Designing and analyzing collaborative activities in multi-surface environments

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ABSTRACT

Multi-surface environments (MSE) combine several surfaces in a variety of physical arrangements to form a seamless information space. Large surfaces, such as tabletops and wall-displays are often used as a shared space to coordinate efforts, and handheld devices, such as tablets and smartphones, are generally used as personal spaces supporting individual tasks. MSE have shown benefits for supporting colocated activities, especially the ones involving rich data exploration, such as collaborative problem-solving and decision-making activities. However, the diversity of MSE also raises complex design questions, as different devices configurations can be suited to different kinds of activities. Besides design, developing collaborative activities in MSE remains challenging. In this dissertation, I study how MSE supports collaboration, and collaborative learning more specifically, in order to address the these questions and challenges.

Firstly, I review previous literature on collaborative activities in MSE, collaboration models, and propose an analytical grid to study collaboration in MSE. This grid consists of four collaboration mechanisms (awareness, regulation, information sharing and discussion) and group's spatial arrangements. I synthesize and propose indicators for analyzing these elements.

Secondly, based on this preliminary work, I study how the configuration and form factors of devices shape collaborative behaviors. I focus on two common MSE configurations: multiple mobiles in outdoor MSE and shared surface with multiple personal devices in indoor MSE. To this end, I designed 1) a problem-solving learning activity in mobile outdoor configuration, 2) a problem-solving activity in shared surface indoor configuration, and 3) a decision-making learning activity in shared surface configuration in a real classroom situation.

I show that in both mobile and shared surface configurations, shared indicators are useful for maintaining awareness and promoting regulation. Manual synchronization in mobile configuration, and using tabletop to control tablets in shared surface configuration can have positive impacts on awareness. In mobile configurations, proxemic interaction should be dealt with care as F-formations are more dynamic and can be associated to different information sharing activities and devices configurations. In shared surface configurations, F-formations are more stable. In shared surface configurations, I show that using a horizontal surface leads to more implicit coordination and balanced interaction with the large display, but to less structured work, while using the vertical surface, group coordination is more explicit and is structured around one main interactor.

Lastly, based on the analysis of how students collaborate and make decisions in a real classroom situation, I derive design implications for decision-making activities in MSE. Building on these implications, an in-depth literature review of decision-making process, and discussions with teachers, I propose Decimake, an authoring tool which can be used by non-experts, such as teachers, to create decision-making applications in MSE.

RÉSUMÉ

Les environnements multi-surfaces (MSE) combinent écrans interactifs dans une grande variété d'arrangements pour former un espace d'information et de travail homogène. Les grandes surfaces, telles que les tables interactives et les écrans muraux, sont souvent utilisées comme un espace partagé pour collaborer alors que les dispositifs portables, comme les tablettes et les smartphones, sont généralement utilisés comme espaces personnels pour réaliser des tâches individuelles. Les MSE ont montré leurs avantages dans le cadre d'activités co-situées, en particulier pour l'exploration riche des données, telles que la résolution collaborative de problèmes et la prise de décisions. Cependant, la diversité des MSE soulève des questions de conception complexes. Les différentes configurations de périphériques devant être adéquatement choisies en fonction des différents types d'activités à supporter. Outre la configuration physique, le développement d'applications pour les MSE demeure un défi. Dans cette thèse, nous étudions comment un MSE peut faciliter des activités collaboratives, et l'apprentissage collaboratif.

Tout d'abord, nous passons en revue la littérature sur les activités collaboratives dans les MSE et les modèles de collaboration. Nous proposons une grille d'analyse pour étudier la collaboration dans les MSE. Cette grille se compose de quatre mécanismes de collaboration (conscience, régulation, échange d'informations et discussion) et les positionnements physiques des utilisateurs travaillant en groupe. Nous synthétisons et proposons des indicateurs pour l'analyse de ces éléments.

A partir de ce travail préliminaire, nous étudions comment la configuration et les facteurs de forme des dispositifs façonnent les comportements collaboratifs. Nous nous concentrons sur deux configurations communes de MSE : utilisation à l'extérieur avec des dispositifs mobiles multiples et utilisation à l'intérieur avec une surface partagée combinée avec plusieurs dispositifs personnels. À cette fin nous avons conçu 1) une activité d'apprentissage de type résolution de problèmes en configuration extérieure, 2) une activité de résolution de problèmes en configuration intérieure, et 3) une activité d'apprentissage pour la décision multicritères dans une situation réelle avec une classe d'élèves.

Nous montrons que dans les configurations avec les mobiles et surfaces partagées, des indicateurs partagés sont utiles pour maintenir la conscience de groupe et promouvoir la régulation. La synchronisation manuelle dans la configuration mobile et l'utilisation de la table pour contrôler les tablettes en configuration de surface partagée peuvent avoir des effets positifs sur la conscience du travail des autres.

Dans les configurations mobiles, l'interaction proxémique doit être traitée avec soin car les F-formations sont plus dynamiques et peuvent être associées à différentes activités de partage d'informations et à des configurations de périphériques. Dans les configurations avec une surface partagée, les F-formations sont plus stables. Dans cette même configuration, nous montrons que l'utilisation d'une surface horizontale conduit à une coordination plus implicite et à une interaction équilibrée entre les membres du groupe. Malgré un travail moins structuré, en utilisant une surface verticale, la coordination de groupe est plus explicite et structurée autour d'un acteur principal.

Enfin, sur la base de l'analyse de la façon dont les élèves collaborent et prennent des décisions dans une situation réelle en classe, nous proposons des recommandations pour la conception d'activités de prise de décision dans les MSE. À partir de ces recommandations, d'une analyse approfondie des processus décisionnels et des discussions avec des enseignants, nous proposons Decimake, un outil de création qui peut être utilisé par des non-experts en informatique, comme les enseignants, pour créer des applications décisionnelles dans les MSE.

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Part I

THESIS

1 INTRODUCTION

Multi-Surface Environments (MSE) combine different type of devices to form a seamless interaction space which is well suited for co-located collaboration. This dissertation explores people's collaborative behaviors in MSE, especially students' collaborative learning behaviors. It focuses on two kinds of configurations of MSE: mobile outdoor MSE and shared surface indoor MSE. We study how users collaborate in these two configurations of MSE and explore that MSE is appropriate for the collaborative activity that requires both group and individual tasks. Based on user studies, we provide insights on collaboration analysis methods and design implications for collaborative activities in MSE. In the end, we propose an authoring tool which can help people without programming experiences to create collaborative decision-making activities in MSE.

1.1 CONTEXT

Effective collaboration can be beneficial for group activity [104]. It reduces individual efforts on the development of the activities in the early stage and makes the joint work more accessible and effective [104]. Collaboration interests an increasing number of people from different fields, such as HCI and education. Different techniques have been developed or adapted to support collaborative learning. Among these, large digital surfaces have gained lots of focuses as they have been proved to be beneficial for co-located collaboration [31]. Nowadays, there is a trend to combine numerous surfaces together for supporting collaborative activities, which is called Multi-Surface Environments (MSE) [154]. This dissertation will study how users behave and collaborate in MSE in order to provide implications for designing and developing applications in MSE, especially the ones for collaborative learning.

1.1.1 *Collaboration*

Collaboration is a complex phenomenon. The definition of the term collaboration itself is vague [55]. Roschelle and Teasley (1995) [128] defined collaboration as "a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem". They distinguish collaboration and cooperation in the way participants perform the actions to a shared objective:

collaboration means the work is accomplished by all the participants together; whereas cooperation means that participants act towards a shared goal, but each of them performs specific and independent actions to achieve part of the overall goal. This definition is widely accepted in the Computer Supported Collaborative Learning community [34]. However, in the field of Computer Supported Cooperative Work, some researchers proposed that collaborative activities always contain three core activities: coordination, cooperation and communication [39, 41, 49, 54], which is well known as 3C model. Coordination concerns the management of people, their activities and resources. In coordinated work, participants' individual actions are only externally related to each other. In cooperative work, participants act towards a shared goal, but each performs specific and independent actions to achieve part of the overall goal. And communication is related to the exchange of message and information among people to reconceptualized the organization and interaction toward the shared goal. In this dissertation, I follow the 3C model which regards collaboration as a more general term, and comprehend it from these three core areas: coordination, cooperation and communication.

