts from the whole class (Figure 5.11). The apprentices were asked to bring the sheet to their own workplace and fill it out with their supervisor at work. The answers would then be discussed and debriefed during the next class at school.

The flow for this Fieldwork exercise is as follows.

- Multiple fieldworks are printed out at the end of the class, using the layouts saved on the groups' LayoutBrowser.
- The sheet contains multiple-choice and open-ended questions to answer. It is comprised of 3 parts: 1) the four best theoretical layouts the class built using the TinkerLamps at school. 2) Several multiple-choice questions, asking them to compare the four layouts according to several criteria, choose the overall best theoretical layout, and explain their reasoning. 3) Several open-ended questions to discuss with their supervisor at work.
- The students bring their fieldwork to their warehouse, discussing with their supervisor to fill in the answers. The discussion is focused around comparing the best theoretical layout to their real warehouse, and choosing the most similar and most different theoretical layouts to their real warehouse.
- The students bring their fieldwork back to school the next time.
- The teacher organizes a class debriefing, discussing the responses from the class.

There was no technological support for the discussion at the workplace or at the next debriefing session at school. The main goal of this feature was to understand the general behavior

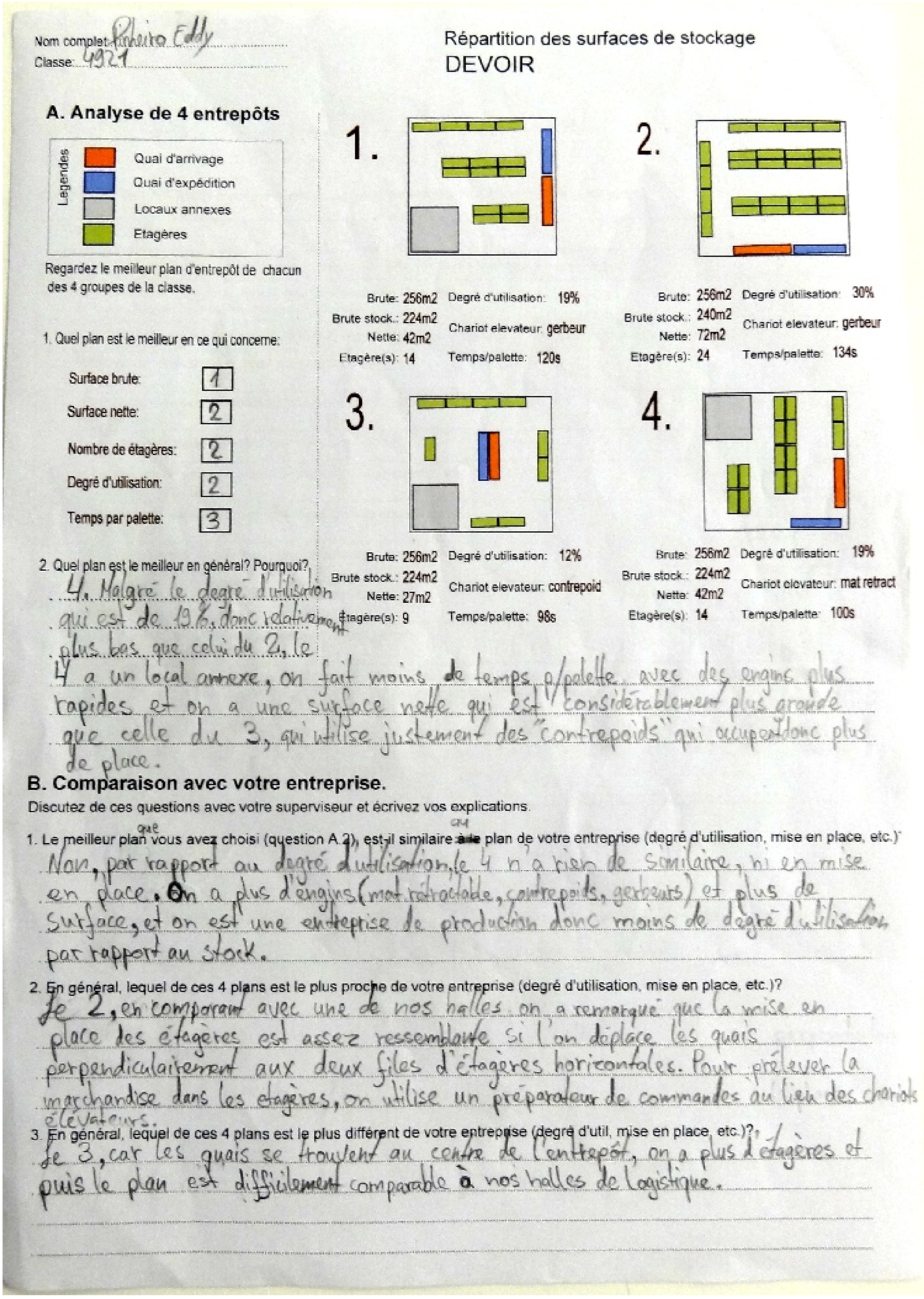


Figure 5.11: The final design of the fieldwork sheet completed by a student in our field study.

associated with how students do the fieldwork at the workplace, and what type of knowledge can be transferred. It served as an initial exploration, informing the design of possible technological tools to support this activity.

5.5.3 Evaluations

We tested the design and the scenario in four classes with a total of 60 apprentices and one teacher (Figure 5.12). The setup of this field study was identical to that of the Warehouse study (chapter 4). We used the same activity, post-test, student population, and structure but with the addition of the Group Reflection Exercise and Fieldwork at the end of the activity.

Because of the multitude of similarities, we compared the test score of this study to that of the Warehouse study to examine the differences in terms of learning outcomes, if any. Although, the two studies were not run at the same time, we hoped that the comparison could bring about some useful insights.

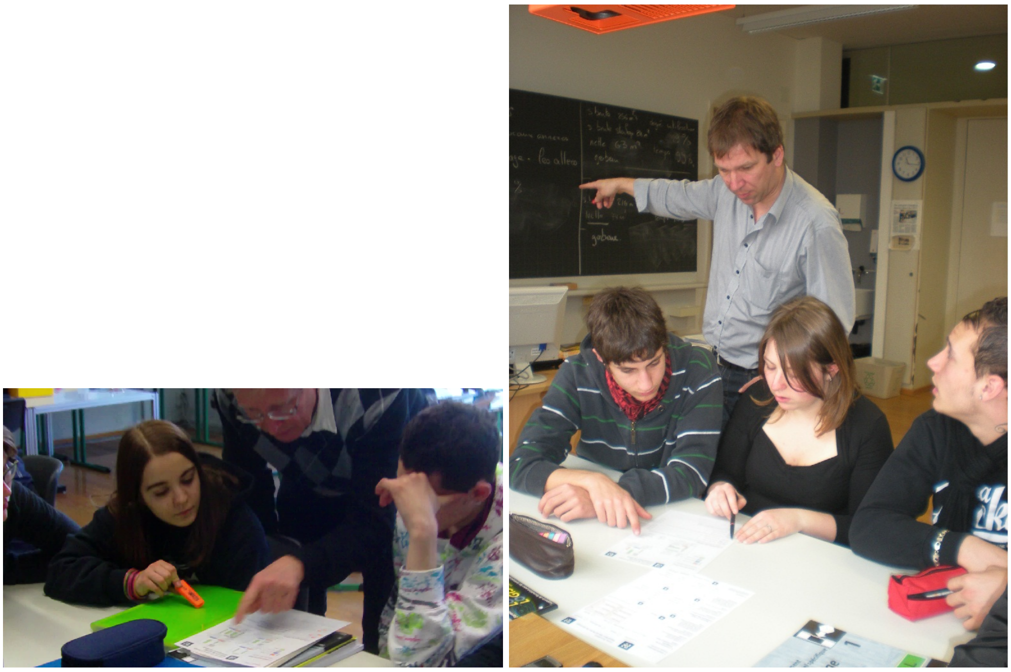


Figure 5.12: The field study of the second iteration of TinkerLamp 2.0. Teachers helping groups with their reflection exercise.

Observations and learning outcomes

We observed that the apprentices had more opportunities and spent more time reflecting, especially during the group reflection exercise. This exercise, in a way, forced them to reflect and discuss the logistics concepts at a high level because they were faced with only paper sheets (the tangible objects were taken away). Effectively, with the introduction of this exercise, the learning activity was divided into two phases: the manipulation phase and the reflection phase. The reflection phase required a lot of concentration and high-level thinking.

Table 5.3 summarizes the test scores of the two studies. For more detailed information on the post-test (identical to that of the Warehouse study, please refer to chapter 4, section 4.5.2, and Appendix C.

Measures	Warehouse study's conditions		TinkerLamp 2.0's second iteration	Statistical test
	Paper/pen	TinkerLamp 1.0		
Understanding score	7.84(2.85)	7.43(2.82)	8.65 (2.74)	ANOVA, $F(2,30) = 1.55, p > .05$
Problem-solving score	5.16(1.70)	5.15(1.78)	6.29(1.47)	ANOVA, $F(2,30) = 7.54, p < .01$

Table 5.3: The average post-test scores (and standard deviation) of the second iteration of TinkerLamp 2.0 versus those of the Warehouse study. There was no statistical difference across the conditions in terms of understanding score, but there was a statistical difference in terms of problem-solving score.

The comparisons can be summarized as follows.

Understanding score. An ANOVA test on mixed-effect model resulted in no significant difference between the three groups of logistics apprentices (using iteration 2 of TinkerLamp 2.0, the original TinkerLamp, and paper/pen) in terms of understanding score, ANOVA test, $F(2,30) = 1.55, p > .05$.

Problem-solving score. A similar test on the problem-solving score resulted in a significant difference between the three groups, confirmed by ANOVA, $F(2,30) = 7.54, p < .01$. Post-hoc pair-wise Tukey's HSD test showed that apprentices studying with the second iteration of TinkerLamp 2.0 performed better in terms of problem-solving than those in the paper/pen condition or the TinkerLamp 1.0 condition.

As we presented in section 4.6.2, the task and the learning score are not tightly connected since we had wanted to give some freedom in terms of what, when and how to discuss during the activity. The problem-learning score (which focused more on the application of knowledge in other situations), and not the understanding score (which focused on closed-form knowledge) of students using this iteration achieved a significance improvement compared to the previous version may reflect this design choice. It however, proved the appropriateness of explicitly embedding more reflection in the activity. With more time spent on the reflection about their solutions at the end and distill the learning concepts, the apprentices using this version of the TinkerLamp appeared to perform better.

Fieldwork

Apprentices were asked to bring the fieldwork sheet to their own workplace and discuss it with their supervisor. The questions involved selecting the most similar layout to their real warehouse, the most different layout from their real warehouse, and the best overall layout out of all of the layout options. 90% of the apprentices did the fieldwork and returned their sheet (even though the teachers warned us that apprentices hardly do any of their homework). 82% of these students discussed the fieldwork with their own supervisor for an average of 16 minutes. Some even brought back the blueprint of the warehouse they were working in.

In a questionnaire distributed in the next class, they all appreciated the exercise and the discussion, saying that it was useful for their understanding of the lesson and warehouses in general. The teacher also expressed enthusiasm and gave positive feedback during the next debriefing session of this fieldwork at school. He was pleased that the apprentices had extra time to relate what they did at school to their real warehouse.

Learning atmosphere

In spite of the encouraging results in terms of problem-solving score, our observation revealed a clear distinction of enjoyment level between the manipulation stage and reflection stage. During the manipulation stage, the students were very excited. They moved around the table, discussed with the group about how to construct a layout and worked together towards a final design. In constrast, the reflection stage and its group reflection exercise was not particularly engaging. It required the apprentices to work in the "old school" mode. Most of the time, only one member of the group took the lead. Other students were bored and did not seem to like participating. As one student said to his group during the activity, "This is not fun." (Figure 5.13)

Figure 5.13: The reflection paper exercise was not engaging. Only one or two students did the group work while the others were not interested in participating.

Teacher support

It remained challenging for the teachers to conduct debriefing activities during and after a simulation session. The spontaneous debriefing during the activity was difficult because the teachers had no means of referring to the built layouts. At the final debriefing of the activity, the transfer of layouts from the group level to class level could be done manually, i.e. tracing the projected layouts directly onto the TinkerSheet, and then transferring them to the class blackboard. While one could argue that this manual transfer of layouts could be useful in terms of reflection, we felt that the continuity of the activities was not very smooth. Too much time was spent when the teacher let the students draw on the blackboard. In three of four classes, the teacher only asked for the warehouse statistics to be copied on the blackboard, not the layout drawings (Figure 5.14).

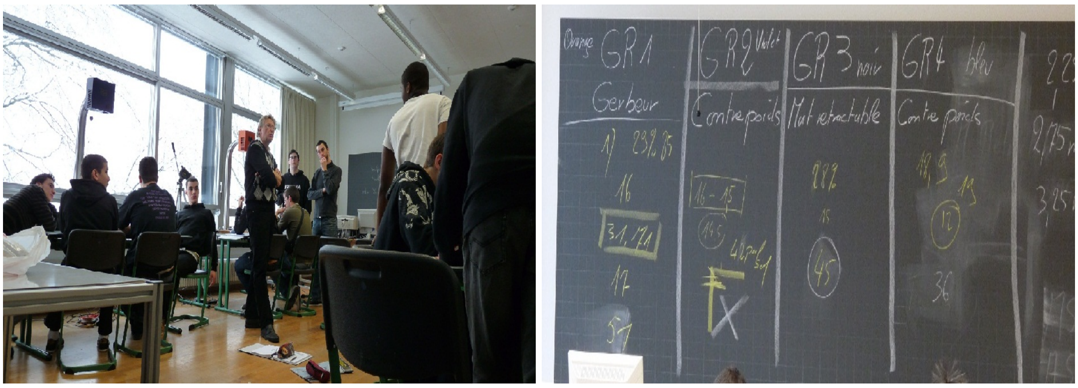


Figure 5.14: The challenges when doing class debriefing for the teacher. (left) He had no means of referring to all of the solutions built during the activity and had trouble doing spontaneous class-wide discussions. The discussion was based on mental representations of the warehouse layouts. (right) In addition, due to time limits, he did not ask the students to draw their layouts on the blackboard, instead only asking them to write the statistics.

5.5.4 Summary of the second iteration

Table 5.4 summarizes the proposed features and the insights from our field evaluations.

5.6 Third iteration: orchestration and class-wide activities support

Besides the open issues from previous iterations, the orchestration-related design goals had not yet been addressed appropriately. There were two key aspects involved:

- **Class progress awareness**. As we showed, working with four TinkerLamps at the same time posed certain difficulties to the teacher's classroom management. It was difficult for the teacher to keep track of the progress of all of the groups. This awareness of class

New feature	**Goal**	**Evaluation**	
Group reflection exercise	Support reflection-on-action and discussion	1) No difference in understanding score, but higher problem-solving score. 2) Not engaging for the students	✓ ✗
Fieldwork	Support continuity and discussion at the workplace	Students finishing fieldwork. Provided opportunities to relate theory and practice and to discuss with supervisor at work	✓

Open issues:

- Make reflection-on-action more fun.
- Supporting better continuity for debriefing sessions.

Table 5.4: Summary of the second iteration.

progress is crucial in helping the teacher plan his next action, e.g. posing appropriate questions to a group, deciding which group to address next, or making a move from group level activities to class level ones.

- **Support for class-wide activities and between-group interaction** Besides the debriefing activity conducted by the teacher, we would like to encourage between-group interaction, such as social learning and playful competition.

To achieve these goals, we chose to include three new components in our system: TinkerQuiz, TinkerBoard, and TinkerKey.

5.6.1 TinkerQuiz

TinkerQuiz was designed to 1) address the problem of making reflection more fun and 2) introduce a new kind of between-group interaction.

Design

TinkerQuiz is a small card used by the students to reflect on the concepts in a more interactive and fun way (Figure 5.19). The TinkerQuiz card is small with different colors and icons on it to give it the feel of a game. One can easily fit a stack of several quizzes in one's hand.

Currently, the system supports four TinkerQuizzes, each with different questions representing different logistics concepts. The questions ask students to compare two warehouse layouts according to a specific criterion. These two layouts are chosen either by the teacher or randomly by the TinkerLamp system among a "museum" of saved layouts. This "museum" is a collection of layouts that best reflects the differences in demonstrating these concepts of

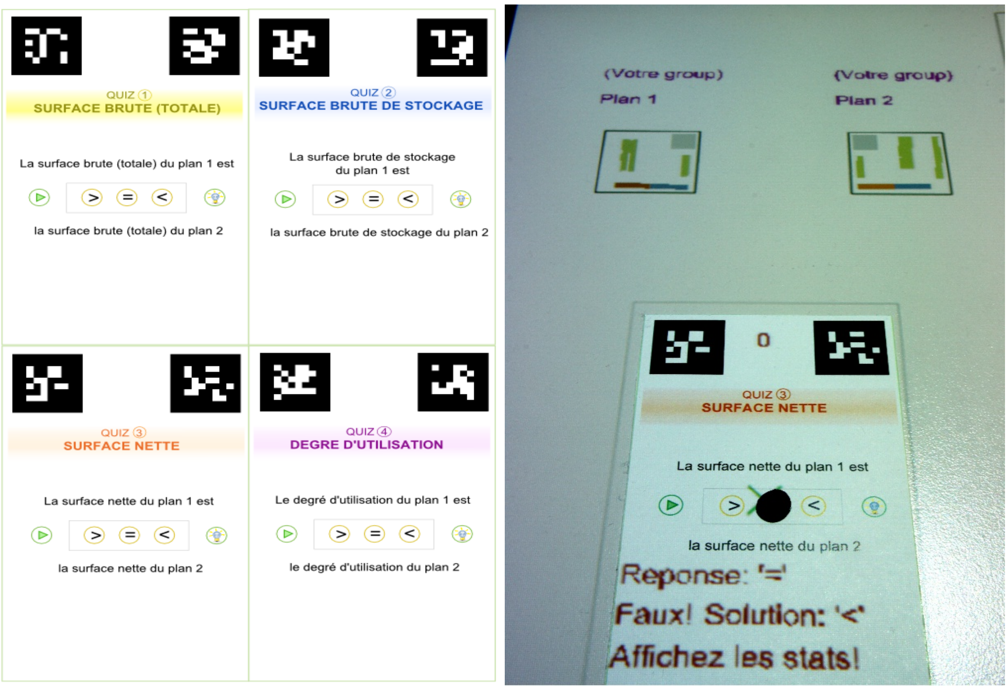


Figure 5.15: a) The set of TinkerQuizzes currently supported. b) Choosing a response with a TinkerQuiz and seeing the solution.

interest, chosen by the teachers and researchers.

When a quiz is placed under the lamp and started, two graphical layouts appear at the top of the quiz. A countdown timer also appears, showing how much time there is left to finish the quiz. This is intended to deliver a sense of pressure to the students. Interaction with the TinkerQuiz is done in the same way as with the TinkerSheet with a small token. Depending on which circle the token is placed, it can submit an answer or show the solution to the quiz.

The TinkerQuizzes can be done at two levels:

Group quiz. The quiz is done by a *group* of *apprentices* locally at their table *during* the activity. The design goals of the group quiz are illustrated in Figure 5.16. The layouts used for this quiz are the layouts that the group built previously using their lamp, or from the museum of layouts. Because the quiz projects different layouts each time, they can repeat the quiz as many times as they want, or as told by the teacher.

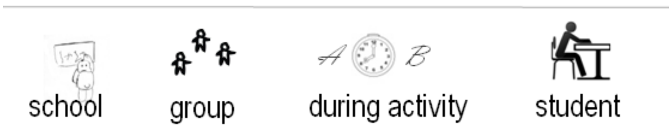


Figure 5.16: The design objectives of the Group TinkerQuiz.

Class quiz. The quiz is done by the whole *class* at the same time with the same question and layouts for every group of *apprentices after* the activity. These design goals are illustrated in Figure 5.17. It is a “class competition game”. The layouts are selected by the teacher from the TinkerBoard and are sent to every lamp through the network.

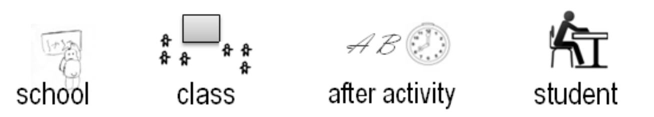


Figure 5.17: The design objectives of the Class TinkerQuiz.

5.6.2 TinkerBoard

Objective

TinkerBoard was designed to 1) support the debriefing session, 2) provide the class progress awareness for teachers, 3) encourage social learning between groups, and 4) encourage reflection about one’s own group actions.

The initial aim of the TinkerBoard was to facilitate debriefing sessions at the end of an activity, i.e. when the teacher discusses with the whole class about the advantages and disadvantages of certain layouts they built. We considered designs that provided a separate, private display for the teacher so that he could choose interesting layouts and display them on the class projection board.

However, after considering the class progress awareness issue, we decided to design the TinkerBoard as a public display in the classroom for the whole *class*, supporting both *teacher* and *apprentices*, and both *during* and *after* the activity (Figure 5.18).

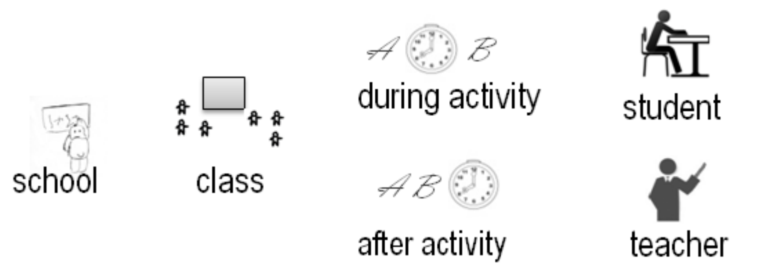


Figure 5.18: The design objectives of the TinkerBoard.

Design

The final TinkerBoard design serves two purposes: 1) a large awareness display for the whole classroom, and 2) an interactive application for the teacher.

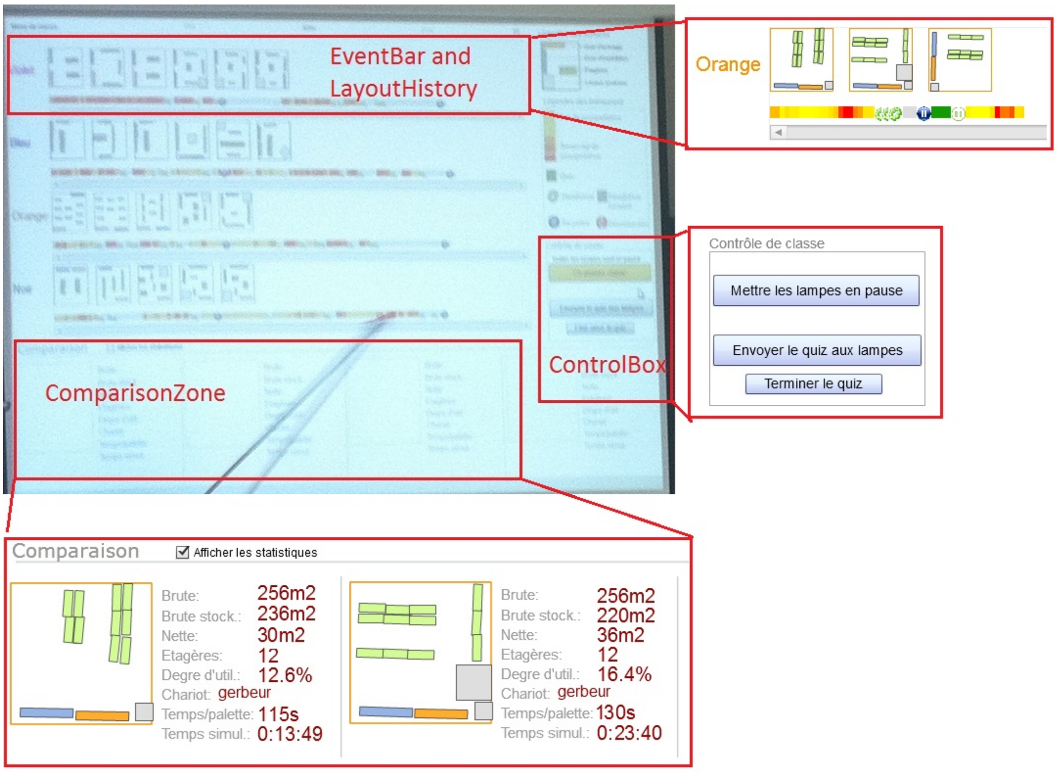


Figure 5.19: Overview of TinkerBoard and its components.

As an awareness display, it makes the whole class history visible on a big projection board. It includes a) an *event bar* showing what activity each group is doing (with different icons representing if they are engaged in building models/doing quizzes/running simulations/etc.), and how busy the apprentices are with physical manipulations (illustrated by small colored bars ranging from yellow to red, red being too many manipulations) and b) a *layout history* displaying all of the layouts each group saved during the activity.

The information provided by this awareness display can facilitate the teacher's orchestration, giving him a mechanism to quickly assess the class progress as a whole and plan his next action. By looking at the display, he can also tell if a group is doing too many manipulations. He can then intervene to encourage more thinking and less manipulating.

This information is also designed to support student's reflection and social learning. By looking at the event bar, the students can be more aware of the activity structure of their group and other groups, and hopefully regulate their actions. By looking at the layout history, they can compare the different layouts they built over time (reflection-on-action) even if some layouts have been deleted from their LayoutBrowser. Furthermore, the students are aware of what the other groups are doing, and can gain inspiration from their layouts. We expected that a good layout could be propagated throughout the class informally through this social learning mechanism.

As an interactive application for the teacher, the TinkerBoard provides support for his activities with the whole class using the following features.

- *Comparison zone*: a zone to compare different layouts and statistics for debriefing.
- *Run Class TinkerQuiz*: the teacher can send selected layouts to all of the TinkerLamp groups for a class-wide quiz and competition.
- *Pause class*: the teacher can blank out the projected feedback in all lamps to attract their full attention.
- *Print*: the teacher can print out group reflection exercises and fieldwork.

In this regard, the TinkerBoard empowers the teacher. It is a central control point of the whole class that only the teacher can interact with.

5.6.3 TinkerKey

Objective

TinkerKey was designed to 1) empower the teachers, providing special privileges for them as a replacement for the pen interaction we tried in the first iteration and 2) encourage reflection from the students.

It aimed to support the *teacher* to interact with either *a group* and the *class during* the activity (Figure 5.20).

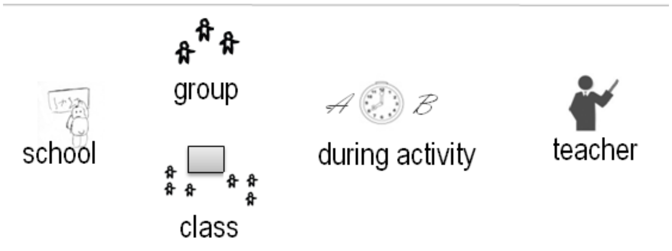


Figure 5.20: The design objectives of the TinkerKey.

Design

TinkerKey is a small paper card used to help the teacher orchestrate the class (Figure 5.21). Each TinkerKey triggers a different functionality in the TinkerLamp, either changing a state, or performing an action.

The scenario is envisioned as follows. The teacher keeps a set of TinkerKeys in his hand, touring the classroom as before. When he sees a need to intervene with a group (such as he finds that a group is doing too many simulations and does not reflect on the statistics) or with the class (when he wants to quickly get attention from the whole class), he places a card on the group's table. Each TinkerKey card is designed to be used at either the group level, which affects the state of only the group for which it is used, or the class level, which affects the state of the whole classroom.

The design of the TinkerKeys is lightweight and unobtrusive, making it possible for the teacher to maintain his usual behaviors in the class. On the other hand, the TinkerKey empowers the teacher by giving them means to interrupt and ask questions more effectively and differently than before.

Five TinkerKeys were implemented at this point:

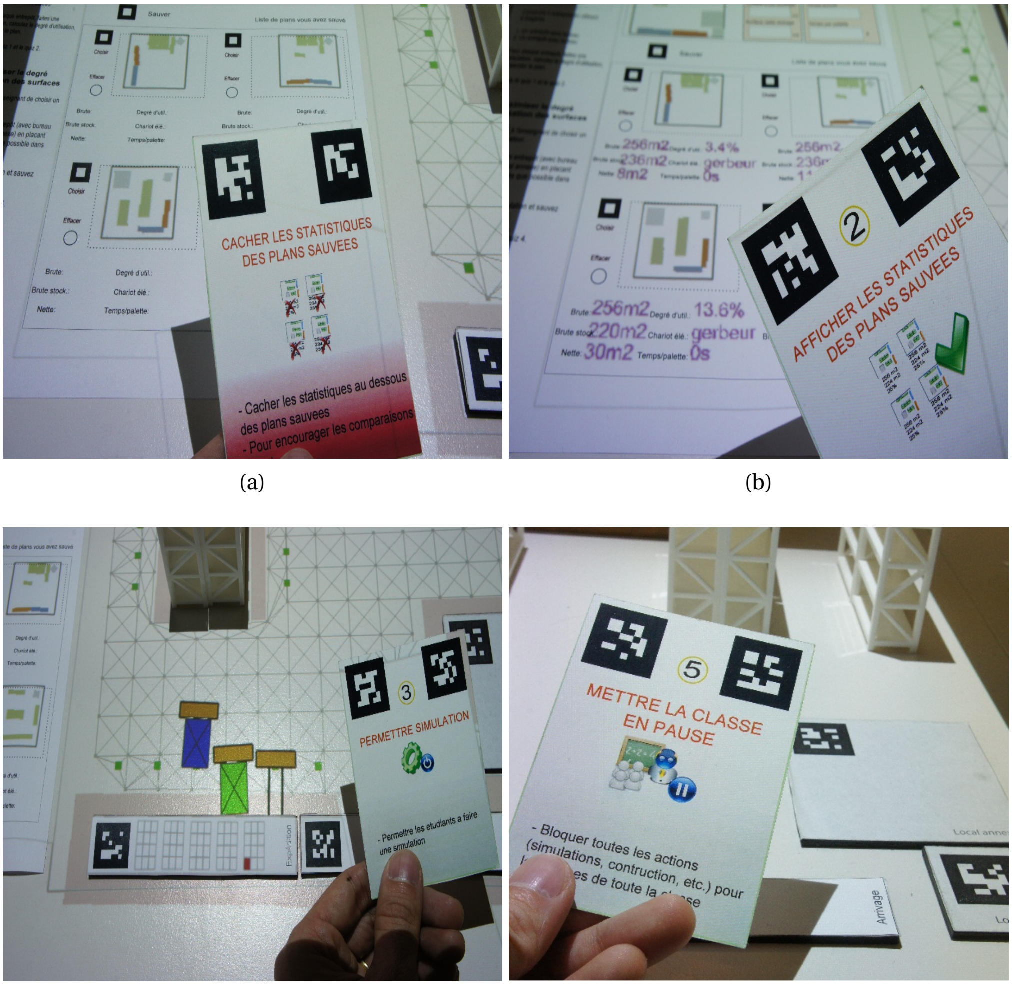
1. Hide Current Stats: to show/hide the statistics of the current warehouse layout the group is building. To support reflection-in-action, asking students to guess the statistics.
2. Hide Saved Stats: to show/hide the statistics of the warehouse layouts the group built and saved. To support reflection-on-action, asking students to compare different layouts.
3. Block Simulation: a group cannot run a simulation until the teacher uses this card to unblock it. To support reflection-in-action, asking students to predict before running simulation.
4. Pause Group: to blank out all of the projected feedback on the group's table. To get full attention from the group on the reflection.
5. Pause Class: to blank out all of the projected feedback in the whole class. To get full attention from the students in order to move to a class-wide activity (e.g. debriefing or class quiz). This TinkerKey works as soon as it is placed on any group's table by sending the command from that group's lamp to other lamps. This functionality is similar to that in the TinkerBoard but allows for more on-the-spot actions.

5.6.4 Evaluation

We ran two full-scale field trials to evaluate the whole TinkerLamp 2.0 system in two vocational schools. This evaluation is described in chapter 6 because of its detailed and long presentation.

5.6.5 Summary of the final iteration

In summary, the design of TinkerLamp 2.0 involves the provision of an ecology of tools: 1) tools to make the activity results of the students more explicit and accessible to their peers or



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

Figure 5.21: (a,b) TinkerKey to hide and show statistics of saved layouts, (c) TinkerKey to allow simulation for a group, (d) TinkerKey to pause the whole class.

teacher, 2) tools to increase the probability of useful discussion, and 3) tools to support the teacher's actions.

These main features of the final design can be summarized as follows:

- LayoutBrowser sheet: a sheet enabling saving 3D models into 2D graphical layouts
- Fieldwork: a print-out of some layouts selected from the whole class to be brought by the apprentices to their workplace and done with their supervisor at work
- TinkerQuiz: different small cards for the students with questions about the learning concepts
- TinkerKey: different small cards for the teachers to help him orchestrate the class

- TinkerBoard: serves two purposes: 1) an awareness display for the whole classroom and 2) an interactive application for the teacher

In Table 5.5, we list all of the features supported in the final design together with their design purpose.

New feature	Level	Role	*Support reflection-in-action*	*Support reflection-on-action*	*Support continuity*	*Empower teacher*	*Support class-wide activities*
LayoutBrowser	group	students teachers	✓		✓		
Fieldwork	individual	students		✓	✓		
TinkerQuiz	group class	students	✓	✓	✓		✓
TinkerKey	group class	teachers	✓			✓	✓
TinkerBoard	class	students teachers	✓	✓	✓	✓	✓

Table 5.5: Summary of the final iteration.

5.7 Implementation of TinkerLamp 2.0

The TinkerLamp 2.0 environment builds on the previous TinkerLamp infrastructure and the Tinker Programming Framework. We also introduced a new key component concerning the networking capability to connect multiple TinkerLamps and the TinkerBoard.

Students' interactions with the lamps through the warehouse model, LayoutBrowser, and TinkerQuiz were implemented in C/C++ with support from libraries such as OpenCV and OpenGL for Computer Vision and Graphics functionalities. Teachers' interactions with the lamps using a TinkerKey, on the other hand, can be processed locally (at the lamp where it is used) or at a class-wide level (commands are sent to the TinkerBoard, then propagated to other lamps).

The TinkerBoard component was implemented separately, connecting to the lamp clients through the TCP/IP network protocol and a set of user-defined commands. This component runs on the teacher's computer and projects to the class projection board. It was implemented using Adobe Flex 4.5 and Flash ActionScript.

5.8 Summary

We presented the design goals and iterations of the TinkerLamp 2.0, a tangible tabletop to support logistics training. This new generation of the TinkerLamp system aimed to specifically address two themes: reflection and orchestration. The design process showed the choices that we made to tackle several aspects around these two themes.

The resulting final design is an ecology of tools to support the whole learning flow at different levels (group, class, or in the field) for different actors (teachers, students). This ecology of tools

- consists of multiple external resources for reflection and discussion (e.g. the warehouse model, the TinkerQuiz, the layout history saved, etc.).
- produces the resources for the continuity of activities (e.g. printing out fieldwork for the students to do in their workplace or saving a layout at a lamp, which will automatically display it on the TinkerBoard for class discussion and debriefing).
- provides resources for actions (e.g. teachers using TinkerKey to intervene at individual groups, TinkerBoard enabling teachers' awareness about the classroom, etc.)

The implications of this chapter are:

- The analysis and summary of the two previous studies (ConceptMap and Warehouse study) suggested that orchestration and reflection are related. Supporting orchestration is a way to support reflection.
- The design goals for TinkerLamp 2.0 led to a design space that other tangible tabletop systems may consider to support both reflection and orchestration.
- The design process, evaluations, and iterations of TinkerLamp 2.0 suggested that in order to fulfill the design goals, similar systems should consider providing an ecology of tools, rather than a stand-alone tangible interface.

6 Evaluation of TinkerLamp 2.0 in Classroom

6.1 Introduction

In order to gain insight about how the TinkerLamp 2.0 system functions in real-world settings, we conducted two field trials in two vocational schools in Switzerland. They took place one after another, one-week apart, to allow time to make relevant changes.

This chapter presents the findings of these two trials. We describe our observations, the usability issues encountered, log analysis, students' questionnaire responses, and teachers' feedback about the system. As it turned out, this new version of the TinkerLamp seemed to fulfill its design goals, providing more support for reflection and orchestration.

The chapter begins with our study method and setup, followed by the details of the analysis. It concludes with a discussion about the study and design implications for similar systems.

6.2 Method

6.2.1 Procedure

Participants

Four classroom groups, totaling 64 students (56 males, 8 females), were observed during two full-day studies, with two different teachers in two logistic schools in Switzerland (located in

Bulle and Yverdon). Each classroom group comprised of 15-17 students.

The two studies took place one after another, a week apart. The week in between the two studies allowed us to make relevant changes according to our observations and users' feedback. The first study (in Bulle) was done with a teacher who had been involved in the design process of TinkerLamp 2.0. The second study (in Yverdon) was done one week later with a teacher who only had experience working with the original TinkerLamp system designed in chapter 4 (hereafter referred to as TinkerLamp 1.0), but not TinkerLamp 2.0.

Conditions

The TinkerLamp 2.0 and the following features, TinkerQuiz, TinkerKey, LayoutBrowser, were used in all classes. The Fieldwork was not included in these field trials since there was no change concerning this exercise since the second iteration. Our priority was to look at how the other technological features are integrated in the classroom.

In each school, the class studying in the morning session worked without the TinkerBoard (called the *NoTinkerBoard* condition). The class studying in the afternoon worked with the entire system (called the *WithTinkerBoard* condition). The reason for this setup was for us to observe the differences (if any) between the two conditions in terms of perceptions, student behaviors, and classroom atmosphere in general. Figure 6.1 summarizes this setup.

Session	First trial (Bulle)		Second trial (Yverdon)	
	No of students	Condition	No of students	Condition
Morning	15	NoTinkerBoard	16	NoTinkerBoard
Afternoon	17	WithTinkerBoard	16	WithTinkerBoard

Table 6.1: The setup of the two trials and features used for each condition.

Technical setup

The classrooms were set up with four TinkerLamps of varying colors (orange, black, blue, and violet) to allow for small groups of typically four students per lamp. Each of the TinkerLamps was connected by a network router to a server located at the front of the classroom. This server computer used the events sent from the lamps to update the TinkerBoard display, as well as to relay the signals to other lamps.

Task structure

In general, the task structure was similar to that described in the Warehouse study (chapter 4). In total, each classroom trial lasted approximately three hours. The first two hours were dedicated to class time using the TinkerLamps and the last hour was dedicated to post-tests and feedback. All activities during this time were video- and audio-recorded.

Before the class, the teachers were given a brief introduction about the new aspects of the TinkerLamps as well as a rough schedule for the class. The teachers began class as normal, introducing definitions and material on the blackboard. Then, after a short, three to five-minute demonstration of the TinkerLamp, the class was divided into four groups and each was assigned to a lamp. The Group TinkerQuiz was done during the group exercises in both conditions. The class TinkerQuiz, on the other hand, was done only in the WithTinkerBoard condition. While students were working with the lamps, all interactions with the tangible models, the LayoutBrowser, or the TinkerQuiz were being recorded in real-time and displayed on the TinkerBoard in the WithTinkerBoard condition.