1.1.2 *Collaborative learning*

Collaborative learning is an umbrella term which covers a variety of educational activities that involve collaboration [140]. The broadest definition of collaborative learning is "a situation in which two or more people learn or attempt to learn something together" [31]. It significantly transforms the traditional teacher-centered classroom to student-centered learning communities [140]. The benefits of collaborative learning have been well established in the past years [31, 88, 128]. In collaborative learning activities, individuals act as group members to share information, coordinate their behaviors, respect others' abilities and make their own contributions. For some of the collaborative learning settings, the main goal is to create a clearly delineated product. Whereas in other settings, the objective is to let participants involve in the analytical and decision-making process of the group work [140].

1.1.3 *Decision-making learning*

Decision-making skills are highly required in scientific education, as it can help students obtain and construct knowledge [42, 52, 123]. Decision-making involves the process of gathering information, identifying and weighing alternatives, and selecting among various alternatives based on value judgments [146]. Collaborative decision-making becomes more relevant in multi-disciplinary education, such as when educators tackle socio-scientific issues, e.g. sustainable de-

Figure 1: InteracTable: an early example of interactive tabletop [141].

velopment [139]. These issues are often ill structured, and always involve consideration for technical, economical, and ethical aspects. To improve students' abilities to made decisions, it is necessary to know how they perform the decision-making process and provide them tools to support that process.

1.1.4 *Interactive surfaces and collaboration*

Interactive surfaces have demonstrated their ability to support co-located collaboration and decision-making activities [19, 105, 127]. The shared surface provides a convenient collaborative work space which allows people to have fluid, barrier free and face-to-face communication [127]. The large workspace facilitates information sharing, and supports for cognitive offloading and shared awareness. Multi-touch also allows users to interact with the surface simultaneously which increases equality of participation [19].

Tabletops are horizontal interactive surfaces which have been used a lot in collaborative learning and collaborative task completion. InteracTable [142] is an early example of an interactive tabletop (Figure 1). It allows a group of users to collaboratively create and edit information. Other early examples also include DiamondTouch [29] and UbiTable [137]. These systems explore the technology infrastructure, design of the system, and applications using interactive tabletops.

Wall displays are vertical interactive surfaces which are often used in information visualization and data manipulation tasks [5, 91]. They can make more complex data entities simultaneously visible and provide extra space for spatially organized findings [5]. Jakobsen and Hornbaek [73] confirm that multi-touch wall displays can support different collaboration styles and fluid transitions in group work. Meanwhile, large wall displays also bring challenges, such as how to select information at the individual and overview level, or how display form factors, such as size and resolution, impact the type of available

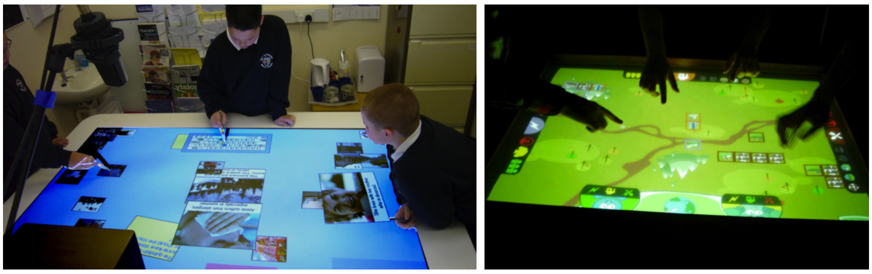


Figure 2: Collaborative learning activities using tabletop. Left: Digital Mysteries [80]. Right: Futura [6]

physical navigation, which in turn impact performance and behavior [5].

Various collaboration patterns and interactions have been studied in wall display environment [73, 92, 120]. Prouzeau et al. [120] provide two selection techniques for collaboration on wall display. Liu et al. [92] propose a set of collaboration gestures on wall display to manipulate content and facilitate collaborative work. These studies help to understand the characteristics of large wall displays as well as provide implications to better support collaborative work.

1.1.5 *Using interactive surfaces for education*

Interactive surfaces raise expectations on how they could change education by supporting face-to-face collaboration [32]. They illustrate the evolution of CSCL from virtual spaces to the physical realm where learners can physically manipulate digital objects and convey intentions through gestures. Interactive tabletops can structure the learning process with timely, reflective feedback; provide provisioning tools to make thinking visible; allow the switch between single and parallel input to support collaboration and increased awareness of group members. With the growing stability of the technology, tabletops have been used in educational activities to support collaborative learning. For example, Digital Mysteries [80] is a collaborative learning application designed for school children using tabletops (Figure 2-left). It allows students to gather and organise key information about a given scenario in order to discuss and build a solution as a group. Futura [6] is another collaborative learning game using tabletop which aims to help people to understand the complexity of sustainable development (Figure 2-right). Players take on the role of important decision makers, responsible for meeting the needs of increasing population for their resources. These studies explore the novel and effective design of collaborative activities on tabletops to better support learning.

1.1.6 *Limitation of interactive surfaces for collaboration*

Although interactive surfaces have their advantages, the shared display is not quite suited for individual exploration and analysis which are sometimes required in collaborative learning activities [35]. To overcome that problem, one strategy is to assign personal spaces from the shared space to participants for performing the individual tasks. For example, in Digital Mysteries, each student has a keyboard on his/her side. Students also have identified color to mark their manipulation [80]. In Futura [6], players have toolbars located on the three sides of the interface representing their roles. This method sacrifices space on the shared surface. Participants could also influence each other when they are required to accomplish the tasks individually.

Besides, the size and weight of large interactive tabletops also limits their use: they are hardly mobile. The furniture aspect makes it harder to have them evolve. They provide little to no support for micro-mobility, like raising, tilting or bending a paper document above normal desk, which is nonetheless helpful for the collaborative learning by facilitating communication, supporting fluidly management of focus on conversation, and making intentions clear to others [94]. Moreover, when dealing with even complex and large amounts of information, the fixed size of the screen may also be a limitation for the information sharing.

1.1.7 *Opportunities of multi-surface environments*

Multi-surface environments (MSE) can mitigate some of the limitation of tabletops while retaining their benefits. They combine various of devices into a shared seamless interaction workspace to support joint work (e.g. Figure 3.) Introducing mobile devices can provide private spaces for users while adding mobility to the activity. Using multiple devices will add extra space for information sharing and presenting. These is little doubt that group decision-making is conducted by individual actors and requires complex interplay between individual- and group-level properties [64]. MSE turns to be well suited for decision-making activities as it can integrate various devices to support the activities that involves both individual and group level.

1.1.8 *Challenges and research questions of MSE*

The large-scale MSE have shown their benefits for supporting colocated activities, especially the ones involving rich data exploration, such as complex collaborative problem-solving and decision-making activities [22, 135]. However, the diversity of MSE also raises questions when building an environment for collaborative activities, such

Figure 3: An Multi-Surface Environment using the combination of a shared surface and three tablets.

as which kind of configuration (e.g. the number of shared surface and personal devices) and form factor (e.g. size, form and orientation of devices) of devices to choose, and how to design applications in different MSE configurations to better support collaboration. These questions need to be answered early in the design phase and could hardly be changed later in the process. The devices configuration and form factors are quite important as they can have a long-term impact on users' collaborative behaviors. Understanding how users behave in MSE can help us gain insights on choosing configuration and better support collaboration.

Moreover, designing and developing cross-device application remains a complex process. Former researchers have explored cross-device interaction techniques [99] and proposed frameworks or toolkits to facilitate the development of multi-device applications [71, 109]. However, these works mainly focus on solving technical issues, such as distributed interface and interaction. There is little support on orchestrating the scenario of collaborative activities in MSE. It is far more complex and time-consuming when designing collaborative learning activities in MSE which requires collaboration between designers and teachers.

1.2 RESEARCH OBJECTIVES

My overarching research goal is to facilitate the design and development of collaborative activities in MSE, especially the activities for learning. Concerning the challenges and questions in MSE, I identify and pursue the following two research objectives:

1. **Understanding how the configuration and form factors of devices in MSE shape users' behaviors.**

   The first broad research objective of this thesis is to study how different configurations and device form factors of MSE influence and shape users' behaviors. Two common configurations of MSE are the main focus: using multiple personal devices in an outdoor situation, and using a shared surface with multiple personal devices in an indoor situation. The impacts of the shared surface orientations (vertical vs. horizontal) on users behaviors is also the concern of this work. By understanding users' collaboration in MSE, we can gain insights on which configuration to choose and how to design applications in MSE to better support collaboration.

2. **Supporting the creation of collaborative decision-making activities in MSE.**

   Besides the configuration and device form factors, the nature of activity (e.g. the collective goals and the distribution of labor) can also influence users' collaboration. Concerning the difficulties of designing and developing the off-the-shelf applications in MSE and the advantages of decision-making on learning, I identify my second objective: providing an authoring tool for creating collaborative decision-making activities in MSE. The target users of this tool are people without programming experiences, such as teachers, who want to create collaborative learning activities in MSE for students.