Measures and Analysis approach

During the last hour of the study, a post-test (similar to the one given in the Warehouse study (chapter 4), detailed in Appendix C, section C.2) and a questionnaire were distributed to evaluate the students' learning and their impressions of the class, respectively (Appendix E). We also asked for the teachers' feedback in a interview held after the class.

The goal of the trials was to explore how students and teachers used the TinkerLamp 2.0 system and any problems they had while using it. We iteratively changed certain features of the TinkerLamp 2.0 system between each site visit based on the observed needs of the users.

6.3 Findings

6.3.1 General observations

Our tutorials before the class indicated that teachers were able to quickly and easily discover how to use all of the TinkerLamp 2.0 features including the interaction with the TinkerBoard, the use of TinkerKey, the running of the TinkerQuiz, and the relation between local interactions (on the student's table) and their impacts on the class (e.g. updating the display of TinkerBoard, sending events to other lamps).

When the learning session started, teachers began by giving a short lecture on the logistics concepts and then divided the class into four groups. Similar to sessions with the previous TinkerLamp system, the teachers generally wandered the classroom, attending to each TinkerLamp group individually and posing questions specific to their built layouts.

What was different in teaching with TinkerLamp 2.0, compared to TinkerLamp 1.0, was the teachers' interaction with the students and the interface. In TinkerLamp 1.0, the teachers usually monitored, in silence, what was happening at each table before deciding to intervene (just by posing questions). During this monitoring time, they looked at the tangible model, observing the students building it. In TinkerLamp 2.0, besides these behaviors, we saw that the teachers also looked at the LayoutBrowser to assess their progress and use different ways to intervene. They used different TinkerKey cards to turn on/off certain visualizations, or put the 'run simulation' feature on hold before asking reflective questions to the group. The teachers assigned different TinkerQuizzes to different groups based on their level of understanding and used the TinkerBoard to support debriefing and class-wide discussions. In general, the design gave teachers more abilities and power to take advantage of "teachable moments". These observations are elaborated further in the next sections.

6.3.2 Reflection-in-action with Group TinkerQuiz

Analysis

Group quizzes incited a lot of reflection between students in a group. These quizzes forced them to discuss and practice reflection-in-action, i.e. thinking about one specific logistics concept in the comparison of two different layouts. Our logs showed that the maximum number of quizzes done by one group during the whole activity was 50 quizzes, the minimum was 14 quizzes (excluding the one group who had technical problems and could do only 4 quizzes). The average number of quizzes done by each group is shown in Table 6.2.

Condition	First trial	Second trial
NoTinkerBoard	13.3	24
WithTinkerBoard	18.5	42

Table 6.2: The average number of quizzes done in each class.

The number of quizzes done by each group in the WithTinkerBoard condition is generally higher than in the NoTinkerBoard condition. We hypothesize that, the curiosity for the class quiz (which was only done in the WithTinkerBoard condition) that was to come in the end, excited the students and encouraged them to practice more.

We examined the log further to see how often each type of quiz was done. Table 6.3 reports this number. The concepts asked for Quiz 1, 2, 3, 4 were about Raw surface, Raw stockage surface, Net surface, and Degree of utilisation, respectively. In general, we saw that the TinkerQuiz 2 and TinkerQuiz 4 were done more times than the others. This is likely because the two concepts asked in these quizzes are more difficult to grasp (requiring more reasoning and mathematical calculations) and therefore would require more practice.

Session	First trial				Second trial			
	Quiz 1	Quiz 2	Quiz 3	Quiz 4	Quiz 1	Quiz 2	Quiz 3	Quiz 4
NoTinkerBoard	3	3.67	2.67	4	5.25	9.75	4.5	4.5
WithTinkerBoard	2.5	9.25	4.25	2.5	8.0	9.0	11.0	14

Table 6.3: The average number of quizzes done in each of the class.

The 90 second countdown timer on the quizzes encouraged collaboration. As an example, after the first group quiz commenced, we noticed one student quickly stood up from her seat to help her group members, saying, “Oh! There’s a timer!”

Overall, we observed that all members of almost every group discussed the quiz questions together before selecting a final answer. Many verbal exchanges and much concentration occurred before one group member chose the answer for the whole group (Figure 6.1). However, because only one quiz card was distributed per group, we noticed a few instances of individuals not contributing to the group discussion.

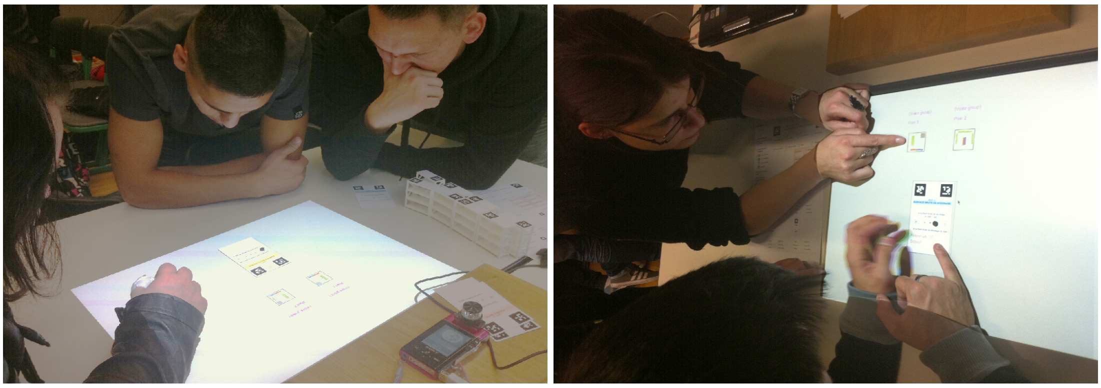


Figure 6.1: Group TinkerQuiz made the students concentrate and discuss more about logistics concepts during the activity.

The TinkerQuiz cards also allowed for flexible orchestration in terms of assigning different activities to different groups or levels. The log stated that the specific quiz start times varied between each group, with a discrepancy of up to 5 minutes. This is consistent with our observations during both studies. We noticed that the teachers assigned more advanced quizzes to more motivated and high-performing groups. This purposeful deliberation was confirmed in the teacher interview.

Usability issues of Group TinkerQuiz

Reflection on group’s own layouts vs. on museum of layouts. A design choice that we made with the Group TinkerQuiz in the first trial, which led to unsatisfactory results, was the repetitive layouts compared in the quiz’s questions. In this study, the two layouts used in the quiz were designed to be chosen at random from the layouts that the group had saved in their LayoutBrowser, the idea being that they would reflect on their own layouts. However, the limited number of layouts saved at the beginning led to repetitive questions which made the students bored after a few trials. Both teachers and students expressed that they would find it more challenging and fun to work on a larger variety of layouts. In the second study, we made sure that the quiz layouts were not selected from the group’s saved layouts but rather an entire museum of layouts designed beforehand that best reflect the logistics concepts to learn.

Flexibility and the unsuccesful locking of TinkerQuiz to force reflection. An important issue was that TinkerQuiz was not “flexible” enough during the first trial. After students chose an answer, each TinkerQuiz would show the solution and was then locked unless the students used a token to make the system show the statistics of the correct solution. This locking aimed to force reflection about the solution before the next quiz could be done. Nevertheless, this rigid enforcement caused usability problems as the students were annoyed and confused about why they could not start a new question with the same quiz. As a result, they tried to put another TinkerQuiz card on the table and started running it. The situation became confusing with two cards running in parallel. Moreover, in most of the cases, showing statistics of the correct solution was just a mere formality for the students to skip to the next question. Consequently, we disabled this locking feature in the second trial and observed no further problem.

A bug which led to unexpected interesting outcome. We also observed a small bug in the TinkerQuiz implementation during the first study in Bulle. One of the answers on a quiz question was coded incorrectly and thus displayed a wrong solution. Interestingly, as the TinkerQuiz showed both this wrong solution and the correct statistics after the question was answered, the teacher was able to use these two conflicting pieces of information to trigger even more debate and discussion from the students. He even seemed satisfied and proud to be able to use the bug to his advantage to build more drama in discussion. This bug, however, was fixed in the second study.

6.3.3 Reflection-on-action and competition with Class TinkerQuiz

Analysis

While the group quizzes encouraged collaboration, class quizzes, which were only present in the WithTinkerBoard condition, incited playful competition. During a class quiz, the order of each group's response was projected on the TinkerBoard at the front of the class. This seemed to encourage the students to submit the correct response faster than the other groups. More specifically, the quizzes were completed very quickly and all group responses were recorded on the TinkerBoard within 15 seconds of starting the quiz.

In the first study, due to technical problems, 3 class quizzes were done at the end of the activity with the class divided into two big groups. In the second study, 5 class quizzes were done with four groups of four students each.

Although taking place at the end of the activity for a limited amount of time (about 10 minutes), the enthusiasm for these quizzes was notable, as the winning groups always cheered. The students were very excited and the whole classroom turned into a "field" for playful competition. A factor that contributed to this atmosphere was the fact that the teachers told the students during the group quizzes that they needed to practice in order to "win" the class quiz later. This helped build the curiosity and drama in the activity. The student questionnaire and teachers' interview also confirmed these observations. Figure 6.9 illustrates these observations.

Figure 6.2: The group who submitted the first response cheered during a class quiz.

Usability issues of class TinkerQuiz

In the first study, one problem was observed regarding the synchronization of the class quizzes. Our implementation allowed the students to have control of the start time of their quiz. Groups often accidentally started before the other groups were ready. We had to reset the system a few times before the students managed to begin the quiz at the same time.

Ideally, the teacher should have control of commencing a class quiz for all groups, but we did not have time to address this problem on a technical basis before the second study. Instead, we suggested that the teacher collect all of the answer tokens and call one member of each group to the front of the class. When everyone was ready, the teacher distributed the tokens, signifying that the students could begin the quiz. We were surprised to observe that this physical participation and running back to other group members also added more excitement. It gave the whole classroom a playful atmosphere. Nevertheless, in the future we hope to address this issue in a more technical and fair way by giving the power to start a class quiz only to the teacher.

Teacher's feedback

The use of TinkerQuiz at the class level required conducting from teachers via TinkerBoard. After a short tutorial and real-time support from researchers, they were able to run the class quiz without any problem. Both teachers reported in their interview that the running of the class TinkerQuiz was easy. Consistent with our observation of class atmosphere, both teachers said that the class TinkerQuiz had clearly increased the students' reflection and motivation compared to the previous version of TinkerLamp. They said that the students really appreciated it and were still talking about it in their next class. The teacher in the second study said *"They liked it because they loved having this kind of competition between the groups"*.

When asked to choose between group and class quiz, the teacher in the first study reported he preferred to have the class quiz, mostly due to the playful atmosphere and the aforementioned limitations of group quiz, namely the limited number of layouts and questions (we fixed these issues after this study).

In contrast, the teacher in the second study preferred the group quiz. The reason was that he would like to have a more flexible way to deal with multiple groups, as he stated: *"The group quiz is more adaptable because we have groups who advance in their activity more quickly than the other groups. Doing this (distributing different group quizzes to different groups) would give us a better productivity."*

Questionnaires about both Group and Class quiz

In terms of usability, we asked the students to rate their level of agreement with 3 statements using a 1-to-7 scale: 1) "It is user friendly" (User-friendly), 2) "Using it is effortless" (Effortless), 3) "I learned to use it quickly" (Fast-learning). The first two statements concern the ease of use aspect and the last one concerns the ease of learning aspect of the interface. In general, the TinkerQuiz was rated as both easy to use and easy to learn in both trials. Table 6.4 illustrates the result of the student's rating.

Question	First trial	Second trial
It is user friendly	$m = 6.00(0.93)$	$m = 5.69(1.14)$
Using it is effortless	$m = 5.86(1.60)$	$m = 5.90(0.83)$
I learned to use it quickly	$m = 6.25(0.84)$	$m = 6.36(0.76)$

Table 6.4: The average rating (and standard deviation) for TinkerQuiz in terms of ease of use and ease to learn.

The written feedback in the open-ended comments section from the students on the questionnaire is consistent with all of the observations above. In the first trial, the most negative aspect about the group quizzes was the wrong answer given, with a total of 9 students reporting this. Next on the negative aspect list were easy questions (stated 4 times) and repetitive questions (stated 7 times). Four students stressed this again at the end of their questionnaire, mentioning that the questions were easy and should include different layouts. They expressed a need for more difficult, more relevant, and non-repetitive questions in general on the quizzes.

In the second study, these issues no longer appeared since we made the requested changes. Surprisingly, this resulted in the most common complaint from the second study being that the quiz was too much like a game and not enough like an exercise. This confirmed that including the TinkerQuizzes was capable of making learning and reflection fun, with the students not perceiving them as an exercise.

Together, the two studies' questionnaire responses did prove the success of our design goal of making reflection more fun. Overall, fun, learning, and collaboration were the most positive aspects reported from both sessions in the open-ended comment section.

The "fun" value was reported on 12 different occasions throughout the studies. Nearly every student who made comments in the open-ended feedback section said *"It was fun"*. The next positive aspect about the quizzes, noted a total of 10 times, was the "learning" value. As a student put it: *"This (quiz) made us think just about the small details that change (between two layouts)"*. The "collaboration" aspect was mentioned 6 times with comments such as *"This allowed us to exchange and think out our response with our friends"*.

6.3.4 Reflection-in-action and orchestration with TinkerKey

The TinkerKey, five cards intended for the teacher's use, served as an orchestration tool for the teacher at both the group and class level. Table 6.5 summarizes the number of times each card was used by the teachers. In general, the teachers used TinkerKey cards in the WithTinkerBoard condition more often than in the NoTinkerBoard condition. However, it may well be that this number merely reflects the familiarity of the teachers with the cards since the WithTinkerBoard condition always came after the NoTinkerBoard condition.

TinkerKey	Teacher in the first trial		Teacher in the second trial	
	NoTinkerBoard	WithTinkerBoard	NoTinkerBoard	WithTinkerBoard
1. Hide Current Stats	6	20	10	26
2. Hide Saved Stats	6	18	12	11
3. Allow Simulation	23	29	27	22
4. Pause Group	4	18	10	25
5. Pause Class	2	8	4	6

Table 6.5: The number of use of each TinkerKey in the two trials.

We observed the teachers using the two TinkerKeys ("Hide Current Stats" and "Hide Saved Stats") throughout the activity to hide statistics for individual groups in order to pose a question. After hiding the stats, they encouraged the students to reflect and discuss the layout before showing them the statistics with a TinkerKey card.

The teacher also used the simulation TinkerKey card extensively. We noted students saying *"Sir, please, we want to do a simulation"* because the groups were not authorized to run a simulation without the teacher's permission. Figure 6.3 illustrates this observation.

At the class level orchestration, we noticed the teacher using the TinkerKey cards to pause the groups and call attention to the class. The "Pause Class" card was used extensively, before every debriefing session or class-wide instruction. Each teacher used it at least 2 times and

Figure 6.3: A teacher used the “Allow Simulation” TinkerKey with a group.

at most 8 times in his class. It clearly helped the teachers gain full attention from the whole class compared to previous studies. An exeption occurred on the morning of the first study when the teacher used the “Pause Group” to pause each and every group instead of using the “Pause Class” card. He later on explained that in the hurry, he was confused about the cards and which side to use, so he decided to use the first card he saw that could solve the situation.

With the TinkerKeys, the teachers showed considerable pride throughout the activities when they were able to interact with the system in a way no one else could (Figure 6.4). For instance, at 11 minutes into the activity, the teacher in the second study asked a group to run a simulation. When the group was surprised that the system did not react to their interaction, he showed his “Allow Simulation” card and said *“It did not run, did it? That’s because you don’t have this card. Ah hah!”*.

Usability issues of TinkerKey

Although we only observed positive outcomes of the cards when used correctly, observations from the first study showed that the teacher had difficulty differentiating the TinkerKey cards between one another as well as which side of a card started or stopped a specific action. We saw the teacher exchanging cards and flipping them over multiple times before being satisfied with his action.

For this reason, we decided to distinguish the TinkerKey cards for the teachers in the second study by doing the following:

- numbering the cards.
- coloring the “start” side of the card green and the “stop” side of the card red.
- making the cards smaller than the student TinkerQuiz cards.

With these modifications, we noticed none of the confusions repeated in the second study.

Figure 6.4: The teachers were empowered with TinkerKeys. Only they could interact and change the state of the system by using different TinkerKey cards.

Teacher's feedback

In the interview, we were able to confirm our observations that both teachers used all TinkerKeys for the purpose that each card was designed. More specifically, they said they used the three TinkerKeys 1, 2, 3 ("Hide Current Stats", "Hide Saved Stats", and "Allow Simulation") for reflection (for example, asking students to predict and think before running simulation). The cards were also used to support teacher's orchestration in terms of managing the pace of the classroom by assigning different activities to different groups if necessary. The teacher in Bulle answered *"The TinkerKey 1 ("Hide Current Stats" card) and 3 ("Allow Simulation" card) allowed me to vary the exercises according to the students' performances and time available."*

Similarly, they said they used the "Pause Group" card to focus students' attention in the group to encourage discussion and reflection, and the "Pause Class" card before doing class debriefing or giving class-wide instructions. Interestingly, we found a response from the student questionnaire that also confirmed this: *"It's good to pause the visual augmentation since we only face the papers (refer to the paper quiz card)"*. Even though the TinkerBoard also has a "Pause Class" function, both teachers said they preferred using the TinkerKey to pause the class.

We asked the two teachers to rate their preferences of each TinkerKey on a scale from 1 to 5, including *1/5 ("I hated it"), 2/5 ("I didn't like it"), 3/5 ("Nothing special"), 4/5 ("I liked it"), 5/5 ("I liked it a lot")*. The two TinkerKey "Hide Current Stats" and "Pause Class" received the best rating from both teachers. Table 6.6 summarizes these preferences.

TinkerKey	Teacher in the first trial		Teacher in the second trial	
	Rating	Comments	Rating	Comments
1. Hide Current Stats	5/5	"I can request the students to answer questions and confirm if it's correct. This allows to vary the activity according to the group level and the time available."	5/5	"Because I can make students reflect and tell them if they had a good reflection."
2. Hide Saved Stats	4/5	"I used it to ask the students why a layout is effective in comparison to the others"	3/5	"I liked the (Hide Current Stats card) better"
3. Allow Simulation	5/5	"This allows making the students reflect before running simulation"	4/5	"It enabled me to pose questions before running simulation."
4. Pause Group	4/5	"Allow me to attract attention from the students in the group"	4/5	"If we want full attention from the whole group, that's a good solution!"
5. Pause Class	5/5	"Allow me to use time during the activity to debrief the theory based on what just happened. (The card) is a way to tell students: Stop for a minute, I block everything to say something, then we continue later"	5/5	"Instead of losing time to request the students to be quiet, they understand right away that they have to turn to me and wait for my instructions.
Scale: 5/5: I liked it a lot. 4/5: I liked it. 3/5: Nothing special. 2/5: I didn't like it. 1/5: I hated it.				

Table 6.6: The preferences for each TinkerKey card as rated by the teachers.

An important point was noticed when the teacher in study 2 recommended *"(the teacher) should not have too many other cards. Otherwise the teacher wouldn't use them"*. This confirmed our observation above. As we described, the teacher was already sometimes confused with only five two-sided TinkerKeys during the first study.