1.3 RESEARCH APPROACH

In order to address my research objectives, I adopted the research approach as shown in Figure 4:

1. **Literature review**: I reviewed the literature to understand former works in MSE and clarify the definition and the models of collaboration. I derived four collaboration mechanisms from the former models (awareness, regulation, information sharing and discussion) and synthesize the analysis methods of these mechanisms in order to better understand and analyze users' behaviors. Different decision-making models were also the focus of the review, which helped me to understand and support the decision-making process using MSE.

2. **Interview and co-design with teachers**: With colleagues, we interviewed and discussed with teachers from a vocational high school to learn about their requirements and expectation on the learning activities. Teachers co-designed the learning activities with us. During the design session, teachers highlighted the learning aspects where their students have weaknesses on (e.g. the analytical ability), which helped us to identify the tasks and steps that can better support students to learn and collaborate.

3. **Lab-studies**: We conducted lab-studies to understand how people behave in MSE using the combination of a shared surface with multiple mobile devices in an indoor situation. We compared the two different orientations of the shared surface (vertical vs. horizontal) to understand how surface orientation impacts users' collaboration in MSE.

4. **Field-studies**: We conducted field-studies with high school students to understand how students behave in the real classroom setting. One study focused on students collaborative learning behaviors using multiple mobile devices in an outdoor situation. The other explored how students performs decision-making activities in the classroom using one shared surface and multiple mobile devices.

5. **Design and implementation**: We designed several decision-making and problem-solving applications for the different studies, including an outdoor orienteering learning game using multiple mobile devices; a trip-planning activity and a decision-making learning activity for high school students using a shared surface and multiple mobile devices. Based on these experiences, I proposed Decimake, an authoring tool which can help facilitate the development of collaborative decision-making applications in MSE.

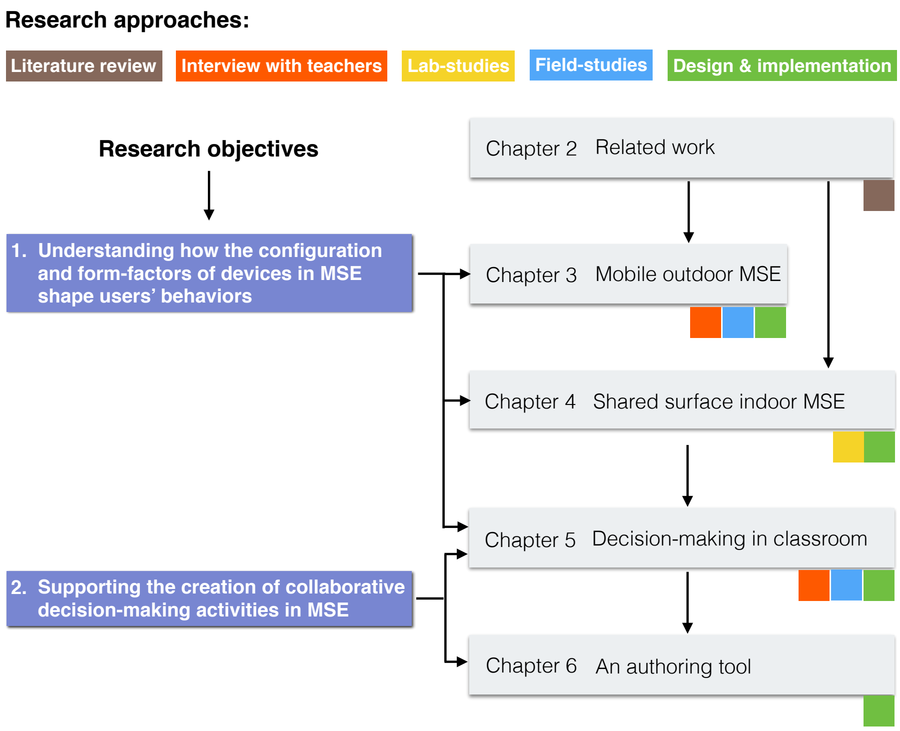


Figure 4: An overview of the dissertation: the connections between research approach/objectives and each chapter.

1.4 CONTRIBUTIONS

This thesis studies users' collaboration in two configurations of MSE: mobile outdoor configuration, and shared surface indoor configuration. I showed how users behave, and how the device usage supports and impacts collaboration. I also present the impacts of the surface orientation on users' collaboration. Based on these studies, I provide design implications for collaborative activities in MSE to better support collaboration.

Besides, I demonstrate how students perform decision-making in a real classroom situation. I define a decision-making model which is built on the study of students' behaviors, an in-depth analysis of decision-making models, and our discussion with teachers. Based on this model, I proposed an authoring tool which can be used by people without programming experiences to create decision-making activities in MSE. The authoring tool can help define decision-making context, add criteria, options and gamification elements, and configure class information.

The analysis methods of collaboration in MSE is also a contribution of this thesis. Based on the literature review on collaborative activities in MSE and different collaboration models, I propose an analytical grid to study collaboration in MSE. This grid consists consists of four collaboration mechanisms (awareness, regulation, information sharing and discussion) and group's spatial arrangements. I provide indicators for analyzing these mechanisms in different MSE configurations.

1.5 THESIS OVERVIEW

The remaining chapters of this dissertation are structured as follow:

Chapter 2 provides a review of related work from two main aspects: MSE and collaboration. It firstly introduces MSE including its concept, evolution, different configurations and applications. It also presents several frameworks that help developers to create cross-device applications in MSE. Then it reviews collaboration from several models, synthesizes the analysis methods of collaboration mechanisms that raise from these models and introduces research interests of this thesis.

Chapter 3 presents a study of one configuration of MSE: using multiple personal devices. It describes the design of an orienteering mobile collaborative learning game and shows how high school students use tablets to collaborate in an outdoor situation. It provides design implications for collaborative activities in a highly mobile condition. It also gives suggestions on how to leverage F-formation to analyze users' collaboration in a highly mobile environment

Chapter 4 reports the study of users' collaborative behaviors in the configuration of using a shared surface with multiple personal devices. It compares two orientations of the shared surface in MSE: horizontal versus vertical. It demonstrates how the combination of a shared surface shapes with personal devices, and how the orientation of the shared surface shape users' collaboration. The results show that in a MSE setting, the orientation of a shared surface nuances previous results showing that horizontal surfaces are better for collaboration, while impacts the way activities are conducted.

Chapter 5 presents the design of Pickit, a collaborative decision-making learning activity using MSE. It demonstrates how high school students use Pickit to make decisions in a real classroom setting. It shows that Pickit is an interesting tool for learning activities as it enables to balance personal and group work. The introduction of personal devices (tablets) makes free riding more difficult. Students were all succeed in making reasonable decisions and providing justifications to support their decisions.

Chapter 6 introduces Decimake, an authoring tool for designing collaborative decision-making applications in MSE. It presents our decision-making model which is built on our study of students behaviors, an in-depth analysis of decision-making models, and our discussion with teachers. It shows the design process of Decimake based on the model, and describes its functionalities. User tests have proved that Decimake is easy to use and helpful for creating decision-making learning activities.

Chapter 7 summarizes the contribution in terms of design implications for collaborative activities, an authoring tool for creating collaborative decision-making applications, and analysis methods for collaboration in MSE. In the end, it gives directions for the future work.

2 RELATED WORK

This chapter begins with an introduction to Multi-Surface Environments (MSE). It summarizes the possible configurations of MSE and applications, and frameworks and toolkits for multi-surface application design. Then, it gives a comprehensive description of collaboration. It introduces the existing collaboration models from the literature, and presents four collaboration mechanisms synthesizing former models. It describes different methods for analyzing these collaboration mechanisms in the environment that uses digital surfaces. It also introduces the collaborative decision-making activity and explains why decision-making activity is suitable to be deployed in MSE and becomes the main context of this dissertation. Finally, this chapter states the position of my work.

Multi-Surface Environments (MSE), which combine numerous surfaces in a variety of physical arrangements to form a seamless information space [108], are becoming increasingly common. They are often composed of a shared space (of one or multiple large displays) used to coordinate efforts and personal spaces on handheld devices. These large-scale MSE have potential to support different kinds activities, such as complex co-located collaborative problem-solving and decision-making activities involving rich data exploration.

Effective collaboration could be beneficial for group activity [104]. However, the definition of the term collaboration itself is vague. Different models have been proposed to define and describe collaboration in the fields of Computer Supported Collaborative Learning (CSCL) [128] and Computer Supported Cooperative Work (CSCW) [39]. How to analyze collaboration and which model to choose is always a question when start to study users' collaborative behaviors. With the emergence of interacting surfaces, the analysis methods for collaboration in the multi-surface environment are even more varied. The design of the activity or the devices used can change collaborative behaviors [121]. As mentioned in the previous chapter, my thesis is focusing on studying users' collaborative behaviors in MSE and provides insights on the design of collaborative activities using MSE.

2.1 MULTI-SURFACE ENVIRONMENTS

In the 1990's, Weiser [152] envisioned a future in which computer technologies will disappear in a fabric of everyday life or become invisible. Computers would become ubiquitous (ubicomp) in an environment in which digital devices would be interconnected by networks and be available in a variety of form factors and sizes. In order to illustrate the ubicomp idea, Weiser and his colleagues built an environment at Xerox PARC (Figure 5) by using a set of devices in different sizes including tabs (centimeter scale), pads (decimeter scale) and boards (meter scale). All these devices were connected to the network. Weiser believed that ubicomp environment would help overcome the problem of information overload and eliminate the barrier of personal interactions to make the group work more efficient.

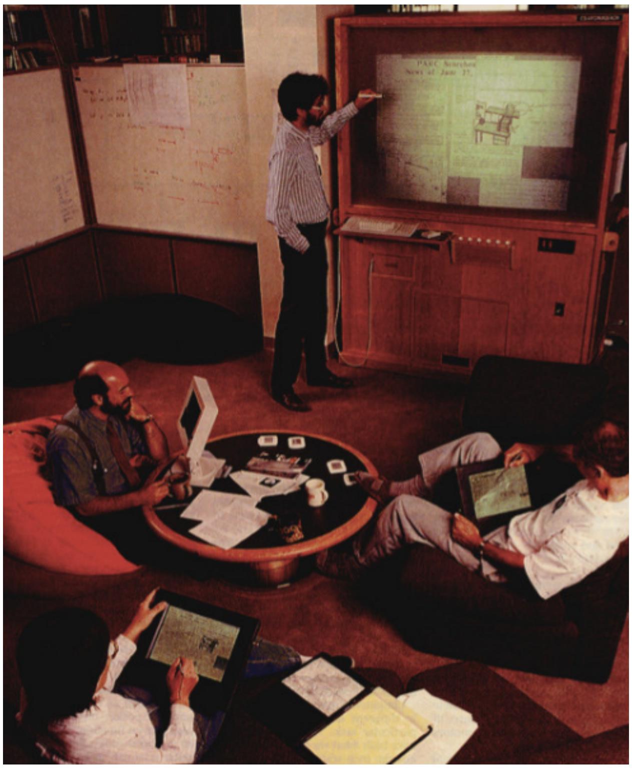


Figure 5: An early system of Ubicomp: Xerox PARC from Weiser [152].

More examples that are linked to Weiser's ubicomp concept are smart rooms, such as i-LAND [141], iRoom [75], and recently WILD room [14]. The i-LAND is a first implementation of building an innovative collaborative workspace in room setting using multiple devices including interactive wall, interactive tab, and computer-enhanced chairs with integrated interactive devices. i-LAND provides the ability to work individually or collaboratively, and the flexibility and mobility of dynamic creation of workspaces. The iRoom is an interactive meeting room which consists of three smart boards, a diagonal display, a display table, cameras, microphones and other interaction devices. It can easily be changed to different layouts what makes it deployable at various environments. The iRoom has been used in a real world environment for collaborative work. The WILD room featuring a wall-sized display, a multi-touch table, and various mobile devices that can be used to help scientists collaborate on the analysis of large and complex datasets.

Figure 6: Recent smart meeting room (Polycom RealPresence Group 500)

Nowadays, with the large-scale use of smartphones, tablets and laptops, and also the increasing presence of shared displays and tabletops, the vision of ubiquitous computing environment has made its way into our homes [77], workplaces [154] and learning environments [81] with different forms of presence [15] (as shown in Figure 6). Ubicomp is no longer a niche research topic but is best seen as the intellectual domain of all of the computing [1]. New terms are used to describe more precisely some of these systems regarding the characteristics of the devices that are used in, such as multi-display environment [107], multi-device environment [95] and multi-surface environments [153]. In this dissertation, I take the name of Multi-Surface Environment (MSE) as I choose to use multi-touch surfaces which are becoming increasingly common in recent years.

When thinking about MSE, some questions, as well as challenges, may arise [36], such as How to design cross-device interactions to transfer data and share information? How to adapt interfaces to different platform UI standards? Which kind of devices should be chosen to use in which condition? How to test and analyze multi-device user experiences? And how should collaboration be supported by using the combination of multiple devices? With the years of development of MSE, some of these challenges have been broadly explored including the cross-device interaction techniques [14, 99] and the frameworks or toolkits for designing cross-device applications []. Some higher level questions require fully functionning MSE have been less studied, such as the impacts of device configuration and factors on users' experiences and collaborative behaviors. In the following section, I will present these challenges that have been explored or solved in MSE and introduce the missing part which is also the main focus of my dissertation: understanding collaboration in MSE.

2.2 MSE CONFIGURATIONS AND COLLABORATIVE ACTIVITIES

When building a MSE, decisions that need to be made early in the design process are which devices to use and how to combine them. These decisions do not only influence the design of the activities but also affect users' collaboration and interaction. MSE could use the combination of difference devices including large interactive surface, vertical or horizontal, tablets, smartphones and personal computers. In this subsection, I classify different configurations of MSE from the literature study based on the use of these devices for a shared or a personal purpose. The large interactive surface always served as shared surface because of their size, such as the tables/boards that were first used, and the recent multi-touch wall displays or tabletops. Smaller devices such as tablets or PCs could be regarded either as shared or personal devices based on the design of the activity. Whereas handheld devices, like smartphones are used for personal purposes. Besides presenting the different configurations, I also introduce the collaborative activities that have been designed in these configurations. As I am focusing on understanding users' collaborative behaviors in MSE, the situations for one user (at home or in the workplace [67, 77]) are not the concern of this thesis.

2.2.1 *Shared surface with personal devices*

The configuration combining one or more shared surfaces with multiple personal devices is the most common one in MSE. The shared surfaces are often chosen in two forms, horizontal or vertical. They usually serve as a group space where users can perform collaborative actions such as pooling information or exchanging ideas. The personal devices could be tablets, smartphones, etc. They are used for achieving individual goals, such as doing personal evaluation or browsing information without being interrupted.

2.2.1.1 *Horizontal shared surfaces*

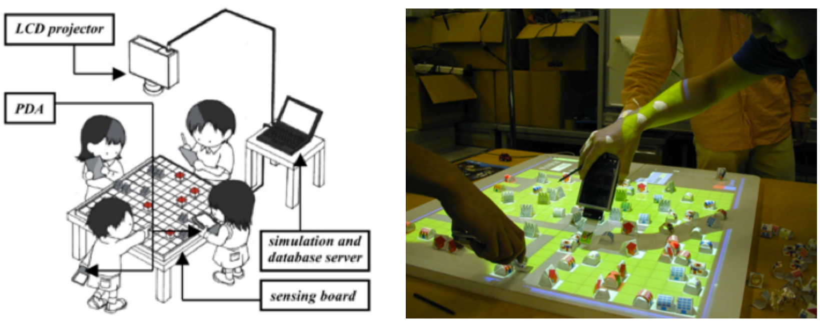


Figure 7: Caretta – an urban planning activity using MSE [143]

Caretta [143] (Figure 7) is an early study of MSE for educational purposes. Caretta uses the horizontal surface as a shared space for urban planning tasks. It is a collaborative inquiry learning activity for the acquisition of scientific concepts. The shared surface is a large sensing board on which users can manipulate physical objects such as houses or stores to redesign a town. PDAs serve as personal spaces to support individual work, such as changing the arrangement of the building and testing the plan. The changes on the personal space can be updated by computer simulation to help users evaluate their own plans. Users can discuss and negotiate with each other in the shared space by manipulating physical objects, but also examine their own ideas in their personal spaces.