6.3.5 Classroom orchestration and class-wide activities with TinkerBoard

TinkerBoard for class-wide discussion and debriefing

In the morning sessions, when the TinkerBoard was not available, the teacher in the first trial merged the normal classroom blackboard use with the TinkerLamp technology by having each group trace their best layout onto the LayoutBrowser and then transfer it to the blackboard for the debriefing session *at the end of the activity*. In contrast, the teacher in the second trial asked the students to write only statistics on the blackboard. With the information transcribed on the blackboard, the teachers proceeded to compare and discuss the positive and negative aspects of each layout with the class. However, spontaneous debriefing *during the activity* did not occur since the teachers did not have any means to refer to the layouts built by apprentices. These observations were similar to those in the Warehouse study.

In the afternoon, with TinkerBoard present, there was however a more seamless transition in two aspects.

- **Foster transition between the building phase and debriefing phase.** The class debriefing at the end of the activity was prepared much faster than the traditional blackboard usage, almost effortlessly. The teachers simply dragged each group's chosen layout from the saved layout history into the comparison zone on the TinkerBoard and started the debriefing right after. In addition, the layout history was available during the debriefing, making references to the intermediate results and solutions possible. The layouts, as well as their accompanying statistics, were represented on the public display and the whole class discussed from there. Figure 6.5a illustrates a teacher comparing four layouts from the groups at the end of the activity.

- **Foster transition between group work and class-wide activities**. The teachers could have spontaneous debriefing with the class at any time, without having to do any extra interactions with the system. We observed teachers looking at the TinkerBoard, and then illustrating the problem-solving strategies, benefits, and drawbacks of the solutions to the students on the TinkerBoard just by walking up to it and pointing to it (often after using TinkerKey to pause the whole class) (Figure 6.5b). In the TinkerBoard condition, the teacher in the first trial had 4 more spontaneous debriefing sessions during the activity than in the NoTinkerBoard condition, while the teacher in the second trial had 5 more.

In the interview, the teachers answered that the interactions with TinkerBoard were simple and easy. They were content with the drag-and-drop feature that allow them to quickly choose layouts from the layout history to the comparison zone for debriefing. They also reported that the information provided was sufficient for their debriefing with the class.

TinkerBoard for class awareness and management

The two teachers agreed that the awareness provided by the TinkerBoard was easy to understand both for them and the students, given the minimal five-minute introduction with the class. The teachers could be seen looking at the TinkerBoard often, usually when they finished discussing with a group. Both teachers confirmed that they looked at the TinkerBoard rarely at the beginning, but very often after becoming accustomed to its presence. In addition, they stated that they were not distracted by it. Figure 6.6 shows an example.

The teacher in the first study said he looked at the event bar more often than the layout history saved by students. His main use of the TinkerBoard was to see how much time each group spent building models, running simulations, and saving layouts and to balance the pace between groups. He said when looking at the TinkerBoard, he compared his mental impression of each group in the class with the real-time information displayed on the TinkerBoard.

Figure 6.5: The TinkerBoard facilitated debriefing and class-wide discussion. (top) The teacher dragged four layouts from four groups to the comparison zones for his debriefing session at the end of the activity. (bottom) A spontanous class-wide discussion was possible with the presence of TinkerBoard. The whole class had a common resource, helping them to refer to the layouts and the strategies.

Figure 6.6: The teacher used TinkerBoard to gain awareness about the class progress.

The teacher in the second study used the TinkerBoard in a simpler way: seeing how many layouts had been saved by each group. He said *"After looking at the TinkerBoard, I'll decide when to follow up with which group"*. Students also looked at the TinkerBoard extensively, supposedly to gain inspiration from the progress and saved layouts of other groups. Throughout the activity, many can be seen looking at the TinkerBoard, pointing to and discussing with other group members. Figure 6.7 illustrates these observations.

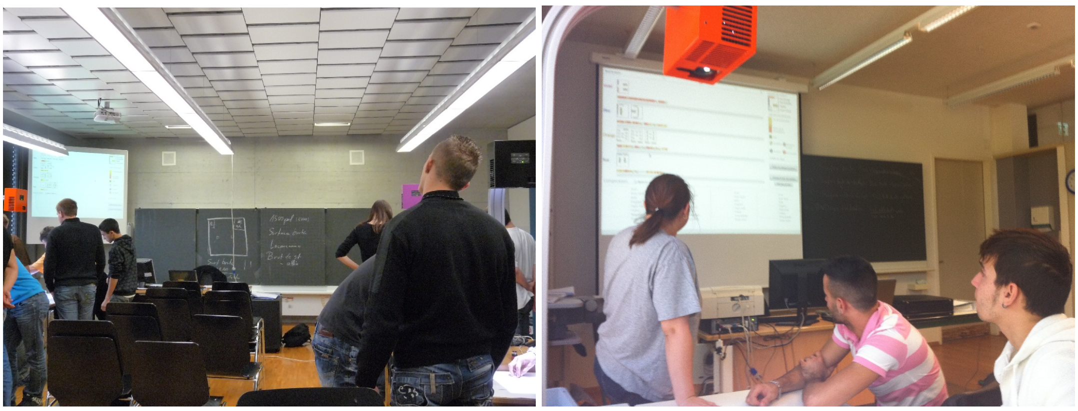


Figure 6.7: Students were seen looking at the TinkerBoard throughout the activity.

TinkerBoard for class TinkerQuiz

During the class quiz, TinkerBoard was the focus of everybody in the class since it showed the results and finishing order of each group. It helped build the competitive atmosphere for this class-wide activity since all of the students were excited to see how fast they responded in comparison to the other groups. The TinkerBoard also provided information about whether their submitted answer was right or wrong, as well as the correct solution. This information about quiz responses from respective groups helped the teachers debrief in an appropriate manner by focusing only on the relevant misunderstandings.

Usability issues of TinkerBoard

We noted during the first study's debriefing sessions that the teacher had difficulty differentiating between which group the layouts in the comparison zone came from. He kept trying to refer to specific groups' chosen layouts, but could not remember which group it corresponded to: *"As you can see here, the net stock area is less in the black group's - no, I mean - orange group's layout."*.

A minor usability problem was discovered through student feedback. They reported that the font size on the TinkerBoard was too small. Some groups were farther away from it than other groups and could not see clearly during the debriefing.

Both of these issues were addressed in the next study: the arrangement of text was modified, the font was made bigger, and a colored frame that matched the group's lamp color was placed around the chosen layouts in the comparison zone.

Questionnaires about TinkerBoard

Students in general agreed that the information on the TinkerBoard was quite easy to understand, and helped them be more aware of their own actions. They also stated that they looked at both the layout history and the event bar on the TinkerBoard during the activity. Table 6.7 summarizes the responses.

In the open-ended comment section, the ability to compare between groups was noted as the most positive aspect about the TinkerBoard. All of the comments are similar to this one: "*(TinkerBoard) allowed us to compare our layouts more easily with the other groups' layouts*". Class awareness was the next positive aspect, mentioned five times in the questionnaire. A student wrote *"We can see where we are in the activity compared to the other groups"*.

6.3.6 Reflection-in-action with LayoutBrowser

The LayoutBrowser helped bridge the traditional paper world with the tangible interface and support further exploration from the students. We observed students continually taking

Question	First trial	Second trial
I looked at the TinkerBoard during the activity	$m = 6.19(0.91)$	$m = 5.50(0.89)$
I looked at the layouts shown on TinkerBoard during the activity	n/a	$m = 5.38(0.96)$
I looked at the event bar shown on TinkerBoard during the activity	n/a	$m = 5.40(1.12)$
It is easy to understand the layouts shown on TinkerBoard	$m = 5.75(1.34)$	$m = 5.19(0.75)$
I am aware of my own actions during the activity	$m = 6.06(1.06)$	$m = 5.94(0.77)$

Table 6.7: The average rating (and standard deviation) using a 1-7 scale for TinkerBoard. The second and third question were not asked to the students in the first trial, hence the data is not available.

advantage of the 'save layout' feature to keep their tangible models in visible 2D graphics, under teachers' instructions and compare those layouts. Our findings about this feature are similar to those in our intermediate evaluations of the first iteration about the LayoutBrowser (chapter 5, section 5.4.3) (Figure 6.8).

Figure 6.8: Teachers and students took full advantage of the LayoutBrowser, discussing and comparing the saved layouts.

Each group in the first study saved on average 15 layouts in the WithTinkerBoard condition, and 12.5 layouts in the WithoutTinkerBoard condition. In the second study, these averages are 11.25 and 9 layouts, respectively (Table 6.8). Together, the number of layouts saved in both studies, and in both conditions seemed significantly higher than those completed with the previous TinkerLamp in the Warehouse study (mean=4.6 layouts), chapter 4, section 4.5.1. The number of layouts saved in the WithoutTinkerBoard were fewer because, in this condition, the time for building models was reduced to leave room for time doing class quizzes.

TinkerKey	Warehouse study	TinkerLamp 2.0, first trial		TinkerLamp 2.0, second trial	
		NoTinkerBoard	WithTinkerBoard	NoTinkerBoard	WithTinkerBoard
Average number of layouts saved	4.6	15	12.5	11.25	9

Table 6.8: Average number of layouts saved by the groups during the activity with the two trials of TinkerLamp 2.0, in comparison with that of the Warehouse study (with TinkerLamp 1.0).

Usability issues of LayoutBrowser

Flexibility and the unsuccessful blanking out of visualizations of LayoutBrowser. Two pilot studies had informed the design of the way the LayoutBrowser worked. Our choice was that the visualizations on the LayoutBrowser should be automatically blanked out (i.e. receive no visual projection) when a TinkerQuiz is in use. We expected that this would force students to answer the quiz without cheating by referencing other statistics.

In the first study, however, we discovered that this limitation actually prevented flexible interaction. One instance we noted occurred when the teacher attempted to explain a quiz answer to a group by showing them the statistics on their LayoutBrowser. Of course, even when placed under the TinkerLamp, no light was projected on the LayoutBrowser since a quiz was being used, thus prohibiting the teacher's efforts. For this reason, this limitation was removed in the second study.

Questionnaires about LayoutBrowser

Similar to other components, the LayoutBrowser was evaluated as fairly easy to use and easy to learn in the student questionnaire. Table 6.9 illustrates the result of the student's rating.

Question	First trial	Second trial
It is user friendly	$m = 5.90(1.13)$	$m = 5.48(1.09)$
Using it is effortless	$m = 5.90(1.65)$	$m = 5.65(0.95)$
I learned to use it quickly	$m = 6.39(0.80)$	$m = 6.45(0.72)$

Table 6.9: Average rating (and standard deviation) using a 1-7 scale for the LayoutBrowser in terms of ease of use and ease to learn.

In the open-ended comment section, students reported a calibration problem with the LayoutBrowser (due to the discrepancy in configuration parameters between the camera and the projector). An example was when students attempted to activate a button with the tokens, for example to save a layout, they had to shift the token up about five milimeters above the intended position. Although this was not an error and simply an imperfect hardware matching between the camera and the projector, it made the interaction less smooth than it should have been. This calibration problem was noted as the biggest complaint on the questionnaire regarding the paper interface, mentioned 17 times.

As for the positive comments, learning and novelty, each mentioned 9 times, were at the top of the list, followed by the ability to relate everything to concrete examples (as opposed to being only theoretical/implicit) and the ability to save and visualize the warehouse surface, totalling 7 comments each. This saving feature made the discussion and comparisons about different warehouse layouts more concrete without requiring implicit mental representations. The comments in the student questionnaire all centered around this benefit: *"It's good because we can compare several ways of designing a warehouse with shelves and annex surfaces"*, *"We can always return to our previous layouts. It's good. It's always interesting to build a warehouse model with the previous ones available next to it."*

6.3.7 Class Atmosphere and Satisfaction

The questionnaires for students included 7 questions about the group and class atmosphere and their satisfaction of the class in general (Appendix E). We present here the findings concerning these questions. Due to the usability issues in the first study which may distort the rating, we use only the 32 responses from the second study for this analysis. We compared the ratings between two conditions, WithTinkerBoard and NoTinkerBoard, to explore the difference in perception and preferences of students.

Interestingly enough, the students felt that the TinkerBoard influenced their perception of the class in three aspects: by encouraging more collaboration within their group, by making the class more fun, and by encouraging more comparison of their group's layouts with those of other groups. However, the TinkerBoard did not have a significant effect on the overall satisfaction level of students about the system or the class in general. Table 6.10 summarizes the results of the above comparisons.

6.3.8 Learning outcomes

As for learning outcomes, we computed and compared the post-test scores of the second trial (Yverdon) to those achieved in the Warehouse study (chapter4), since the two studies had the same setup, structure, student population and post-test (for a detailed description of the post-test, which is the same to that of the Warehouse study, please refer to Appendix C). While the two studies were not run at the same time, we hoped that the comparison could bring about some useful insights.

The results of students' post-tests were very encouraging. Table 6.11 summarizes the understanding score and problem-solving score of the second trial (in both WithTinkerBoard and NoTinkerBoard conditions), in comparison with those of the Warehouse study.

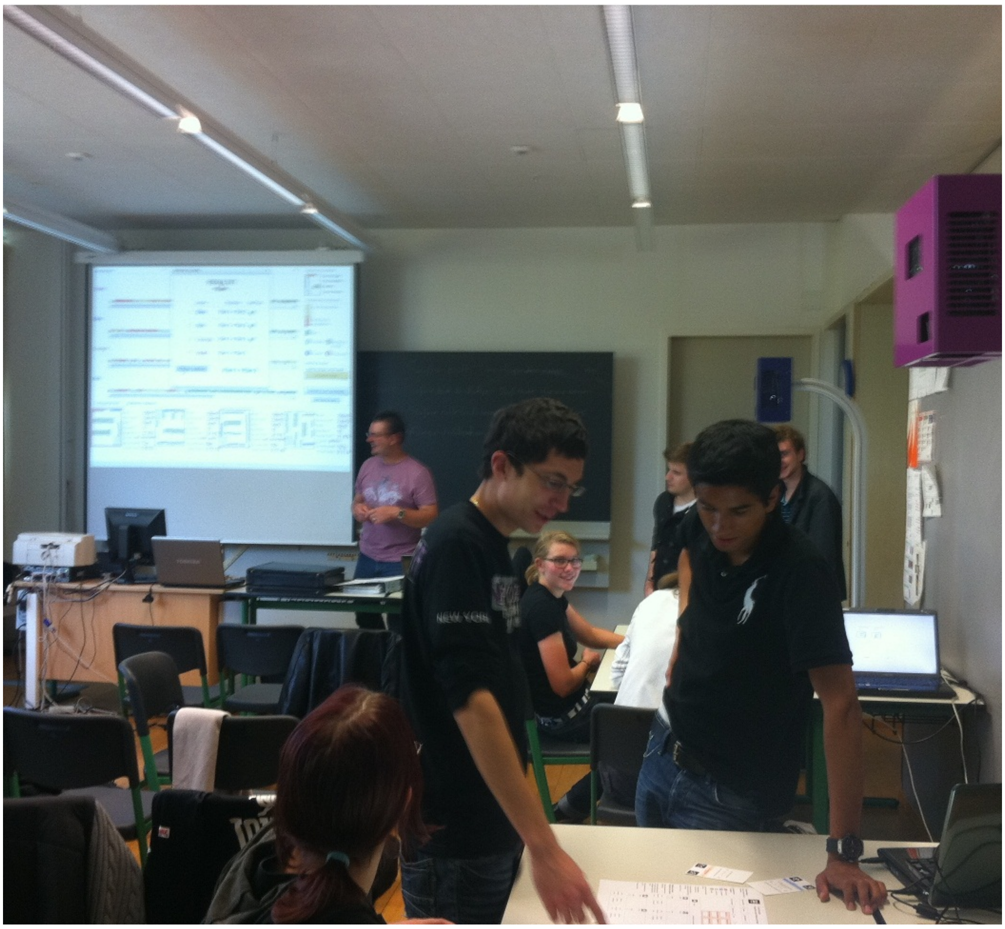


Figure 6.9: The playful atmosphere was visible in the class when groups participated in class quizzes. Everyone was excited and smiling.

Statistical tests showed that the TinkerLamp 2.0 system (namely the WithTinkerBoard condition) resulted in higher results in both understanding score and problem-solving score.

Understanding score. An ANOVA test on a mixed-effect model using group as random factor showed a significant difference between the four conditions ($F(3,21) = 3.98, p < .05$). A pair-wise Tukey test showed that the scores in the TinkerLamp 2.0 WithTinkerBoard condition were significantly higher than both the TinkerLamp 1.0 ($z = 3.05, p < .01$) and the Paper/pen ($z = 2.60, p < .05$) conditions. None of the other pair-wise comparisons is significant.

Problem-solving score. Similar tests resulted in a significant difference between the four conditions in terms of problem-solving ($F(3,21) = 4.42, p < .01$). The Tukey contrast resulted in several findings:

- The WithTinkerBoard condition is significantly higher than both the TinkerLamp 1.0 ($z = 2.72, p < .05$) and the Paper/pen ($z = 2.71, p < .05$) conditions.

Statement	WithTinkerBoard	NoTinkerBoard	Statistical test
There was a strong sense of collaboration within our group	$m = 5.73$	$m = 4.56$	Wilcoxon, $\boldsymbol{W = 60.5, p < .05}$
The class atmosphere was fun	$m = 6.27$	$m = 5.50$	Wilcoxon, $\boldsymbol{W = 72, p < .05}$
I was aware of the other groups' actions during the activity	$m = 5.06$	$m = 5.00$	Wilcoxon, $W = 125, p > .05$
I compared our plans with those of the other groups	$m = 4.33$	$m = 2.80$	Wilcoxon, $\boldsymbol{W = 65, p < .05}$
I wanted to do better than the other groups	$m = 4.38$	$m = 5.57$	Wilcoxon, $W = 153.5, p > .05$
I am satisfied of the system	$m = 6.25$	$m = 5.75$	Wilcoxon, $W = 101.5, p > .05$
I appreciated the class	$m = 6.00$	$m = 5.44$	Wilcoxon, $W = 107, p > .05$

Table 6.10: Summary of the difference in terms of perception about the class between two conditions: WithTinkerBoard and NoTinkerBoard. The test results in bold are those found with significant difference between two conditions.

Measures	Warehouse study's conditions		Evaluation of TinkerLamp 2.0 conditions	
	Paper/pen	TinkerLamp 1.0	TinkerLamp 2.0 NoTinkerBoard	TinkerLamp 2.0 WithTinkerBoard
Understanding score	7.84(2.85)	7.43(2.82)	9.38(2.03)	10.31(1.70)
Problem-solving score	5.16(1.70)	5.15(1.78)	6.44(1.65)	6.59(1.53)

Table 6.11: The average learning outcomes scores (and standard deviation) of the second trial of TinkerLamp 2.0 versus those of the Warehouse study. Mixed-effect modeling resulted in statistical difference in favor for the TinkerLamp 2.0.

- The NoTinkerBoard condition is marginally higher than both the TinkerLamp 1.0 ($z = -2.42, p = .07$) and the Paper/pen ($z = -2.41, p = .07$) conditions.
- No significant difference between the WithTinkerBoard and NoTinkerBoard condition was found.

Figure 6.10 illustrates these results.