Geographic applications are type of applications that require dealing with complex geospatial data and analysis, and cannot be done easily with ordinary paper maps [136]. Tabletops can tackle these limitations. For instance, some researchers developed GeoTUI, a tangible user interface on a tabletop environment to support map manipulation and analysis for geophysicists [24]. MSE can also be used for geographic applications as they are flexible for providing more complex information for different person with different backgrounds. For example, SkyHunter [135] (Figure 8-left) is a prototype using MSE to support collective oil and gas exploration. It helps experts from different domains to collaborate and make decisions on choosing specific locations for drilling oil. In SkyHunter, each expert from specific domain has an iPad running a customized application corresponding to his/her expertise. The shared tabletop shows the maps with different scales and types, and can also be used to integrate data from different sources and disciplines in the collaborative exploration process.

Another strategy is taking personal devices as "magic-lens" to get additional information of the map which is shown on the shared surface [129]. For example, Chan et al. [20] use programmable infrared (IR) technique and design an interactive tabletop system that enables interaction beyond the surface using invisible markers. Users can use a tablet which attached to an IR camera to explore 3D buildings from above the 2D map show on the tabletop (Figure 8-right).

The setting of integrating a horizontal surface with multiple personal devices has broad applications, besides these former mentioned applications, it can also be used for sharing photos, such as HyperPalette [7], BlueTable [155] and PhoneTouch [130]; planning a trip [45]; projecting contents from the personal device to the shared display [13, 138] for demonstration or group discussion; and playing digital card games [37, 79, 132, 133].

2.2.1.2 *Vertical shared surfaces*

MSE with a vertical surface, such as a wall display, can be in meeting rooms. For example, the NiCE Discussion Room [61] (Figure 9) is

Figure 8: Geographic applications in MSE. Left: SkyHunter for oil and gas exploration [135]. Right: i-m-View for 3D geographical information exploring [20]

a digital meeting room which integrates a large wall display with personal laptops and interaction with regular paper to support group discussion. In the NiCE Discussion Room setting, regular paper and laptops serve as personal spaces. The private sketches participants draw on the paper, and the contents on their personal laptops can be shared to the group via the large sketching wall.

Figure 9: NiCE Discussion Room: a MSE meeting room using vertical surface [61].

Beside the meeting room, wall displays are also suited for browsing map information. Diez and his colleagues [30] develop SharedViews , an emergency planning system using MSE (Figure 10). In SharedViews, the large shared display shows the street map and several interaction points which correspond to topics of the emergency situation. Users can get information of each interest point on their mobile phone by scanning the linked QR code.

The one shared surface with personal devices setting has a wide range of applications. The literature shows that the horizontal surfaces are more popular than vertical ones. The activities designed for horizontal surfaces range from geospatial applications, to information sharing and digital games. While the vertical surfaces are only

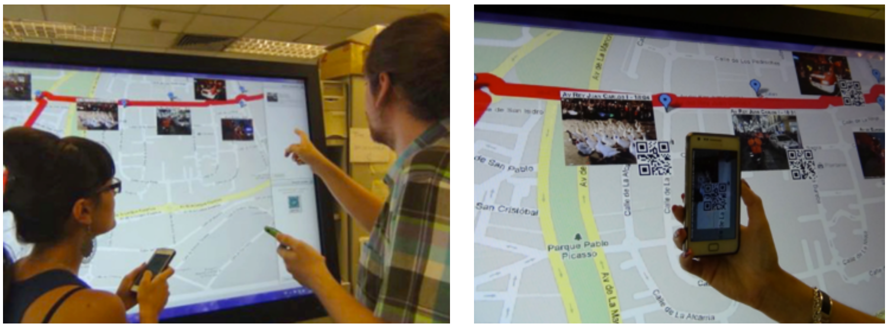


Figure 10: SharedViews, a map-based emergency planning system using vertical surface [30].

be found in two types of activities: group meeting and map based activities.

2.2.1.3 *Multiple shared surfaces*

When dealing with more complex data, only one shared surface may not meet the requirements to display all the information. In that case, multiple shared surfaces can be added into MSE. Using more than one shared surface is more suitable for the tasks that require complex data visualization and analysis. For example, Forlines et al. [48] use the combination of multiple large displays to adapt a single-display application, Google Earth. The tabletop shows a bird's-eye-view of a geospatial location; two vertical displays focus on the same geospatial location, but viewing it from the different point of views that are adapted to each display's orientation (Figure 11). The combination of these three large display creates a unique environment which provides the detailed and comprehensive geospatial information to the users. Tablets are also used with multi-shared surfaces to allow users to add private annotation and also operate the layers' menu individually without covering large portions of share shared tabletop.

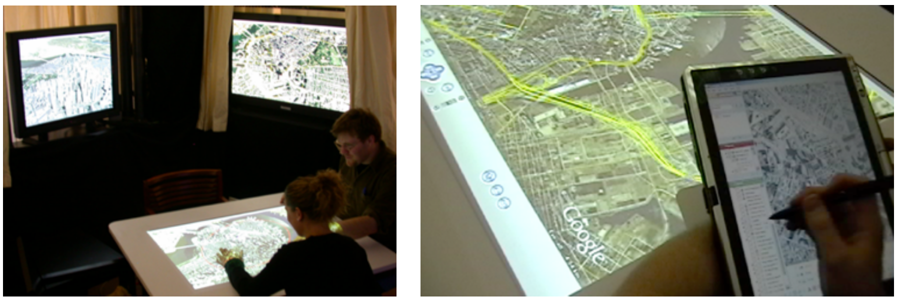


Figure 11: Google Earth application by Forlines et al. [48]

Emergency response is a complex process that involves communication and collaboration from multidisciplinary group of experts and requires the continuous analysis and monitoring of a number of information source and amount of data. Chokshi and his colleagues [22] developed ePlan Multi-Surface, a MSE for more complex emergency response planning exercises (Figure 12). They use both tabletop and wall display as the shared surfaces. In ePlan Multi-Surface, iPads are used by three different roles supporting individual planning activities, such as adding annotations; tabletop is used to integrate the role-specific plans and let users gather to discuss information before an action is taken and shared with the room; the big wall display is used as an information radiator to share factual information about the situation, such as map overview, areas under review by iPad application, live traffic cameras, new feeds, annotations, and messages, as well as an agreed upon plan.

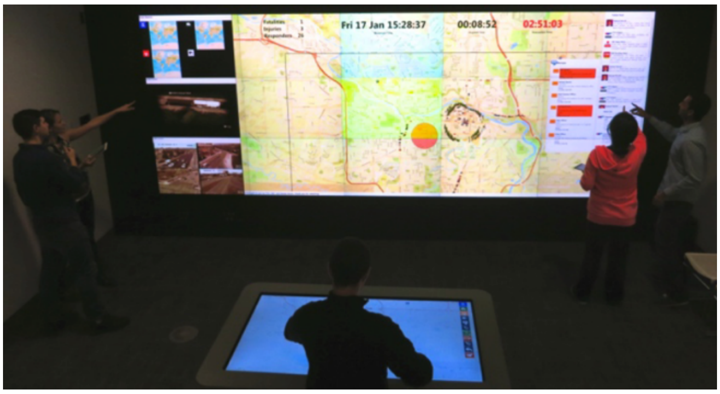


Figure 12: ePlan Multi-surface: an environment for emergency planning exercises [22]

Figure 13: An example of astrophysicists meeting in Wespace [154]

Multiple shared surfaces can also be used in group meeting situations in which several members gather together to share information and demonstrate their ideas. For example, Wespace [154] is a collaborative work space that integrates a large data wall with a tabletop which has been developed for a population of scientists who frequently meet in small groups for data exploration and visualization (Figure 13). The multi-touch tabletop acts as the group input and command center for visual exploration task and facilitating face-to-face collaboration. The large data wall provides two view modes to users: either displays different applications side-by-side or overlapped. What a user sees and manipulates on the tabletop has an identical visual correspondence on the wall. Wespace also allows users to bring their own personal applications and laptops to the shared surfaces.

Synthesis: all the systems that provide both shared and personal spaces adopt a similar strategy, which is taking the shared surface, whether horizontal or vertical, as group spaces where users can perform the collaborative process, such as **sharing information, exchanging ideas, discussing and negotiating**. While personal devices are always regarded as private spaces for performing the individual activity, such as **browsing detailed information, providing personal opinions and individual evaluation**. Users can change the digital contents on the shared surface by manipulating their personal device or simply pass information from one to another.

Both horizontal tabletops and vertical wall displays have their pros and cons. Tabletops allow more users to gather around without hindering the view of each other, whereas there may be problems with the orientation of contents shown to each user [86]. Wall display has the affordability for seeing the contents on it even from a distance. However, given the same size as tabletops, it allows less number of users to interact at the same time compare to the tabletop condition.

2.2.2 *Multiple shared surfaces*

Another configuration in MSE is having multiple shared surfaces without personal devices. This configuration can be used in the highly collaborative environment where the group work plays a crucial part.

For example, classrooms are one of the situation that may use this configuration. In the classroom setting, students are divided into small groups, and distributed a shared surface for group learning activity. The SynergyNet [63] project is an early example that has developed a classroom environment with networked multi-tabletop for elementary school students (Figure 14-left). The project aims to design collaborative learning environments where digital resources and information can be shared easily between learners and with teachers. The teacher can visualize, interact with and control each group's tabletop screen from the teacher console.

MTClassroom [102] is also a multi-tabletop environment that captures aspects of students' learning and interaction processes as they work in small groups (Figure 14-right). The system incorporates a connected wall projector that teacher can use to display the content of a specific tabletop to lead reflection at classroom level.

Figure 14: Two examples of using multi-tabletop in the classroom. Left: SynergyNet'project [63]. Right: MTClassroom [102]

Kharrufa and his colleagues [81] deployed a multi-tabletop environment in a school for six weeks. They analyzed the small number of authentic multi-tabletop deployments and helped characterize the technological and educational ecology of these classroom setting. They provided a three-dimensional framework (*planes dimension*, *space dimension* and *time dimension*) of design recommendations for future multi-tabletop applications designed for and deployed within the classroom.

Synthesis: these examples show that multiple shared surfaces is suited to situations where group work is highlighted, and there are no requirements for performing individual activities. All the discussions and information are supported by and displayed on the shared surfaces, shown to all the group members. In this setting, shared tabletops are normally used for completing group activity. And the wall display, if exists in the environment, would be controlled either by the teacher, or by the group meeting leader, used for demonstration and reflection.

2.2.3 *Multiple personal devices*

Former studies use typical MSE which integrate one or several large shared surfaces with or without personal devices in the environment. These settings are commonly seen in the indoor situation. However, due to the price and size, large surfaces may not always be at our disposal. Besides, they are also not suitable for the activities that involve lots of movements (e.g. outdoor activities). In that case, personal devices such as mobile phones and tablets will play the dominant part.

The emergence of connectivity and location services on mobile devices, first with WiFi then with iMode in Japan, then Edge and 3G elsewhere led to a number of experiments in mobile applications. These technologies allow mobile devices to be used in the outdoor environment meanwhile keep the connection with each other. Early examples include CYSMN [47], Human Pacman [21], Treasure [12], and Feeding Yoshi [16]. The primary motivation for creating such activities was to explore new types of engaging experiences in virtual worlds blending digital and physical elements [96].

The last configuration of MSE I would like to present is only using personal devices in environment where large displays are not available. In that situation, each user will have at least one digital device and need to share data across these personal devices. I regard that kind of environment as the type of mobile-based MSE.

Two early example of using mobile-based MSE in outdoor games are Savannah [44] and Treasure [12]. Savannah is an outdoor collaborative learning game in which students can use hand-hold computer to interact with physical world to develop conceptual understanding of animal (lions) behaviors (Figure 15-left). In Savannah, all the mobiles act as clients which are wirelessly connected to a PC-based game server. During the game, the server uses the information received from the mobile clients to determine what happens in the game and thus what the children/lions experience. Treasure is another example of an outdoor multi-player game which allows player to use PDAs to pick up virtual "coins" that may be scattered outside network coverage. Players can collaborate with their teammates to double the points given for an upload, and can also steal cons from opponents (Figure 15-right). Like in Savannah, players' PDAs run a game client and a PC is running the game server. In these two early studies, all the personal devices (clients) are connected to a server and used isolated as private spaces, these is not client-to-client communication.

Figure 15: Two examples of using mobile devices in outdoor games. Left: Savannah [44]. Right: Treasure [12]

Mobile devices can also be integrated together to create a large multi-surface tiled displays on which visual content can be shown on a larger area consisting (Figure 16). This kind of systems usually have the ability to discover the new devices brought into the huddle, and can adapt or extend the view automatically [89, 122]. Some studies apply that concept and create applications in that system, such as photo sharing [93, 110, 131], map navigating [89, 122], and video playing [90], etc. In these studies, mobile devices can be served both as personal devices and shared devices.

Figure 16: Two examples of combining presonal devices to form a large tiled displays. Left: HuddleLamp [122]. Right: JuxtaPinch [102]

2.2.4 *Synthesis of MSE configurations*

Table 1 synthesizes all the possible configurations in MSE that have been mentioned in this section. These collaborative activities in MSE, regardless the configuration, show that MSE can support divergent thinking and facilitate information pooling, especially in our current environment in which information is growing tremendously. Moreover, MSE also allows users to collaborate interchangeably and seamlessly using both shared and personal spaces which makes users more engaged in the task and have a better understanding of the current situation.

2.3 FRAMEWORKS AND AUTHORING TOOLS

Even though various studies have been done in MSE, creating multi-device applications is still a challenge. It involves building distributed interaction and also distributed interfaces. Significant efforts have been put by the HCI community in providing frameworks and design toolkits to mitigate this issue. The goal of such frameworks is to facilitate the development of applications that make use of and adapt to, the available devices in MSE [71].

One of the early examples is ICrafter [117], allowing user to flexibly interact with the devices or applications in the ubiquitous computing environment. Other works such as iStuff [10] offers rapid prototyping platform for multi-device interaction. However, the functionality in these early projects are limited, since they do not provide methods for state synchronization and resource modelling.

As digital devices are becoming increasingly common in recent years, more frameworks have been proposed and addressed that problem, such as VIGO [82] and Shared Substance [50]. However, this comes at the cost of changes in existing applications as developers need to adapt their applications to the new models. Other works leverage web technologies to develop web-based frameworks. For example, XDstudio [109] is a GUI builder allowing developer to dis-

		Shared					Personal		
		Horizontal	Vertical	Phone	Tablet	PC	Phone	Tablet	PC
Shared space with personal devices	HyperPalette [6]	■					■		
	Caretta [136]	■					■		
	BlueTable [148]	■					■		
	Poker surface [34]	■					■		
	PhoneTouch [123]	■					■		
	TIDE [131]	■					■		
	i-m-View [18]	■						■	
	Fei et al. [42]	■						■	
	Scott et al. [125]	■						■	
	Surface ghosts [126]	■						■	
	Bachl et al. [7]	■						■	
	SkyHunter [128]	■						■	
	MobiSurf [127]	■					■	■	
	SharedViews [27]		■				■		
	NiCE Discussion Room [58]		■						■
	Ubiquitous Graphics [122]		■					■	■
	Kerne et al. [75]				■		■		
	Virtual Projection [12]					■	■		
	Forlines et al. [45]	■	■					■	
	ePlan [20]	■	■					■	
	Wespace [147]	■	■						■
Only shared space	MTClassroom [96]	■							
	Digital Mysteries [76]	■							
	SynergyNet [60]	■							
Only personal devices	Savannah [41]						■		
	Treasure [11]						■		
	MobileVideoTiles [86]			■					
	Schmitz et al. [124]			■					
	Dynamic tiling display [85]			■	■				
	HuddleLamp [115]			■	■				
	JuxtaPinch [104]			■	■				

Table 1: A synthesis of MSE configurations.

tribute UI elements via drag and drop. Panelrama [157] supports the automatic distribution of user interface element containers (panels) across devices. The Tandem Browsing toolkit [62] provides developers with a declarative framework to define multi-device web pages. Finally, PolyChrome [9] supports the creation of collaborative visualization applications in MSE.

These frameworks or design toolkits provide a rapid and easy way for researchers or developers to design applications in MSE. However, they only provide technical solution for the application implementation, there is little support for orchestrating the scenario of activity in the educational domain. There are tools for scripting learning scenarios [4]. For example, the StoryTec [51] is an authoring tool for adaptive educational games which combine visual programming approach and high-level logic for authors. It provides a "drag and drop" creation method to create digital storytelling learning games which can be published both on PCs and smartphones. Digital Mysteries[1] [80] offers an authoring tool that allows teachers to create mysteries from scratch or edit existing mysteries. The eAdventure[2] [145] authoring tool is used for creating educational adventure video games which provides built-in assessment mechanism and supports for real-time adaptive learning scenarios. These authoring tools help users orchestrate pedagogical scenario and develop learning activities which can be run in a traditional digital environment, such as on tablets, PCs or tabletops. However, they do not consider the the interaction and interface distribution between devices which are the essence in MSE.