6.4 Discussion

6.4.1 Benefits and potential improvements of TinkerLamp 2.0

Our evaluations of the TinkerLamp 2.0 system in the two field trials showed that it fulfilled its design goals. The findings showed that the system provided many opportunities for reflection and discussion, as well as empowering the teacher in classroom orchestration. The continual transition between group- and class-wide activities was supported by the new TinkerLamp system and brought a playful atmosphere into the classroom. Though this evidence is informal

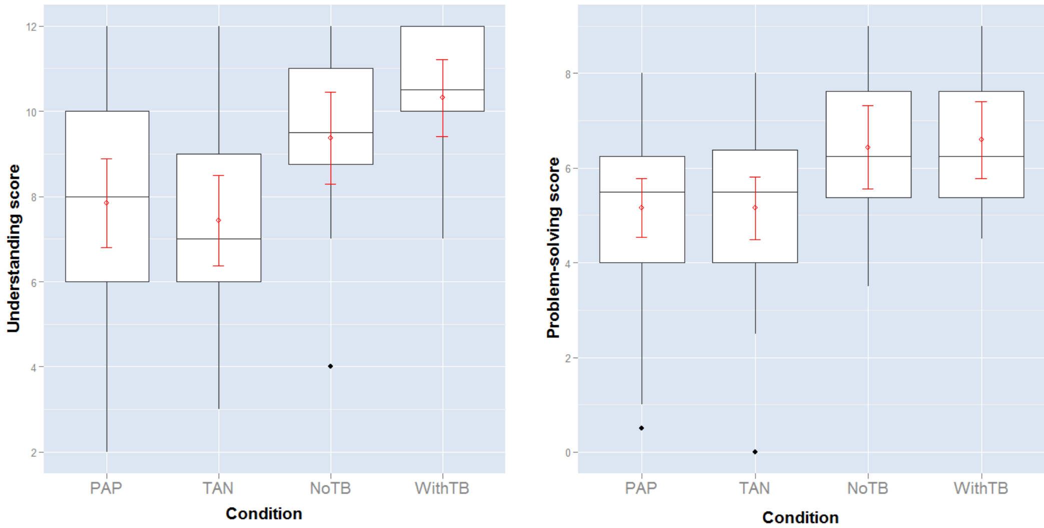


Figure 6.10: Learning outcomes of TinkerLamp 2.0 system, compared to paper/pen and TinkerLamp 1.0. (left) Understanding score. (right) Problem-solving score. Condition abbreviations: *'PAP'*: Paper/pen, *'TAN'*: TinkerLamp 1.0, *'NoTB'*: TinkerLamp 2.0 NoTinkerBoard, *'WithTB'*: TinkerLamp 2.0 With TinkerBoard. The black boxes and lines are boxplot of the data. The red lines represent the 95% confidence interval of the data.

and still needs to be confirmed, the TinkerLamp 2.0 seemed to improve student's learning outcomes compared to the previous system.

Our findings provided insights on the benefits and potential improvements of the different tools.

Support continuity by a class shared display

The *TinkerBoard* fulfilled its goal to bridge the different activities and facilitate the continuity of learning (e.g. seamlessly transitioning from the building phase to the debriefing phase or transitioning from group activity to class activity). This board is more than just a monitoring or awareness tool. It is a "classroom self-regulation" tool, supporting both teachers and students at the same time. Our observation, however, showed that it took some time for the users to become accustomed to the display. This implies the importance of showing only the most necessary information in the classroom.

More fun reflecting and practicing using interactive cards

The *TinkerQuiz* supported both group and class-level reflection but in a fun way. It is interactive, has a pressure element with the timer as a group quiz, and triggers playful competition between groups as a class quiz. It also has a shape similar to a card game. The students were motivated to practice and reflect more, as opposed to the second iteration design with paper exercise which forced reflection but was not engaging (chapter 5, section 5.5). A group completed as many as 50 quizzes during the activity.

There were, however, some students that were not engaged. This problem could be addressed in future work by distributing more quizzes per group, possibly even one per person to ensure participation from all students. In that case, the TinkerQuiz can act as a bridge between individual, group, and class-level activities.

Empowering teachers with simple paper interface

The *TinkerKey* really brought the teacher to the front of the class. Compared to previous studies, the teacher showed considerable pride in having the most crucial and powerful role. The teachers had special privileges in interacting with the system, rather than just walking around to each table and discussing with the students. Inspired by our observations, the future implementation can consider designing some TinkerKey to help build the drama in the class, such as creating conflict between results to trigger debate and discussion.

The choice for TinkerKey over pen-based interaction (in iteration 1, chapter 5, section 5.4.2) emphasized the importance of visibility, simplicity, familiarity and transparency of the tool over its intelligence and power. Future systems should also consider designing a limited number of tools with a limited amount of functions for the teachers. Five TinkerKeys were already enough as our teachers said. Any more than that and they would be confused.

Using paper interface to support more exploration and Multiple External Representations

The *LayoutBrowser* supported further exploration from the students, helping them overcome the tentativeness of breaking down tangible models. It enabled the students to build more than twice as many layouts as compared to the Warehouse study (chapter 4).

The saved representations of warehouse layouts provided the teachers and students an external and shared resource for reflection-in-action and discussion. The LayoutBrowser has a close relation with all other components in the TinkerLamp 2.0 system (e.g. TinkerQuiz and TinkerBoard) in that it saves the tangible models into 2D graphics, and then transfers these graphics to the other component models. Together, these different representations provided users with multiple opportunities and perspectives when learning logistics concepts, which is what Multiple External Representations approach argued for.

Class-wide activities for a more playful and collaborative classroom

While there was no significant difference between the satisfaction level and the perception of the class in general in the two conditions, the class with the TinkerBoard and Class TinkerQuiz was rated by the students as being *more fun, encouraging more collaboration, and triggering* *more between-group reflection*. We consider it a confirmation of the importance of supporting the whole learning workflow with an ecology of resources, rather than a stand-alone application.

6.4.2 Limitations of the study

Similar to our previous studies, this evaluation took a holistic approach, examining the effects of TinkerLamp 2.0 in its entire workflow, a real classroom with a real school task. Due to the complexities of the system, the setting, and other practical reasons, it was not possible to have a more rigorous and controlled comparison with a baseline condition. In order to gain a more thorough analysis of how the system really affects learning and teaching, a longitudinal study would be necessary. This is also one of the objectives of our future work.

6.4.3 Design implications

Flexibility for different teaching strategies and situations

We highlight the importance of flexibility when designing interactions to support learning and orchestration in the classroom. Let us re-consider our unsuccessful attempt to automatically blank out all visualizations on the LayoutBrowser when a TinkerQuiz is in use. We had expected that this automatic lock would force students to focus only on the quiz without cheating by referencing other statistics. However, quite the opposite occurred: this rigid rule prevented the teacher's efforts in explaining the quiz using those statistics. When we unlocked this restraint, the flexibility level was consistent with the user's needs. The teacher could show the statistics when he wanted. At the same time, he could still make sure that his students did not cheat by asking them to flip the LayoutBrowser over, moving it out of the TinkerLamp projection, or even collecting the LayoutBrowsers if necessary.

In another example, one of the points that was repeatedly mentioned by the teachers was the following trade-off. On the one hand, they would like to manage different groups differently. On the other hand, they also would like to make sure every group is at the same level, understanding the same concept correctly. The TinkerQuiz achieved this flexibility by allowing the teachers to distribute advanced Group TinkerQuizzes to advanced groups *at the group level*. On the other hand, they could also organize a class competition using the same TinkerQuiz cards *at the class level*, as a knowledge checkpoint for every group.

Continuity between different learning phase to support reflection

As we showed in chapter 3 and 4, tangible tabletops tend to hinder high-level reflection due to their manipulation temptation and concrete physicality. We showed in this chapter that other representations can and should be used to complement the tangible model to overcome this problem.

Learning would be greatly improved if the technologies supported the continuity of learning workflow in the classroom by giving the same resource different external representations and circulate them in the classroom. Tangible models can be combined with their 2D graphics and/or printed counterparts to enforce learning. Those representations can be exploited at different levels and different points in time.

As an example, the saved layouts on the LayoutBrowser in the TinkerLamp 2.0 were a learning resource that had multiple representations, and were used as an integrated and essential part of the TinkerLamp 2.0 system: They were extensively discussed at each group's table; They were mirrored on the TinkerBoard for class-wide discussion; they were used for the TinkerQuiz; the showing of their statistics were turned on/off by the TinkerKey; and they were printed out on a Fieldwork for apprentices to take back to workplace. In other words, the saved layouts on the LayoutBrowser acted as a resource to support continuity of the workflow. The result was that the students' learning outcomes were higher than in the previous stand-alone TinkerLamp setup where information had been isolated at the student's tables.

Empowering teachers and "teachable moments"

The TinkerKeys provided us with a promising way to empower teachers. What we strived for was special privileges for the teachers when interacting with the system. This helped our teachers interact with the system in a way no students could, enabling them to adapt this ability to their ever-changing orchestration plan. As we observed, the teachers in our studies showed considerable pride when possessing the five "magic" cards. They felt empowered. They were still in control of the class despite the technologies on the students' tables.

Classroom orchestration and teaching are often contingent on what happens in real time in the classroom. Teachers need technologies that help them adapt their actions to the unfolding events. A main implication from our trials is that we should consider enabling the teachers to take advantage of "teachable moments."

We define "teachable moments" as *"moments where the teachers see an event that is potentially interesting for learning, and decides to focus the group or class on discussing it"*. These events are unpredictable by nature but can be taken into account by a flexible design.

Some examples of how we supported the teachers to exploit such "teachable moments" include the following:

- TinkerBoard enabled the teachers to do spontaneous debriefing and class discussion anytime they wanted.
- TinkerKeys enabled the teachers to hide statistics of the layouts, block simulations, or pause the class when they determined that the students needed to reflect at that moment.

- The running of the Class TinkerQuiz allowed the teachers to build drama in the activity, encouraging students to practice more often with their Group TinkerQuiz.

6.5 Summary

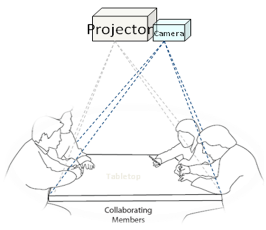
In this chapter, we discussed the evaluation and implications of TinkerLamp 2.0 in a classroom setting. TinkerLamp 2.0 represents our attempt at improving the previous system, making it better in terms of reflection and orchestration.

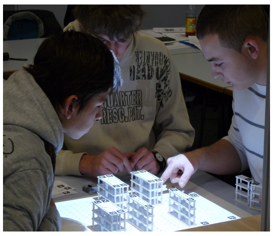
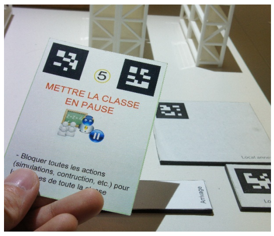
As we showed, a good way to support these two themes (reflection and orchestration) is to provide the classroom with an ecology of tools. Each of the TinkerLamp 2.0's features turned out to be effective. Together, the system facilitated the teachers' work, making it easier for them to manage the class and the learning resources in real-time. The tools also provided the students with reflection opportunities throughout the activity by making use of different representations of the same resource to support the continuity of learning workflow.

The implications of this chapter are:

- The evaluations of TinkerLamp 2.0 confirmed the appropriateness of designing tangible tabletops as an ecology of tools, rather than stand-alone application. This design resulted in more opportunities for reflection, higher learning outcomes, better support for class-wide activities and classroom orchestration and more playful atmosphere, compared to any previous iteration.
- Implications for the design of tabletop systems in the classroom:
  - supporting the flexibility of designing tools in the classroom
  - facilitating the continuity of learning workflow with multiple representations
  - empowering teachers with appropriate tools, allowing them to take advantage of "teachable moments".

7 Conclusions



7.1 Summary of contributions

We introduced the design and implementation of three tangible tabletop systems: the DockLamp, the TinkerLamp, and the TinkerLamp 2.0. These three systems cover a range of different interactions with the tabletop:

1. Using mostly paper pieces with finger-based interaction support (the DockLamp)
2. Using mostly physical objects with paper-based interaction support (the TinkerLamp)
3. Using many complementary interactions including tangible, paper-based, and awareness display (the TinkerLamp 2.0)

Our experience with these systems informs us that in order to be effective in the classroom and have a positive effect on learning, tangible tabletops need to *explicitly* address two important themes: *reflection* and *orchestration*. Theoretical perspectives, user feedback, and the insights from our analyses of the DockLamp and the TinkerLamp 1.0 led to the design of our TinkerLamp 2.0 system. The TinkerLamp 2.0 system was tested and proved to provide more facilitation of teacher's orchestration, and more reflection opportunities for students (many of which came from supporting orchestration), which in turn resulted in improved learning outcomes.

In the following sections, we gather the lessons we learned throughout our work, both inside and outside of the laboratory to discuss our main findings.

7.1.1 Benefits and drawbacks of tangible tabletop

This thesis provided evidence that tangible tabletops have certain benefits and drawbacks when it comes to supporting learning. Interestingly, the findings converged despite the broad range of different task types, settings, and samples. Among others, we highlight the following points.

- Tangible tabletops provide potential grounds for fruitful interactions, i.e. *more concrete manipulations, more exploration, and richer collaboration strategies.* This finding was confirmed, for example, by the collaboration analysis and usability questionnaire in the ConceptMap study (section 3.7.6) and the better performance measures in the Warehouse study (section 4.5.1).

- Tangible tabletops can trap users into "manipulation temptation", which may *prevent them from maintaining a good balance between physical manipulations and high-level reflection.* In other words, there may be a lack of reflection when learning with tangible models. Both the ConceptMap and Warehouse studies showed a non-significant difference in terms of learning outcomes between tangible tabletops and traditional devices such as personal computers or paper/pencil. Qualitative analyses of these studies (section 3.7.3 and 4.5.4) revealed that students using tangible tabletops were often trapped into doing physical manipulations, and neglected high-level discussion.

- Tangible models of tabletop systems can be better exploited when they are part of an *"ecology of resources"* where they and other resources are all connected and used for discussion and learning. Not only being the primary objects of interest in the activities, the concept map model of the DockLamp, and the warehouse model of the TinkerLamp 1.0 could serve as external resources used for teaching and reflection. These external resources should be complemented with other representations (e.g. the 2D layouts on the LayoutBrowser and the TinkerBoard of TinkerLamp 2.0) to support for the discussion of high-level concepts.

7.1.2 Orchestration and reflection

A key contribution of this work is the deployment of our systems in the classroom in order to understand the design space as well as the needs of the teachers and students within this authentic context. Existing tangible tabletops developed for learning have mainly focused on support for students. Our message is that developing tools to empower the teachers is also very important. If the teachers only walk around the classroom to discuss with the students at each table, without the ability to alter the technology and activities on the spot and therefore exploit learning situations to encourage reflection, we risk wasting one of the most crucial factors to the success of the students' learning in classrooms.

There are two main implications from our work concerning the importance of orchestration.

First, and importantly, the Warehouse study, the intermediate evaluations and field trials of the TinkerLamp 2.0 highlighted the crucial potential of *supporting orchestration as a way to support reflection*, and to overcome the lack of reflection from students. It can be the key to solving the manipulation temptation problem. Helping teachers effectively exploit the learning resources in the classroom in real-time with appropriate tools enables them to provide more reflection opportunities, and thus, more learning around the tangible tabletops.

Second, orchestration is important in a technology-enhanced classroom since classroom activities now take place both at the pedagogical and at the computational level. These scenarios articulate activities with and without digital technologies. The activities also integrate multiple social planes such as individual reading, team argumentation and plenary sessions, and may involve a variety of interaction modalities such as digital tangible artifacts, tabletops, interactive paper, etc. Different groups also have different results and understanding about the concepts to learn. The teacher needs to be facilitated with his orchestration work to deal with the unfolding of these events.

In order to effectively support both reflection and orchestration, tangible tabletops should support *the multiple external representations of tangible inputs*. We use our experience with our three systems to argue that tangible models on the tabletops should not be the sole focus of the learning activity. Focusing only on tangible tabletops in the learning activity may cause reflection and orchestration issues in classroom settings. Rather, tangible models should simply act as a supporting element in the whole ecology, or an external representation within the multiple representations space (Ainsworth, 2006). Our TinkerLamp 2.0's provide multiple representations of the same information, e.g. warehouse models, on different components, such as the LayoutBrowser, TinkerQuiz, TinkerKey, TinkerBoard, and already existing factors in the classroom, such as the blackboard. Each of these representations provides a complementary view of the information, contributing to the actual learning outcomes, not just the physicality of tangible inputs.

7.1.3 Supporting teachers and classroom orchestration

We believe that *equiping the classroom with an ecology of appropriate tools* within which the learning resources can be easily transfered and exploited is a promising way to fully support orchestration. Orchestration can be seen as a movement towards a new blended version of teacher- and student-centric designs that promotes the seamless transition between activities at different levels (individual, group, class). For this reason, a stand-alone application may not suffice.

Throughout its design process, TinkerLamp 2.0 evolved from being a stand-alone application to an ecology of tools. Its components, such as the LayoutBrowser, TinkerQuiz, TinkerKey, TinkerBoard, and already existing factors in the classroom, such as the blackboard, the teacher, the students, and other social activities are all connected. We implemented orchestration functionalities using a paper-based interface (TinkerKey and TinkerQuiz) and an awareness display (TinkerBoard). These two technologies seemed very promising since they were visible at all times during the activity, and hence could help the teachers do spontaneous debriefing, perform class-wide discussions, and intervene with special privileges when they needed to.

However, we argue, by using our experience with the TinkerLamp 2.0 that, when designing this ecology of tools to empower teachers, one should consider the following guidelines.

- *Flexibility.* A classroom is influenced by many factors and steps involved in the workflow. As a result, unpredictable events may arise in a classroom, and some of them may make the technology fail to achieve its purpose. The classroom requires technologies that have sufficient flexibility to allow teachers to adapt their use on the fly. The locking feature of TinkerQuiz (section 6.3.2) was an example of how the learning activity was affected by a rigid implementation.
- *Continuity.* Students have more opportunities to learn and enforce knowledge from the complementarity of individual, group, and class-wide activities, as well as the multiple ways that a resource can be represented and used. The replications of warehouse layouts in multiple representations (the tangible model, the LayoutBrowser, TinkerQuiz, TinkerBoard, etc.) with TinkerLamp 2.0 (section 6.4.3) validates this point.
- *"Teachable moments"* are "moments where the teachers see an event that is potentially interesting for learning, and decides to focus the group or class on discussing it". While these moments are unpredictable by nature, a flexible design can help the teachers take advantage of these moments to leverage more discussion or encourage more useful activities from the students. Our observations of the TinkerBoard and TinkerQuiz (section 6.3.5 and 6.3.3) provide some examples.

7.2 Limitations

In the thesis, we tried to maintain the ecological validity as much as possible. In particular, we chose a holistic approach for the studies in this thesis. The studies compared the tangible tabletop systems with the traditional devices (PC or paper/pencil) as complete units. They were designed to evaluate the technologies when they function as a whole.

However, the limitation of this approach is that it is difficult to associate the effects to a specific factor. In addition, for the Warehouse study and the evaluations of TinkerLamp 2.0, various factors in a classroom (which could not and should not be controlled) could contribute and affect the learning processes. For example, we only had a small sample of teachers but decided to include them in the studies to preserve the realistic settings. These factors make the post-test scores fragile; they could have been easily distorted. We therefore believe that the qualitative details offer more insightful findings to inform the design of similar systems.

Due to the technical nature of our schools and the logistics domains, there was an unbalance between the number of male and female participants in our studies. We did not observe any noticeable behavioral difference in terms of the main phenomena described in the thesis, such as tangible manipulations, manipulation temptation or test scores. However, there are certain situations where this unbalance may have impacted the results which we did not put enough focus on. For example, this becomes particularly relevant around the competition atmosphere in the trials of TinkerLamps. Further analyses are needed to reveal whether such competition may be a stronger preference among males.

7.3 Implications for further research

The TinkerLamp 2.0 system presents a promising solution for the logistics training program. However, the aim of this thesis is not to suggest that the TinkerLamp 2.0 is the final answer to our specific context. It is rather to use the experiences and the insights we gained during the design process to figure out possible directions for future research.