On the other hand, most of the former frameworks are aimed at people who have experience in programming or developing. There is no tool for non-experts to create off-the-shelf applications in MSE which is nonetheless needed. For example, it is difficult for teachers to develop the learning activities in MSE to fit their teaching goals. The design process of learning activities in MSE are always complicated and time consuming which requires the collaboration between teachers and developers.

To help non-experts develop learning activity in MSE, we need to consider a tool that aids on both technical and educational aspects. This tool should be used for implementing the distributed interface and interaction. It can also help users orchestrate learning scenarios. Therefore, providing an authoring tool that addresses these two issues is one of my PhD objectives. This tool can be used by teachers to create learning activity in MSE based on their teaching purpose. Moreover, it can also be helpful for researchers who want to develop learning activities in MSE to make choices and take decisions at an early stage to minimize the risks in the design and development pro-

1 http://www.reflectivethinking.com/digitalmysteries
2 http://e-adventure.e-ucm.es

cess. Researchers can shorten the time on testing ideas and implementing possibilities.

So far we have studied the definition of MSE, the possible configuration and the collaborative activities in MSE, and frameworks for cross-device application design. Nonetheless, there is still a lack of study on understanding users' actual collaborative behaviors in MSE which is so important as it can provide us the insights and recommendations on the future design of collaborative activities in MSE. Before we start to study users' collaboration, we firstly need to understand what the collaboration means.

2.4 UNDERSTANDING COLLABORATION

Collaboration has interested an increasing number of people from different fields [104]. To understand collaboration and study how to analyze it in MSE, the section presents the literature review in the fields of Computer Supported Cooperative Work (CSCW) and also Computer Supported Collaborative Learning (CSCL). In this section, I firstly synthesise the existing models and frameworks that explain computer supported collaboration. Then I extract several collaboration mechanisms from these models. I explain these mechanisms in details as they will serve an important role to study collaborative behaviors in MSE.

2.4.1 *Collaboration models*

In CSCW field, groupware is a general term that is frequently used for describing the applications that support groups activity. Ellis et al. [39] proposed the 3C model for the design of groupware to ensure the support for clear and fluid group interaction: *communication*, *coordination* and *collaboration*. Communication aims to integrate telecommunications and computer processing technologies to bridge the gaps between asynchronous world (e.g. electronic mail) and synchronous world (e.g. telephone) [39]. Collaboration is a cornerstone of group activity which demands that people share information. Coordination can be viewed as an activity in itself when participants are performing a task. It can enhance communication and collaboration. This original 3C model has evolved and been adopted to explain collaboration with some terminological differences [49]. *Collaboration*, which is denominated by Ellis, has been replaced by *cooperation* meaning characterizing a joint operation in a shared space. *Communication* is related to the exchange of a message and information among people. And *coordination* is related to the management of people, their activities and resources.

Similarly, Grudin and Poltrock [54] purpose that collaborative activity typically involves three core features: *communication between par-*

ticipants, *collaboration or cooperation in a shared information space*, and *coordination of the collective contributions*. Communication features enable people to communicate with one another. Shared-information-space features provide virtual places where people create and manipulate information which often include a shared repository to store and retrieve information. Coordination features facilitate interactions between or among participants.

Engestrom et al. [41] use the Activity Theory to explain collaborative activity, which also contains three core activities: *coordination*, *cooperation* and *communication*. Activity Theory is a psychological theory focusing on studying different forms of developmental processes of human work activity, which is suited for analyzing group activities [87]. Coordination represents the normal and routine flow of interaction. In coordinated work, participants act upon a common object, but their individual actions are only externally related to each other [11]. Cooperation means participants focus on a shared problem, but with distributing of labor, each performing one or more actions according to the overall goal. Communications are interactions in which participants focus on reconceptualizing their own organization and interaction in relation to their shared objectives. Both the object and the script are reconceptualized, as is the interaction between the participants [87].

These models share the idea that collaboration is composed of three areas: *coordination*, *cooperation* and *communication*. Thus, we build our model based on these models, to comprehend collaboration above these three areas. **Coordination** concerns the management of participants, their activities and resources [39]. In coordinated work, participants act towards a shared goal dealing with time and organizational constraints [98], but their individual actions are only externally related to each other. **Cooperative** work is accomplished by the division of labor among participants. Participants act towards a shared goal, but each performs specific and independent actions to achieve part of the overall goal [11]. **Communication** is related to the exchange of messages and information among people to reconceptualized their own organization and interaction toward their shared goal.

2.4.2 *Collaboration mechanisms*

The collaboration model provides an overview of composition of collaboration. However, these three areas (coordination, cooperation, and communication) are still high level and sometimes interlinked which do not provide an efficient way for collaboration analysis. In order to understand concrete behaviors of collaboration, researchers break down the collaborative behaviors to seek the core mechanisms inside collaboration.

Okada [114] proposed a multi-layered hierarchical model in 2007 to classify collaboration (Figure 17). The layers from top to bottom are: *collaboration*, *sharing*, *awareness*, and *conexistence*. Collaboration layer is on the top of model supported by sharing. The sharing layer retains discussing or exchanging opinions, information and work, which is supported by awareness. The awareness is related awaring of other participants, space and around objects. The coexistence is the basis which should be considered from the both the spatial and temporal dimensions. Coexistence is also referred as co-action in some works [111]. If the coexistence state is low, that means the level of awareness is also weak. In Okada's model, we are interested in *sharing* and *awareness* layers as they provide a concrete view of participant behaviors and can be the core mechanisms for analyzing collaboration. We assume that coexistence is the prerequisite of collaborative activity.

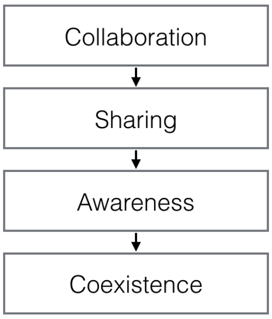


Figure 17: A hierarchical collaboration model from Okada [114].

Elmarzouqi et al. [40] propose the Augmented Continuum of Collaboration Model (ACCM) which has three outside layers: collaboration, cooperation and coordination; and several functional spaces inside: communication, conversation, coproduction, awareness and regulation. Even though this model is different from our collaboration model, the inside functional spaces are still interesting. It introduces two additional spaces: *regulation* and *awareness*. Authors explain regulation as a mechanisms that makes the participants to be organized in a shared environment.

Yull and Rogers [158] propose a model that is composed of three mechanisms to analyze collaboration around multi-user interfaces: *awareness*, *control* and *availability*. Awareness of others is the degree to which awareness of users' ongoing actions and intentions is present or made visible moment-to-moment. Control of action is the extent of each user's control over actions and decisions. Availability of information represents the ways in which background information relevant to user's behavior and to the task is made available or externalized. This model also has awareness which is mentioned by Okada [114] and Elmarzouqi et al. [40]. The control can also be related to regulation when the purpose of control is for regulating the behaviors. Availability of information is linked to sharing of information in Okada's model when the shared information is relevant to participants' behaviors.

These former models describe and interpret collaboration in various ways. However, they still have common mechanisms which might be represented differently. Based on the synthesis of the existing models, I extracted four collaboration mechanisms that underline interactions of users doing collaborative tasks and are also potentially linked to the usage of devices in MSE: *awareness*, *regulation*, *information sharing* and *discussion* which represents a sub-category of communication.

2.4.2.1 *Awareness*

I take awareness from Okada [114], Elmarzouqi [40] and Yuill [158]'s models. Awareness is a term used widely in the literature on shared workspaces which defined by Dourish and Bellotti [38] as "an understanding of the activities of other, which provides a context for your own activity". Benford and Eahlén [17] introduce the concepts of focus and nimbus to describe awareness. Nimbus refers to what people make available to other, whereas focus refers to what people can perceive from one's activity. Awareness involves knowledge of what others are doing, and how it fits within the larger activity which covers both high level tasks but also knowledge of physical and spatial arrangements of other participants [56, 59] that could be interpreted through various lenses. Location awareness represents knowing the partners' whereabouts [112], which may have impact on inferences about partners' intents and strategies [113], the division of labor [33], and the construction of a shared understanding of the situation [112]. Informal awareness (of one's community) is having the general sense of who is around and what others are up to the kinds of things that people track when they work together in the same physical environment [53]. Social awareness indicates a person maintaining awareness about others in a social or conversational context [57]. Workspace awareness is the most closely related to our MSE settings. It represents up-to-the-moment understanding of group member's interaction with a shared workspace that involves knowledge about what others are doing and what they are going to do next, rather than just about the workspace itself [57]. Workspace awareness focuses on tasks where groups manipulate objects and is limited to events in the workspace and ongoing interaction [66].