7.3.1 Manipulation temptation in other contexts

Reflection are important for learning with tangible tabletops. Tangible models and physical manipulations are not enough to lead to more positive learning outcomes. They need to be complemented with an adequate amount of high-level thinking and discussion. These findings, however do not only apply to our context, but also to other leaning contexts involving user interfaces that are novel, concrete, easy to manipulate or individualized, e.g. tangible interface, tabletop interface, mobile, touch-based interface, etc.

Consider for example a classroom that makes use of the increasingly popular mobile learning approach (e.g. with each student having an iPad). On the one hand, this approach can be a great help. There is a psychological factor: owning mobile devices increases student motivation and deepens the commitment to using and learning with them. Further, the learning material is mostly colorful and inviting which may prompt students to go back and forth and practice more. Mobile devices also are highly personalized devices, which helps each student/group learn at their own pace in their class. The students who pick up things fast need not waste time going repeatedly through basic lessons. On the other hand, access to an abundance of mobile learning and information may tempt learners to abandon discussion or time for deep reflection. There is a risk that the interface may become too stimulating and trap learners into manipulating the interface too much, involved in 'trial and error' actions without thinking and learning, or not listening to the teacher.

Learning is both an active and reflective process. Although we learn by doing, constructing, building, writing, etc., learners also learn by thinking and discussing with their peers about activities and experiences. Both action and reflection are essential ingredients in the construction of learning. The optimal learning environment needs to consider this factor, providing sufficient time for both action and reflection. Figuring out which factors encourage or decourage reflection and action for different contexts and technologies is an interesting research direction.

7.3.2 Designing for the ecosystem

Our summary of contributions suggest that future educational tangible tabletops should be designed as a part of a larger ecosystem and complemented with other components to support the whole learning flow. Our findings give a technological and empirical example for two theoretical frameworks in tangible interface research (Hornecker and Buur, 2006; Fernaeus and Tholander, 2006), both of which promote the consideration of Tangible User Interfaces in a broader context, rather than just the tangible model itself.

We would like to go a step further than the tangible tabletop context and promote a focus shift of HCI and CSCL research, *from system functionality to the physical and social context of interactions with and around the interface*. There has been a converging view across multiple disciplines (e.g. theories such as distributed cognition (Hutchins, 1995; Rogers and Ellis, 1994), situated cognition (Suchman, 1987), embodied interaction (Dourish, 2001), situated learning (Brown et al., 1989), product user experience research (Forlizzi and Battarbee, 2004), and ecology of learning resources (Luckin, 2008)) that human behaviour, including learning, is a dynamic interaction between human with human and between human with the environment and technologies, within a real and complex context. However, most research in HCI and CSCL have only involved a stand-alone application. These findings may become irrelevant when the tool is put in real use along with other tools and when the context involves more actors. We need more explorations in the broader context around our tool, which will make research and development be more likely to be appropriated in authentic settings.

Further research can investigate what and how technologies can facilitate the students and teachers to move between different contexts (e.g. school and workplace), learning phases (e.g. building and debriefing) and levels (e.g. group and class level), what the best technical and pedagogical arrangement are to facilitate class-wide orchestration.

7.3.3 Classroom-experience evaluation

The design for the ecosystem approach brings about the challenge of how to evaluate the system. The classroom is a complex environment with many constraints between the teachers, the students, the curricula, and the relationships between all of these. It can only become more complex with a variety of tools developed for the learning workflow. Understanding such an ecosystem is not a straightforward task since it can be described or evaluated at different levels (miliseconds, seconds, minutes, sessions, etc.) and dimensions.

Dillenbourg et al. (2011) propose a framework to evaluate educational technologies in which the role of educational technologies is assessed in “three circles of usability”. The first circle concerns the learner’s interaction with the technology. The second circle concerns the group process and how the technology influences the collaboration among learners. The third circle, which has been missing in the literature, focuses on the classroom as a whole. Orchestration, as well as the classroom level management and activities, can be considered a usability problem in this circle. We consider our work an early exploratory work in this direction. There is still very much to be explored.

We need a new way of thinking about the evaluation in classrooms. Given the complexity of the classroom ecosystem, it is reasonable to expect that multiple sources can provide a more reliable and comprehensive picture of the effectiveness of the interface on learning than just one source. A few directions for future research include the exploration of frameworks for evaluating the experience in classrooms and the definition of metrics to evaluate the “smoothness” of orchestration and technology-enhanced classrooms.

7.4 Closing Remarks

This thesis presents the outcomes of four years of research, during which three tangible tabletop systems were designed, implemented, and evaluated in both the lab and classroom settings. It not only shows the benefits of each system, but also their limitations. It concludes with a succesful integration of our TinkerLamp 2.0 into teaching and learning practices. The system provides adequate support for students’ reflection and teachers’ orchestration. It brings about useful insights as to how to improve learning around similar interfaces.

However, throughout the thesis, we adopted the view that the extent to which tangible tabletops, and technologies in general, can improve learning is largely dependent on educational scenarios, involving different actors (students’ skills, teachers, classroom motivation and energy, etc.), rather than an inherent characteristic of the technology. How to improve learning and teaching is an interesting but complex question. The answer to it requires more research on the diverse set of parameters that form the physical, social, and cultural context within which technologies are used. After all, it is *the students, the teachers, their interactions with each other and with the technologies*, that are important, not just the technologies.

A The Computer Vision algorithms of the DockLamp

A.1 Fingertip detection

We detect fingertips' positions by applying a three-step process. The first step is hand extraction which distinguishes hand regions from the rest of video frame. Then we use template matching technique to detect fingertips on the hand regions. A background model is to be updated for the next loop.

Hand extraction

Moving hands are extracted using background subtraction technique. It means that we make a subtraction between the current video frame recorded by camera and the estimated background (an image including only static objects on the table) to gain a difference image.

The process is done in the rgb (normalized RGB) color space ($r = R/S, g = G/S, b = G/S, S = R + G + B$, with R, G and B being the values in the red, green and blue channel of a RGB video frame) as it can eliminate lighting effects on color chromacity. The value of a pixel (x, y) in the difference image is the maximum difference value in all color channels between pixel (x, y) in the background and pixel (x, y) in the current frame.

The Otsu's algorithm Otsu (1979) is then performed on the difference image to get a thresholded binary mask. This algorithm automatically decides a threshold that separates the parts of the difference image belonging to background from those belonging to moving objects. Any moving object that is smaller than a predefined threshold, which represents the size of a normal hand, is eliminated to discard noises and small coincidental moving entities.

We use a validation step to ensure only moving blobs that have enough skin-colored pixels inside will be marked as a hand. We based this step on the technique proposed in J. Kovac (2003). A pixel is considered as a skin-colored pixel if it satisfies a heuristic rule[1] defined in

[1] $((R > 95) \wedge (G > 40) \wedge (B < 20) \wedge (|R - G| > 15) \wedge (R = max(R, G, B)) \wedge (R - min(R, G, B) > 15)) \vee ((R > 220) \wedge (G >$

RGB color space with $(R,G,B) \in [0,255]^3$. After this step, we obtain a so-called "hand mask" whose pixels have value of 1 (or white) if they are inside the hand regions and 0 (or black) if outside (Fig. A.1).

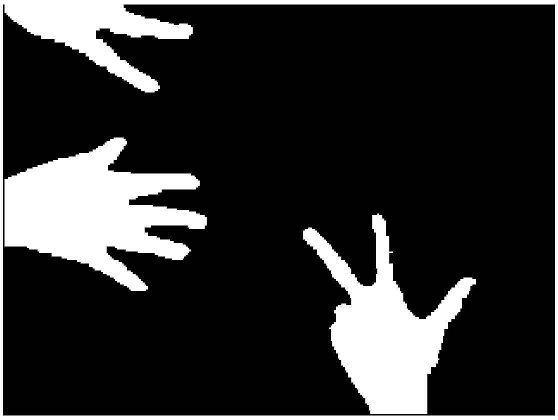


Figure A.1: A hand mask resulted from background subtraction, auto-thresholding and skin validation. The white part shows detected hand regions.

Fingertip detection

A fingerip can be seen as a connected component of several points that are near one end of a cylinder (the finger). An observation shows that if a circle having a certain radius whose center is one of those points is to be drawn on the image, it would be divided into two parts: one part is totally inside of the fingertip (red segment in Fig. A.2a), the other is totally outside(blue segment). Based on this fact, we use a geometric template that can detect multiple fingertips (Fig. A.2b). A similar idea is used in Letessier and Berard (2004) but in their work, the cylindrical property of the finger is not ensured, so their model might mistakenly detect a point at the end of a triangle as a fingertip.

A pixel p is a fingertip point if a set of following conditions is satisfied ($r1, r2$ are manually chosen thresholds):

- Every pixel within a distance $r1$ from p have a value of 1 in the hand mask since it lies in the finger region.
- When checking every pixel on the circle border whose center is p, radius is $r2$, we see 2 arc segments ($\overset{\frown}{ADB}$ and $\overset{\frown}{ACB}$), every pixel on $\overset{\frown}{ADB}$ has value of 0, every pixel on $\overset{\frown}{ACB}$ has value of 1. (Note that A, B, C are found at runtime. D is only used for explanation)
- Let C be the middlepoint of arc $\overset{\frown}{ACB}$. Count the number of 1-valued pixels on the circle whose center C, radius $r2$. This number needs to be in a specific range.

$210) \wedge (B > 170) \wedge (|R - G| \leq 15) \wedge (B = min(R,G,B)))$

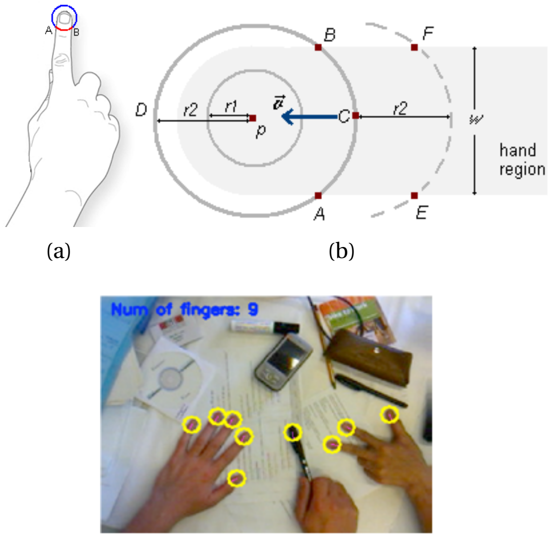


Figure A.2: The template used for fingertip detection and its result. a) Observation: a circle drawn on any fingertip is divided into two parts b) Our geometrical template is checked against every pixel p in the image c) Result of fingertip detection. Pens that are hold in hand can also be detected.

- The lengths of line segment AB and EF are as long as a fixed threshold w which represents the finger width. This rule ensures the cylindrical property of the finger.

The finger orientation can be easily achieved from the model by drawing a vector $\vec{v}$ from C towards p (Fig. A.2b). Figure A.2c shows the result of this step.

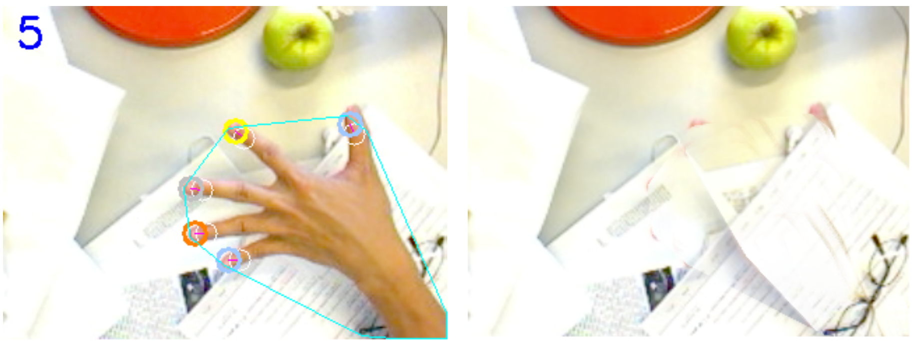
Background updating

A common and effective background estimation approach is the running average technique Letessier and Berard (2004); Klemmer et al. (2001); Wu et al. (2008). One problem with the running average technique is that it often includes user's hand into background and in the meantime cannot reflect spontaneous events (e.g. physical objects such as mobile phones and pens suddenly put on the table) that often occur in real-life situations. Even "worse", the DockLamp, unlike traditional designs, enables users to rotate the whole lamp, causing sudden changes in the video scene.

To overcome this problem, we suggest a solution using statistical information of the pixels in conjunction with information at object level, namely fingertips and moving hands. Let H be the set of convex hulls of hands with at least one fingertip, the value of a pixel p in background model at time $t+1$, denoted as $B_{t+1}(p)$ is computed as follows (α is a coefficient, $I_t(p)$ is the value of pixel p in current frame at time t).

$$B_{t+1}(p) = \begin{cases} B_t(p) & \text{if } p \in \{H\} \\ (1-\alpha)\cdot B_t(p) + \alpha \cdot I_t(p) & \text{otherwise} \end{cases}$$

The equation above illustrates two properties of the value of pixel p in background model at time $t+1$. First, its value will not be changed if it is inside a hand's convex hull that consists of at least one fingertip. In other words, all hands having at least one fingertip would not be updated unexpectedly into the background model. Background regions corresponding to hands and fingers are still preserved as in the previous frame. Second, if the pixel is not inside any of the hands detected, its value is normally computed according to the running average technique, i.e. as a weighted sum of its previous value and the value of the pixel at the same position in the current video frame. We use a high value for α in the equation ($\alpha = 0.08$ in our experiments) to make the system almost immediately update the changes taking place on the table. Fig. A.3 shows an example for our knowledge-based approach.

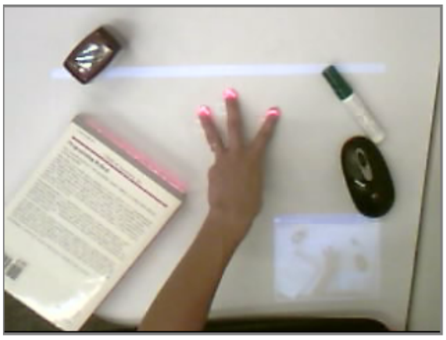


(a) (b)

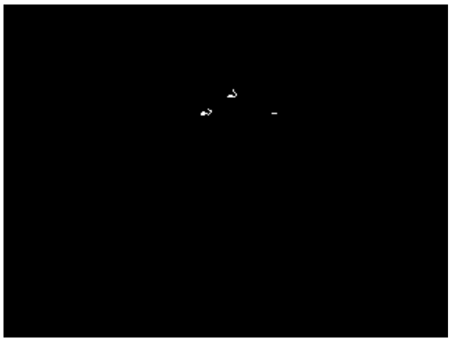
Figure A.3: We use convex hulls of detected hands and fingertips to support background estimation. a) Video frame and detected fingertips b) Estimated background

A.2 Touch detection

As previously mentioned, "clicking" behaviour is generally implemented by dwelling, i.e. keeping the finger unmoved for a certain amount of time, or by multiple cameras. Integrating a small laser source in the DockLamp's base enables us to detect touch using only a color camera. Our laser source spreads a very thin sheet of harmless diffused laser just above the table. The finger touching the surface will result in a red-colored dot in the video frame. In our configuration, it is interesting to see that a touch could be reliably identified at those pixels that have $(230 < R < 255)$ and $(0 < G < 160)$(Fig. A.4). We group those red pixels into a connected cluster. The average coordinate of a cluster represents a touch. In practice, we also check touch validity by ensuring that it is close to one of the fingertips detected at the previous step.



(a)



(b)

Figure A.4: Touch detection: a) The red dots appear on fingers when they touch the table b) Detected touches.

A.3 Touch on Paper detection

Based on the two components above, we envision a natural and intuitive method for interacting on augmented tabletops with users using their fingers to point or touch the paper. To this end, we use the ARTag library Fiala (2005) to track real papers in real-time. Each paper within the workspace contains a visual marker at a corner that helps the system to detect its position. A paper can be considered as a control device with some control regions marked on it. Each control region has a particular action associated with it and can be activated by touching it with a finger.

For this purpose, we specify control regions on the paper in real world measurement system (cm or mm) and match this control region with fingertip/touch's positions to know if the control region has been activated. More specifically, a control region can be defined as a region P in real world system with respect to the ARTag marker that is printed on the paper. A mapping of real world measurement system to camera's measurement system (pixels) is obtained by calibrating the camera initially. Using this mapping we can obtain the region P in pixel distance, and still with respect to the marker. Once the position of marker in camera's system is known every frame, we can obtain the coordinates of the region P in camera's system. The system will then use these coordinates along with fingertip and touch positions to decide whether to activate the region P's action. That is, any fingertip or touch that appears in the region P will send a specific command to the computer. The Paper Keyboard presented above is an example of this type of interaction.

B Materials for the ConceptMap study

B.1 Document

Potentiel de repos

Tout neurone présente de part et d'autre de sa membrane une tension électrique qu'on appelle le "potentiel de membrane". Le neurone au repos (qui ne transmet pas d'influx nerveux) a généralement un potentiel de membrane d'environ -65 mV. Le potentiel de membrane d'un neurone non stimulé s'appelle le potentiel de repos. Ce potentiel négatif s'explique par le fait que l'intérieur du neurone est chargé négativement alors que l'extérieur est chargé positivement. On dit ainsi que le neurone est polarisé.

Le potentiel de repos n'existe qu'à travers la membrane ; autrement dit les liquides qui se trouvent à l'intérieur et à l'extérieur du neurone sont électriquement neutres. Le potentiel de repos est engendré par des différences dans la composition ionique des milieux intérieur et extérieur. Ainsi, l'intérieur du neurone contient une plus faible concentration de sodium (Na+) et une plus forte concentration de potassium (K+) que l'extérieur. Dans le liquide extracellulaire, les charges positives des ions sodium sont principalement équilibrées par les ions chlorure (Cl-). Dans le liquide intracellulaire, les protéines (A-) chargées négativement facilitent l'équilibration des charges positives des ions potassium (K+).

Les différences ioniques découlent d'une part de la différence de perméabilité ionique de la membrane, et d'autre part, du fonctionnement de la pompe sodium-potassium. A l'état de repos, la membrane est environ 75 fois plus perméable aux ions K+ qu'aux ions Na+. Ces perméabilités de repos sont reliées aux propriétés des canaux ioniques à fonction passive présents dans la membrane.

Les gradients de concentration des ions K+ et Na+ expliquent leur diffusion du milieu où ils sont les plus concentrés vers le milieu où ils sont les moins concentrés, c'est-à-dire vers le milieu extérieur pour les ions K+ et vers le milieu intérieur pour les ions Na+. Par ailleurs, les ions K+ diffusent plus rapidement que les ions sodium. Il s'ensuit que les ions positifs qui diffusent vers l'extérieur sont un peu plus nombreux que ceux qui diffusent vers l'intérieur, ce qui laisse un léger surplus de charges négatives à l'intérieur du neurone; ce phénomène engendre un déséquilibre des charges électriques (gradient électrique) à l'origine du potentiel de repos.

Comme il y a toujours une certaine quantité de K+ qui sort de la cellule et une certaine quantité de Na+ qui y entre, on pourrait penser que la concentration des ions Na+ et K+ de part et d'autre de la membrane va s'égaliser, ce qui entraînerait la disparition de leur gradient de concentration respectif. Or, tel n'est pas le cas puisque la pompe sodium-potassium échange les ions Na+ du milieu intérieur avec les ions K+ du milieu extérieur du neurone. En d'autres termes, les ions K+ sont pompés à l'intérieur du neurone en même temps que les ions Na+ sont rejetés à l'extérieur.

Genèse d'un potentiel d'action

Toute stimulation qui s'exerce sur la membrane du neurone entraîne l'ouverture des canaux à ions Na+ dépendants du voltage : c'est la phase ascendante du potentiel d'action. Du fait de leur concentration plus faible et des charges négatives à l'intérieur du neurone, les ions Na+ pénètrent dans le neurone par ces canaux. Le déplacement des ions Na+ vers l'intérieur du neurone est alors plus important que le déplacement des ions K+ vers l'extérieur.

Le mouvement des charges positives vers l'intérieur du neurone entraîne une diminution de sa négativité interne : c'est la dépolarisation. Si la dépolarisation atteint un seuil critique d'excitation (d'environ -55 mV), la membrane initie alors un potentiel d'action. A mesure que s'accroît la quantité de sodium qui entre dans le neurone, le potentiel de membrane se modifie et ouvre d'autres canaux Na+ dépendants du voltage jusqu'à ce que ces derniers soient tous ouverts. La modification du potentiel de membrane se poursuit ainsi jusqu'à ce qu'il atteigne un pic qui correspond à la valeur d'équilibre du potentiel d'action. Pendant une courte période, la polarité membranaire est inversée : l'intérieur du neurone est positif alors que l'extérieur est négatif.

Très rapidement après l'émission du potentiel d'action, les canaux Na+ dépendants du voltage se ferment et la perméabilité de la membrane aux ions Na + redevient très faible. Les canaux à ions K+ dépendants du voltage s'ouvrent avec un délai de 1 ms et les ions K+ sont expulsés très rapidement. Au fur et à mesure que les ions K+ sortent, le potentiel de membrane redevient négatif et retrouve sa valeur de repos d'origine : c'est la repolarisation (phase descendante du potentiel d'action). A la fin de la phase descendante, juste avant que les canaux K+ se ferment, le potentiel de membrane peut avoir une valeur plus négative que sa valeur de repos : c'est l'hyperpolarisation. Cette sur-négativité à l'intérieur du neurone est due à un excès de perméabilité aux ions K+ qui contrebalance la perméabilité naturellement très faible aux ions Na+. La pompe sodium-potassium se met alors à fonctionner en accéléré pour rétablir les distributions ioniques initiales.

Quand la membrane génère un potentiel d'action et que ses canaux Na+ dépendants du voltage sont ouverts, le neurone est incapable de répondre à une autre stimulation quelle que soit son intensité : c'est la période réfractaire absolue. Elle est suivie par une période réfractaire relative qui correspond au moment où se produit la repolarisation. Durant la période réfractaire relative, le seuil d'excitation est très élevé : seule une stimulation exceptionnellement intense peut ouvrir les canaux Na+ dépendants du voltage et permettre ainsi le déclenchement d'un nouveau potentiel d'action.

Propagation d'un potentiel d'action

La naissance d'un potentiel d'action en un point de l'axone du neurone entraîne, par établissement de courants locaux, une dépolarisation de la membrane adjacente, responsable de l'ouverture de canaux dépendants du voltage (Na+ puis K+), d'où l'apparition d'un nouveau potentiel d'action. Les courants locaux correspondent au déplacement latéral des ions le long de la membrane (par exemple, de la région dépolarisée vers la région encore polarisée pour les ions Na+).

Dans le système nerveux, la propagation du potentiel d'action est toujours unidirectionnelle, du segment initial de l'axone à son arborisation terminale. Le segment initial (jonction entre le corps cellulaire et l'axone) est la zone d'initiation du potentiel d'action car elle est riche en canaux Na+ dépendants du voltage et présente le seuil d'excitation le plus bas. Par ailleurs, quelle que soit la distance que le potentiel d'action doit parcourir pour être ensuite transmis à une autre cellule, son intensité ne diminue jamais.

La vitesse de propagation du potentiel d'action dépend de certaines propriétés physiques de l'axone comme son diamètre. Elle est plus élevée dans les axones de gros diamètre (une plus grande surface signifie qu'une plus grande quantité d'ions peut contribuer à la modification du potentiel de membrane). Pour améliorer la transmission nerveuse, le neurone dispose d'une autre stratégie : elle est ainsi plus rapide dans les axones entourés par une gaine de myéline. La gaine de myéline n'est pas continue sur toute la longueur de l'axone mais comporte des interruptions - les noeuds de Ranvier - espacées de 1 mm et perméables aux ions. Le potentiel d'action ne se propage pas de proche en proche tout au long des axones myélinisés mais seulement d'un noeud de Ranvier à l'autre par des sortes de "sauts" : on parle de conduction saltatoire. L'ouverture des canaux dépendants du voltage ne se fait donc qu'à ce niveau.

L'arrivée du potentiel d'action à l'extrémité de l'axone (la terminaison présynaptique) provoque un certain nombre de phénomènes électrochimiques. Il existe au niveau de la terminaison synaptique des canaux à ions Ca2+ dépendants du voltage. L'arrivée du potentiel d'action déclenche la dépolarisation de la membrane présynaptique et l'ouverture des canaux Ca2+. La concentration en calcium étant beaucoup plus élevée à l'extérieur qu'à l'intérieur, les ions Ca2+ vont pénétrer dans la terminaison présynaptique. Il existe aussi au niveau de la terminaison présynaptique des molécules chimiques appelées neurotransmetteurs qui sont stockés dans des vésicules synaptiques. L'entrée en masse du calcium va avoir pour effet de provoquer la libération des neurotransmetteurs dans l'espace intersynaptique. Ces neurotransmetteurs vont se fixer sur des récepteurs spécifiques appelés "récepteur-canaux", situés sur la membrane des dendrites du neurone postsynaptique. Ces canaux vont à leur tour s'ouvrir pour laisser passer des ions à l'intérieur du neurone.

B.2 Pre- and Post-test

The pre-test and post-test of this study are identical.

Le potentiel de repos

Il y a une plusieurs réponses possibles pour les questions ci-dessous.

Q1. Le(s) quel(s) de ces phénomènes explique(nt) le fait que le potentiel de repos soit négatif?

- ☐ **A.** Il y a plus d'ions négatifs que d'ions positifs dans le liquide qui se trouve à l'intérieur du neurone.
- ☐ **B.** Les ions négatifs qui diffusent vers l'intérieur du neurone sont plus nombreux que ceux qui diffusent vers l'extérieur.
- ☐ **C.** La membrane du neurone est plus perméable aux ions positifs qui se trouvent à l'intérieur qu'aux ions positifs qui se trouvent à l'extérieur.
- ☐ **D.** La diffusion des ions positifs vers l'extérieur est plus rapide que la diffusion des ions positifs vers l'intérieur du neurone.

Q2. Que se passerait-il si l'on bloque artificiellement les pompes sodium-potassium ?

- ☐ **A.** Cela conduirait à la disparition des gradients de concentration des ions K+ et Na+ de part et d'autre de la membrane.
- ☐ **B.** Il y aurait plus d'ions Na+ à l'intérieur du neurone qu'à l'extérieur.
- ☐ **C.** Il y aurait autant d'ions K+ à l'extérieur du neurone qu'à l'intérieur.
- ☐ **D.** Cela conduirait à une diminution du potentiel de membrane entre les milieux intérieur et extérieur du neurone.

Vrai	Faux	
		Q3 : Plus la concentration en ions Na+ à l'intérieur du neurone est grande, plus le potentiel de repos est positif.
		Q4 : Si la concentration en ions K+ à l'extérieur du neurone est nulle, alors la pompe sodium-potassium s'arrête de fonctionner.
		Q5 : Le potentiel électrique est égal à zéro aussi longtemps que l'électrode qui l'enregistre est positionnée à l'extérieur de la membrane du neurone.
		Q6 : En l'absence de potentiel de membrane, la somme des charges positives est strictement égale à celle des charges négatives dans chaque compartiment du neurone.
		Q7 : Si le potentiel de membrane d'une fibre nerveuse augmente, alors le potentiel devient plus positif.
		Q8 : Au repos, les ions positifs sont attirés par les charges du milieu extérieur, les ions négatifs par les charges du milieu intérieur.
		Q9 : La pompe sodium-potassium admet plus de charges positives à l'intérieur du neurone qu'à l'extérieur.
		Q10 : Plus la concentration en ions K+ à l'extérieur du neurone est grande, plus le potentiel de repos est négatif.

Genèse d'un potentiel d'action

Il y a une plusieurs réponses possibles pours les questions ci-dessous.

Q11. Il est impossible pour un neurone de générer plus de 100 potentiels d'action par seconde. Parmi ces propositions, laquelle (lesquelles) est (sont)-elle(s) cause(s) de ce phénomène ?

- ☐ **A.** Car après la dépolarisation, il existe une période pendant laquelle la membrane du neurone présente un seuil d'excitation très élevé.
- ☐ **B.** Car après la dépolarisation il existe une période pendant laquelle les charges ne peuvent plus circuler à travers la membrane du neurone.
- ☐ **C.** Car après la dépolarisation, il faut du temps pour que l'intérieur du neurone soit de nouveau chargé négativement.
- ☐ **D.** Car après la dépolarisation, la membrane du neurone est très perméable aux ions positifs qui diffusent vers l'extérieur du neurone.

Q12. Que se passerait-il si les canaux K+ dépendants du voltage mettaient plus de temps que 1ms à s'ouvrir durant un potentiel d'action?

- ☐ **A.** La membrane du neurone resterait alors très perméable aux ions Na+.
- ☐ **B.** Le potentiel de membrane resterait sur un plateau proche du pic du potentiel d'action.
- ☐ **C.** La fréquence maximale du potentiel d'action augmenterait sensiblement.
- ☐ **D.** Cela empêcherait un excès de perméabilité aux ions K+ à la fin de la phase descendante.

Vrai	Faux	
		Q13 : Si la membrane neurone restait en permanence dépolarisée, elle ne pourrait plus conduire de potentiel d'action, ce qui entraînerait la fin du neurone.
		Q14 : Plus l'instant de stimulation est proche de la fin de la période réfractaire absolue, et plus l'amplitude du potentiel d'action émis est faible
		Q15 : Dans la phase ascendante du potentiel d'action, l'amplitude du potentiel de membrane diminue si la concentration extracellulaire en sodium est réduite.
		Q16 : Pour un axone placé dans de l'eau sans sodium et stimulé électriquement, le courant membranaire observé se limite à un courant sortant de potassium.
		Q17 : Un courant négatif injecté par l'expérimentateur à l'intérieur du neurone le dépolarise ; un courant positif éloigne son potentiel du seuil d'excitation.
		Q18 : La période réfractaire relative d'un neurone est le temps pendant lequel le potentiel de membrane est supérieur au seuil d'excitation.
		Q19 : Lorsque la membrane du neurone est excitée, un courant sortant d'ions K+ apparaît qui se maintient pendant toute la durée du potentiel d'action.
		Q20 : Le seuil représente le potentiel membranaire pour lequel la perméabilité ionique de la membrane est en faveur du potassium plutôt que du sodium.

Propagation du potentiel d'action

Il y a une plusieurs réponses possibles pours les questions ci-dessous.

Q21. Pourquoi les potentiels d'action ne peuvent aller que dans un sens ?

- ☐ **A.** Car le seuil d'excitation de la membrane du neurone est beaucoup plus bas dans un sens que dans l'autre.
- ☐ **B.** Car il est impossible de déclencher un potentiel d'action au niveau du corps cellulaire du neurone.
- ☐ **C.** Car la zone de la membrane qui vient d'être dépolarisée est temporairement inexcitable.
- ☐ **D.** Car un courant continu dans un circuit électrique ne circule que dans une seule direction.

1. **Comment l'efficacité de la propagation des potentiels d'action pourrait-elle être améliorée?**
   - ☐ **A.** En diminuant le seuil à partir duquel la membrane de l'axone initie un potentiel d'action.
   - ☐ **B.** En augmentant le diamètre de la gaine de myéline qui recouvre certains axones.
   - ☐ **C.** En diminuant le nombre de nœuds de Ranvier qui permettent la conduction saltatoire.
   - ☐ **D.** En augmentant la quantité d'ions qui circulent à travers la membrane de l'axone.

Vrai	Faux	
		Q23 : Les ions positifs du milieu extérieur se déplacent de la région polarisée de la membrane vers la région dépolarisée
		Q24 : Le codage par modulation de fréquence des potentiels d'actions présynaptiques est converti en codage par concentration de neurotransmetteurs.
		Q25 : Lorsqu'on injecte de la tétrodoxine (un bloqueur naturel des canaux Na+) au niveau de la terminaison présynaptique, on empêche alors la libération des neurotransmetteurs.
		Q26 : Les flux en ions Na+ et K+ sont moins importants dans une fibre recouverte de myéline que dans une fibre amyélinisée.
		Q27 : Pour qu'une propagation normale de l'impulsion nerveuse se produise, le rapport du potentiel d'action au seuil d'excitation doit toujours être inférieur à 1.
		Q28 : Le potentiel d'action continue à se propager même si celui-ci ne produit pas de voltage suffisant pour stimuler la membrane adjacente.
		Q29 : Les canaux à ions Na+ dépendants du voltage sont présents sur toute la longueur d'un axone recouvert d'une gaine isolante de myéline.
		Q30 : Lors du déclenchement d'un potentiel d'action, si on marquait radioactivement les ions Na+ au niveau du segment initial de l'axone, on les retrouverait ensuite dans la terminaison présynaptique.

B.3 Questionnaires

QUESTIONAIRES

Merci de classer les interfaces sur une échelle d'**un** à **sept** ou la laisser **en blanc** si vous ne savez pas, avec: *1 (pas du tout d'accord) - 2 - 3 – 4 – 5 - 6 – 7 (tout à fait d'accord)*								
1.	Je suis généralement satisfait(e) de la facilité d'utilisation de ce système.	1	2	3	4	5	6	7
2.	Ce système a été simple à utiliser.	1	2	3	4	5	6	7
3.	Je peux effectuer un travail de qualité avec mon groupe avec ce système.	1	2	3	4	5	6	7
4.	Je suis capable d'effectuer mon travail sans perdre de temps avec mon groupe avec ce système.	1	2	3	4	5	6	7
5.	Il a été facile d'apprendre à utiliser ce système.	1	2	3	4	5	6	7
6.	Je pense être devenu productif rapidement avec mon groupe avec ce système.	1	2	3	4	5	6	7
7.	L'interface du système est agréable.	1	2	3	4	5	6	7
8.	J'aime utiliser l'interface de ce système.	1	2	3	4	5	6	7
9.	Je suis généralement satisfait de ce système.	1	2	3	4	5	6	7

Des aspects les plus **négatifs**

1.

2.

3.

Des aspects les plus **positifs**

1.

2.

3.

Commentaires générales:

C Materials for the Warehouse study

C.1 Two TinkerSheets used for the study

Fiche Simulation 1.5.1 (1/2)

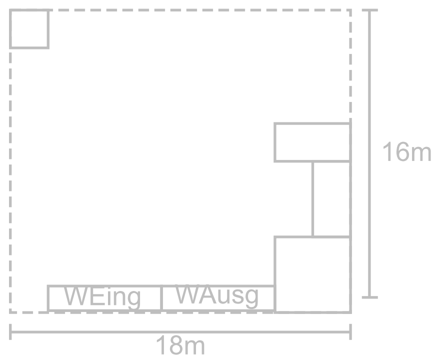
Répartition des surfaces de stockage

1. Locaux annexes

Sur la surface interactive, placez les locaux annexes comme indiqué sur le plan d'entrepôt ci-contre.

La position des locaux est reportée en temps réel sur le plan ci-contre, ce qui vous permet de contrôler que votre mise en place est correcte.

Plan de l'entrepôt



2. Surface brute de stockage

Le système affiche des informations sur la surface brute, la surface brute de stockage et le degré d'utilisation des surfaces. Recopiez ces valeurs.

Rappel:

Surface brute = longeur de l'entrepôt x largeur de l'entrepôt

Surface brute de stockage = surface brute - surface des locaux annexes

Surface brute = m²

Surface brute de stockage = m²

Degré d'utilisation des surfaces (1) = $\frac{\text{Brute de stockage}}{\text{Brute}}$ = %

3. Surface nette de stockage

Placez maintenant 10 étagères dans l'entrepôt. Le système affiche des informations sur la surface nette de stockage et le degré d'utilisation des surfaces. Recopiez ces valeurs.

Observez comment ces valeurs changent lorsque vous rajouter des étagères. Essayez de maximiser le degré d'utilisation.

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La position des étagères est-elle importante?

Surface nette de stockage = m²

Degré d'utilisation des surfaces (2) = $\frac{\text{Nette de stockage}}{\text{Brute}}$ = %

Degré d'utilisation des surfaces (3) = $\frac{\text{Nette de stockage}}{\text{Brute de stockage}}$ = %

Fiche Simulation 1.5.1 (2/2)

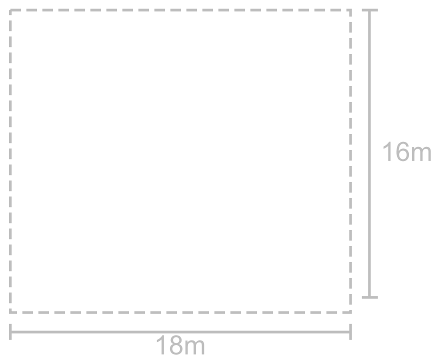
Répartition des surfaces de stockage

1. Locaux annexes

Sur la surface interactive, placez les locaux annexes comme indiqué sur le plan d'entrepôt ci-contre.

La position des locaux est reportée en temps réel sur le plan ci-contre, ce qui vous permet de contrôler que votre mise en place est correcte.

Plan de l'entrepôt



2. Type de chariot élévateur

Demandez à votre enseignant quel type de chariot vous allez utiliser pour cet exercice et définissez-le ci-contre.

Gerbeur ○

Mât rétractable ○

Contrepoids ○

2. Surface brute de stockage

Reportez les valeurs affichées ci-contre par le système.

Surface brute = m^2

Surface brute de stockage = m^2

Degré d'utilisation des surfaces (1) = $\frac{\text{Brute de stockage}}{\text{Brute}}$ = %

3. Surface nette de stockage

Essayez de maximiser le degré d'utilisation des surfaces (3). Vous êtes libres d'utiliser autant d'étagères que vous le souhaitez.

Quand vous êtes satisfaits, reportez les valeurs affichées par le système ci-contre, dessinez votre entrepôt sur le plan au sommet de cette feuille et passez à la phase suivante.

Surface nette de stockage = m^2

Degré d'utilisation des surfaces (2) = $\frac{\text{Nette de stockage}}{\text{Brute}}$ = %

Degré d'utilisation des surfaces (3) = $\frac{\text{Nette de stockage}}{\text{Brute de stockage}}$ = %

4. Simulation

Lancez une simulation, et observez le comportement des chariots élévateurs. Notez ensuite le temps total et le temps moyen pour sortir 40 palettes. Modifiez votre entrepôt pour essayer de baisser ces temps (utilisez pour ce faire une nouvelle feuille).

Mise en place ○ — Palettes sorties : / 40

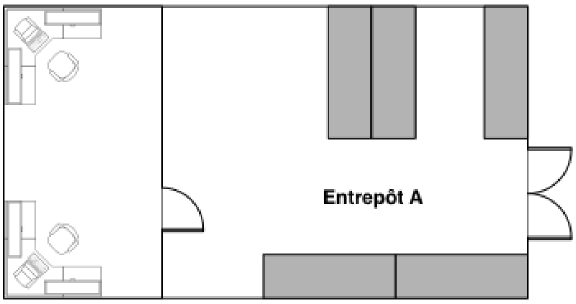
Prêt à simuler ○ — Temps écoulé :

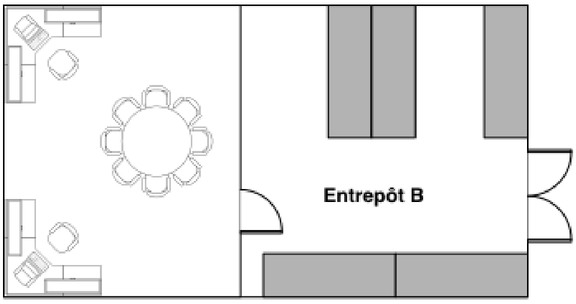
Simuler! ○ — Temps par palette : 179 s.

C.2 Post-test

Nom : **Date :**

Classe : **Stockage :**





1. Comparez les entrepôts A et B et cochez ce qui convient.

a) Concernant la **surface brute** / 0.5

- ☐ A a plus de surface brute que B
- ☐ B a plus de surface brute que A
- ☐ A et B ont la même surface brute
- ☐ Je ne sais pas

b) Concernant la **surface brute de stockage** / 0.5

- ☐ A a plus de surface brute de stockage que B
- ☐ B a plus de surface brute de stockage que A
- ☐ A et B ont la même surface brute de stokage
- ☐ Je ne sais pas

c) Concernant la **surface nette** de stockage / 0.5

- ☐ A a plus de surface nette de stockage que B
- ☐ B a plus de surface nette de stockage que A
- ☐ A et B ont la même surface nette de stokage
- ☐ Je ne sais pas

d) Concernant le **degré d'utilisation** des surfaces / 0.5

- ☐ A a un plus grand degré d'utilisation que B
- ☐ B a un plus grand degré d'utilisation
- ☐ A et B ont le même degré d'utilisation
- ☐ Je ne sais pas

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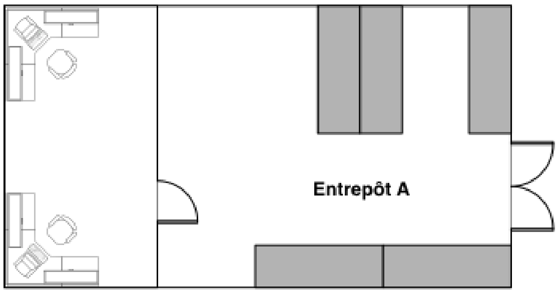

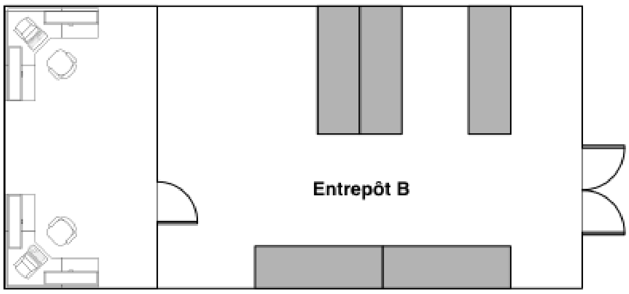

2. Comparez les entrepôts A et B et cochez ce qui convient.

a) Concernant la **surface brute** / 0.5

- ☐ A a plus de surface brute que B
- ☐ B a plus de surface brute que A
- ☐ A et B ont la même surface brute
- ☐ Je ne sais pas

b) Concernant la **surface brute de stockage** / 0.5

- ☐ A a plus de surface brute de stockage que B
- ☐ B a plus de surface brute de stockage que A
- ☐ A et B ont la même surface brute de stokage
- ☐ Je ne sais pas

c) Concernant la **surface nette** de stockage / 0.5

- ☐ A a plus de surface nette de stockage que B
- ☐ B a plus de surface nette de stockage que A
- ☐ A et B ont la même surface nette de stokage
- ☐ Je ne sais pas

d) Concernant le **degré d'utilisation** des surfaces / 0.5

- ☐ A a un plus grand degré d'utilisation que B
- ☐ B a un plus grand degré d'utilisation
- ☐ A et B ont le même degré d'utilisation
- ☐ Je ne sais pas

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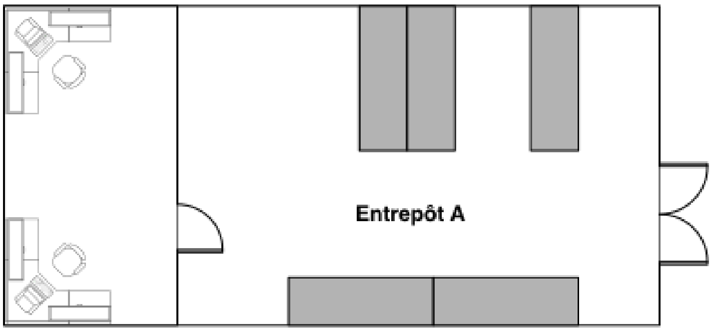
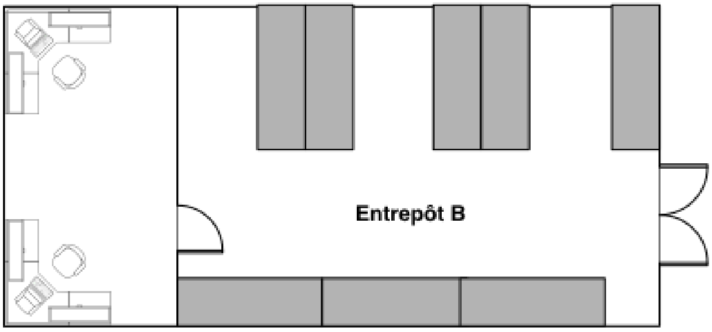




3. Comparez les entrepôts A et B et cochez ce qui convient.

a) Concernant la **surface brute** / 0.5

- ☐ A a plus de surface brute que B
- ☐ B a plus de surface brute que A
- ☐ A et B ont la même surface brute
- ☐ Je ne sais pas

b) Concernant la **surface brute de stockage** / 0.5

- ☐ A a plus de surface brute de stockage que B
- ☐ B a plus de surface brute de stockage que A
- ☐ A et B ont la même surface brute de stokage
- ☐ Je ne sais pas

c) Concernant la **surface nette** de stockage / 0.5

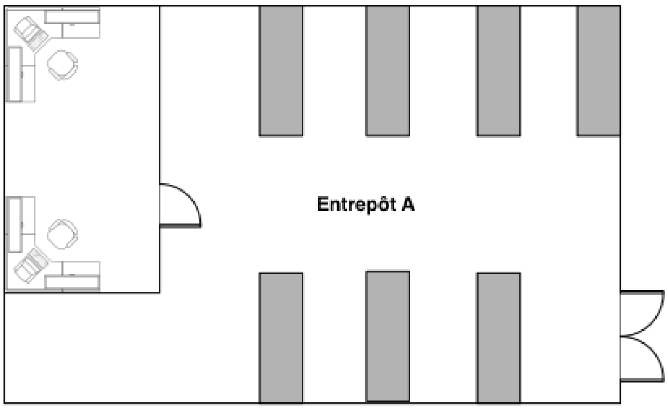
- ☐ A a plus de surface nette de stockage que B
- ☐ B a plus de surface nette de stockage que A
- ☐ A et B ont la même surface nette de stokage
- ☐ Je ne sais pas

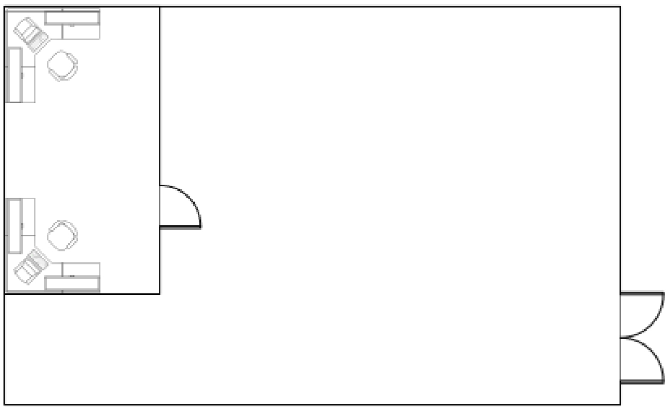
d) Concernant le **degré d’utilisation** des surfaces / 0.5

- ☐ A a un plus grand degré d’utilisation que B
- ☐ B a un plus grand degré d’utilisation
- ☐ A et B ont le même degré d’utilisation
- ☐ Je ne sais pas

4. Votre direction vous demande de faire des propositions afin d'augmenter le degré d'utilisation de l'entrepôt A sans changer les dimensions du bâtiment. Quelles propositions allez-vous soumettre à votre hiérarchie ? (décrivez et faites un schéma)

/4





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C.3 Conversation analysis scheme

DISCUSSION TYPE

Manipulation discussion.
Definition. How often the students reflect or discuss low level about an the activity, i.e. how or where to put a physical object. The discussion is at the low level of abstraction and task-focused.
Examples. ‘We should put this one like this’, ‘No, here you have to put it like this’.

Reflection discussion.
Definition. How often the students reflect or discuss high level concepts (e.g. raw surface, net surface) that they are expected to learn and understand during an activity. The discussion is at a high-level of abstraction and learning-focused.
Examples. ‘Raw surface is with the shelves right?’, ‘Yeah, raw is without anything’, ‘No, you don’t have to do the calculation if it’s the same’.

COLLABORATION QUALITY

Mutual understanding.
Definition. How often the students elicit and give feedback to make sure their contributions understandable for their partner.
Examples. ‘The shelves are all the same?’, ‘Yeah.’

Dialogue management.
Definition. How smoothly the conversation is “flowing”, how well the turn-taking is managed.
Examples. ‘Can I try?’,‘Yeah go ahead, go ahead!’,‘If we try to bring back those shelves? Try it out!’.

Information pooling.
Definition. How often the students externalize knowledge or ask each other questions and give explanations.
Examples. ‘Did you understand the thing with the raw storage surface and the net storage surface?’, ‘Raw storage surface, if you want, its only with the shelves’.

Reaching consensus.
Definition. To what extent the proposals are critically reflected upon by members.
Examples. ‘Do we have to see it on the screen?’, ’Yes of course, the square, it’s the walls, it needs to be inside!’

Reciprocal interaction.
Definition. How equally the students contribute towards the problem solution.

Examples. (same dialogue) A: 'Here we cannot move them at all, it's the minimum', B:'Can we put them all the way at the back or not?', C:'Yeah, I was thinking the same'

D Materials for the intermediate evaluations of TinkerLamp 2.0 iterations

D.1 Questionnaire

QUESTIONAIRES

Merci de classer les interfaces sur une échelle d'**un** à **sept** ou la laisser **en blanc** si vous n'avez pas d'avis, avec: *1 (pas du tout d'accord) - 2 - 3 – 4 – 5 - 6 – 7 (tout à fait d'accord)*								
Utilité								
1.	L'interface est utile.	1	2	3	4	5	6	7
Facilité d'utilisation								
2.	L'interface est facile à utiliser.	1	2	3	4	5	6	7
3.	Elle est simple à utiliser.	1	2	3	4	5	6	7
4.	Elle est conviviale.	1	2	3	4	5	6	7
5.	Elle nécessite le nombre minimal d'étape pour faire ce que je veux.	1	2	3	4	5	6	7
6.	Elle est flexible.	1	2	3	4	5	6	7
7.	Son utilisation est sans effort.	1	2	3	4	5	6	7
8.	Je peux l'utiliser sans instruction écrite.	1	2	3	4	5	6	7
9.	Je n'ai pas remarqué d'incohérences en l'utilisant.	1	2	3	4	5	6	7
10.	Je peux l'utiliser avec succès à chaque fois.	1	2	3	4	5	6	7
Facilité d'apprentissage								
11.	J'ai rapidement appris à utiliser l'interface	1	2	3	4	5	6	7
12.	Je peux facilement me rappeler comment l'utiliser	1	2	3	4	5	6	7
13.	Il est facile d'apprendre à l'utiliser	1	2	3	4	5	6	7
Satisfaction								
14.	Je suis satisfait(e) de l'interface.	1	2	3	4	5	6	7
15.	Il est amusant de l'utiliser	1	2	3	4	5	6	7
16.	Elle fonctionne de la façon dont je voudrais qu'elle fonctionne	1	2	3	4	5	6	7
17.	Elle est merveilleuse, un peu « magique »	1	2	3	4	5	6	7
18.	Il est plaisant de l'utiliser	1	2	3	4	5	6	7

Des aspects les plus **négatifs**

1.

2.

3.

Des aspects les plus positifs

1.

2.

3.

Commentaires générales:

E Materials for the two field trials of the final TinkerLamp 2.0 iteration

E.1 Questionnaire

QUESTIONNAIRES

Nom complet: ……………………………………………….

Merci de classer les interfaces sur une échelle de ’**un** à **sept** ou de laisser **en blanc** si vous n’avez pas d’avis:

1 (pas du tout d’accord) - 2 - 3 – 4 – 5 - 6 – 7 (tout à fait d’accord)

		Interaction avec le **LayoutBrowser**							Interaction avec le **Quiz**						
Interaction individuelle															
1.	L’interface est conviviale	1	2	3	4	5	6	7	1	2	3	4	5	6	7
2.	Son utilisation est sans effort	1	2	3	4	5	6	7	1	2	3	4	5	6	7
3.	J’ai rapidement appris à utiliser l’interface	1	2	3	4	5	6	7	1	2	3	4	5	6	7

Interaction au niveau du groupe et de la classe								
4.	Il y avait beaucoup de collaboration au sein de mon groupe	1	2	3	4	5	6	7
5.	L’ambiance de classe était amusante	1	2	3	4	5	6	7
6.	Je suis au courant des actions des autres groupes pendant l’activité	1	2	3	4	5	6	7
7.	J’ai comparé mes plans avec ceux des autres groupes	1	2	3	4	5	6	7
8.	Je voulais faire mieux que d’autres groupes	1	2	3	4	5	6	7
Satisfaction								
9.	Je suis satisfait(e) du système	1	2	3	4	5	6	7
10.	J’ai apprécié la classe	1	2	3	4	5	6	7

TinkerBoard								
11.	J’ai regardé le TinkerBoard	1	2	3	4	5	6	7
12.	J’ai regardé les plans sur le TinkerBoard	1	2	3	4	5	6	7
13.	J’ai regardé la barre événement sur le TinkerBoard	1	2	3	4	5	6	7
14.	Il est facile de comprendre les plans sur le TinkerBoard	1	2	3	4	5	6	7
16.	Je suis conscient(e) de mes actions	1	2	3	4	5	6	7

Les aspects les plus **négatifs** de l'interaction avec le LayoutBrowser:

1.

2.

Les aspects les plus **positifs** de l'interaction avec le LayoutBrowser:

1.

2.

Les aspects les plus **négatifs** de l'interaction avec le Quiz :

1.

2.

Les aspects les plus **positifs** de l'interaction avec le Quiz:

1.

2.

Les aspects les plus **négatifs** de l'interaction avec le TinkerBoard :

1.

2.

Les aspects les plus **positifs** de l'interaction avec le TinkerBoard :

1.

2.

Autres caractéristiques que vous aimeriez avoir sur le Quiz ou le TinkerBoard: ____________________

____

____

Commentaires généraux: ____________________

____

____

List of Figures

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Son DO-LENH

Research interests: Human Computer Interaction (HCI), Tangible and Tabletop Computing, Technology-Enhanced Learning (TEL), Computer-Supported Collaborative Learning (CSCL)

Languages: English (advanced), French (intermediate), Vietnamese (native)

EDUCATION

- **PhD in Human Computer Interaction**, Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland, 2012

  - *2 best paper awards* (in ECTEL 2010 and CHI for Education 2011), 1 book chapter, multiple peer-reviewed publications

- **MSc in Computer Science**, University of Sciences, Hochiminh City (HCMC), Vietnam. Master thesis in EPFL, Switzerland, 2007

  - *Graduated in top 3* (out of 50)

  - *1st Prize* (out of 374) of the city's student scientific research contest, *2 Honor Awards* from the City Council. *2 Scholarships* from Swiss Federal Government, and Toshiba

- **BSc in Software Engineering**, University of Sciences, HCMC, Vietnam, 2003

  - *Graduated in top 3* (out of 200). Graduation thesis grade: 10/10

  - *3 Honor Awards* from the Vietnam Ministry of Education and Training, and the Rector of university, *1st Prize* (out of 200) in the student's research contest research at university. *1st Prize* (out of 70 teams) at the annual competition for IT students in the city. 8 scholarships from National Student Association, NOKIA, and the university

ACADEMIC EXPERIENCE

- **Research Assistant**, EPFL, Switzerland, 2007–2012

  - Research on tangible and tabletop interfaces for educational settings

- **Fellow**, Harvard University, United States, 2009

  - Research on multi-touch tabletop interfaces for lab, museums and health-care settings

- **Lecturer**, University of Sciences, Vietnam, 2003 – 2006

  - Teaching Web-programming and research on geographical information systems

SELECTED PROJECTS

01/2009 – present, **EPFL**, http://dualt.epfl.ch/page62923.html

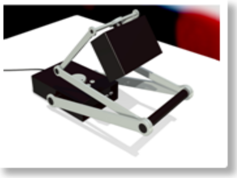
- Designed, implemented and evaluated tangible, paper and interactive applications for the TinkerLamp, a projector-camera learning environment
- *Evaluation:* usability testing, observation, fieldwork with 200+ participants, quantitative and qualitative analysis, deployment in real schools
- *Programming:* C/C++, OpenGL, Flex, ActionScript, Python

son.dolenh@gmail.com

06/2009 – 11/2009, **Harvard University**, http://sdr.seas.harvard.edu/content/research-projects

- Developed and evaluated games with tangible objects for the therapy of children with cerebral palsy
- *Evaluation:* usability testing, fieldwork, interviewing, lab study, observation in hospital, quantitative and qualitative analysis
- *Programming:* C#/WPF

10/2006 - 12/2008, **EPFL**, http://craft.epfl.ch/page66273.html



- Designed and implemented real-time fingertip detection algorithms and paper-based interactions
- *Evaluation:* usability testing, lab study with 50+ participants, interviewing, observation, quantitative and qualitative analysis
- *Programming:* C/C++, OpenGL, Java

TECHNICAL SKILLS

- *Programming:* C/C++, Flex, ActionScript, Python, .NET (VB.Net, C#), Java, Perl, SQL, HTML, UML
- *Tools*: OpenCV, OpenGL, R Statistics, MATLAB and others
- *User Experience*: usability testing, fieldwork, experimental design, observation, questionnaire, wireframe, interviewing, quantitative and qualitative analysis, paper prototyping, deployment in real settings

EXTRACURRICULAR ACTIVITIES

- *Best volunteer*, South East Asian Games (SEA Games 2003) (25 awarded out of 7200), *Leader* of Press Center Volunteers (200 members)
- *Local Committee Lausanne*, Switzerland, International Association for the Exchange of Students for Technical Experience (IAESTE), 2008-2009
- *Head of Public Relation*, Organizing Committee of Vietnam National Informatics Olympic (2005)
- *President* of University's Extracurricular Activity Club (2000-2002)
- *Chief editor* of the IT Scientific Magazine for students and lecturers (2004-2006)
- *On university team* (15 selected out of ~20.000) participating in the national competition for creative students (2000)
- Multiple other prizes and awards for volunteer, extracurricular and sport activities.

MAIN PUBLICATIONS

- Classroom orchestration: The third circle of usability, P. Dillenbourg, G. Zufferey, H. S. Alavi, P. Jermann, S. Do-Lenh, Q. Bonnard, S. Cuendet, and F. Kaplan. In Proc. of the Computer-Supported Collaborative Learning (CSCL'11), volume 1, pages 510-517, 2011.
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