2.4.2.2 *Regulation*

Regulation is derived from Elmarzouqi et al. [40]'s model. It is also inspired from Roschelle and Teasley's work [128] when they talk about reducing conflict work and setting up strategies, and Yuill and Rogers's [158] model when consider about the constrains or relax control on tabletops to regulate participants contributions. Regulation represents the processes members use to plan, monitor, evaluate and regulate the joint activity [148]. It can also be regarded as an aspect for evaluating collaborative learning activity [150]. For Hadwin et al. [59], regulation could be classified into self-regulation, co-regulation and shared social regulation based on the constructivist perspectives of learning. Self-regulation is individual behavioral processes that a learner uses to direct and control towards completion of an academic goal [160]. Co-regulation are interactions or dynamic processes between two or more peers that coordinate self-regulation learning processes [59]. Shared social regulation are interdependent or collectively shared regulatory processes groups use to regulate their joint work on a task [148]. It involves multiple members constantly monitoring and regulating the joint activity, which cannot be reduced to mere individual activity [150]. The shared social regulation is the main focus of our study when analyzing collaborative activities in MSE as we focus more on collective behaviors and group goals instead of individual ones.

2.4.2.3 *Information sharing*

Information sharing is mainly inspired by Okada's "sharing layer" [114] in which information has broader meaning including opinions and also works. It is also inspired from Poltrock and Grudin [116] who named an aspect of collaborative activity information sharing. Information sharing is required to initiate a collaboration process. It involves building a common ground [23], which means that members collaborate in ensuring understanding and in grounding their mutual knowledge and assumptions. In MSE, information sharing is an important aspect we should pay attention, as the variability and flexibility of MSE can highly influence the way participant performing sharing behaviors, which in turn will have an impact on their collaboration. By using different combination of devices and applying different interaction techniques, participant may sharing information in different patterns, such as only sharing information verbally, passing the digital object from on device to another, or simply sharing or exchanging their devices.

2.4.2.4 *Discussion*

Discussion is not mentioned directly in former models. However, it is linked to communication which is on the higher level of collaboration model. Communication is the basis of collaborative activities and exists almost in all the collaboration models, either explicitly [40, 116] or implicitly [11, 114, 128]. However, communication itself is such a broad term that it can be involved in other collaboration mechanisms when participants are performing them verbally. For example, it would happen when participants are talking about the strategies, narrating for sharing information, or enquiring to maintain awareness. In order to be more precise and clear when analyzing collaboration, I choose to focus on discussion which is a specific type of communication, especially the discussions that are taken to reach a decision. In this dissertation, I define discussion as a process of talking among people to exchange ideas and reach a consensus based on the available information. It happens when participants are collecting and evaluating arguments for and against the available options, and taking decisions for alternatives on the way to a final solution. Discussion always requires information sharing to begin.

These four mechanisms can be analyzed as standalone behaviors. They can also be considered as interlaced or consequential behaviors, as one mechanisms could lead to another (e.g. a goo level of awareness may causes regulation and discussion). Table 2 shows the hierarchical model of collaboration. The top layer is collaboration and its three areas: coordination, cooperation and communication; the bottom layer contains four core mechanisms: awareness, regulation, information sharing and discussion.

Collaboration			
Communication	*Coordination*	*Cooperation*	
Collaboration mechanisms			
Awareness	*Regulation*	*Information sharing*	*Discussion*

Table 2: The hierarchical model of collaboration.

2.5 ANALYSIS METHODS OF COLLABORATION

In the former section, I clarified the model of collaboration and its mechanisms. To analyze collaboration in MSE, we also need to link these mechanisms to the digital environment, such as how the devices help participants maintain awareness, how they use the devices to regulate behaviors, share information and discuss, and how their movements and positions around surface(s) influence these collaboration mechanisms. In this section, I am going to illustrate analysis methods of collaborative mechanisms used in former studies, and also analysis methods of participants' physical movements and positions in the environments that are equipped with surface(s).

2.5.1 *Analyzing awareness*

One common way to analyze group awareness consists in observing participants behaviors during the task performance or from recorded videos. Some indicators have been defined to facilitate the analysis of awareness. These indicators are related to participants' attention and the effort that they make to maintain a good understanding of partners' actions. For example, to compare users' collaboration between vertical and horizontal shared surfaces, Roger and Lindley [126] analyzed participants' awareness by observing their gaze towards the screen; the talk to maintain awareness, such as when participants raise their voices and speak aloud about what they were planning and writing; and body movements when they are turning to face to other, peering over other members' shoulders, or moving to the side of the display. Time taken to respond to a partner's action is also an indicator to analyze awareness, like Ha et al. [58] did when they investigate participants' collaborative interactions around a tabletop display using different type of input device (stylus, mouse, and touch-based interactions). The shorter response time indicates a higher level of awareness. They also noted the "collisions" behaviors as a lack of awareness when two participants performing tasks together unnecessarily.

When using multi-touch surface for collaborative tasks, more indicators for awareness should be considered, as participants can interact at the same time. Hornecker et al. [66] derive a set of awareness indicators from the literature to compare the awareness level using two kinds of input in tabletop environment: multi-touch and multiple mice. They define two negative awareness indicators: *interference* and *verbal monitoring*. *Interference* means "unintended negative influence on another user's actions". It is similar to "collision" that Ha et al. defined in their work [58]. *Verbal monitoring* happens when participants "resort to more explicit mechanisms for coordination such as asking what the other is doing that can interrupt the flow of action".

The positive awareness indicators include *reaction without request*, which means "participants react to and assist each other in response to something without being explicit asked for help"; *parallel work* is "coordination of activity or division of labor without previous negotiation or allocation of activity"; *complementary actions* happens when two people work together, one continuously performs the action of the other; and *object handover* when two people handovers objects on a smooth trajectory without interruption.

Verbal shadowing is the awareness work which happens when one is describing what s/he is doing to others without being asked. It can be used to assess the practices by which awareness is maintained in both self and others. The awareness work also consists of raising voice and body movements that mentioned in Roger and Lindley's study [126].

Besides video analysis, questionnaires can also be used for accessing the level of awareness. In the study of comparing single and multiple displays for group work, Wallace et al. [151] used questions about how aware participants were of their collaborator's actions, and how aware they felt their collaborators were of their own actions. When comparing level of awareness using different techniques, the question can be how well the different techniques helped participants stay aware of others' actions [8, 115].

As questionnaires, interviews have also been used as an additional way for understanding participants behaviors and getting more feedback. It provides a direct way to know about participants experience and get qualitatively access. For example, in the study of comparing users' collaboration in MSE using different size of shared surfaces, Zagermann et al. [159] interviewed participants and asked how they were aware about partners' activity in different conditions.

In this dissertation, we are mainly inspired by the set of awareness indicators defined by Hornecker et al. [66], as they are well considered and suited for analyzing behaviors in the environment of multisurface. Table 3 synthesis the indicators for analyzing awareness.

2.5.2 *Analyzing regulation*

Regulation gathers the processes involved in planing, monitoring, evaluating and controlling joint activities. It occurs during interactions between group members as well as their interactions with the digital environment. The border between regulation and awareness is sometimes vague. Awareness can lead to regulation, and results in discussion. For example, *verbal monitoring*, the awareness indicator defined by Hornecker et al. [66] which means one asking another what s/he is doing, can also be taken as regulation. Regulation could transit to discussion. As awareness, regulation can also be analyzed by observing participants' behaviors during the task such as analyzing how participants take roles and distribute the labor [103], and examining how participants elaborate strategies [159].

Rogat and Linnenbrink-Garcia [125] proposed a video observation and coding protocol for analyzing social regulation in collaborative activities, which is also used by Evans et al. [43] when studying students' collaborative learning processes around a tabletop in an authentic classroom setting. In this protocol, Rogat and Linnenbrink-Garcia analyzed the social regulation from three main categories including *planning*, *monitoring*, and *behavioral engagement*. Planning is referring to *reading and interpreting task directions, designating task assignments, discussing how to go about solving the problems*. Planning has two subcatetories: task planning and content planning. Monitoring represents *evaluating content, understanding the shared product, assessing progress, or plan for completing the task*. Monitoring processes also have sub-categories, referring to which aspect of the collaboration was being monitored, including monitoring content, plan and progress. Behavioral engagements means *encouraging an off-task group member to*

Data source	Categories	Indicators	Ref
Video	Negative	Interference / Collisions	[66]
		Verbal monitoring	
		Long time taken to respond to a partner's action	[58]
	Positive	Reaction without request	[66]
		Parallel work	
		Complementary actions	
		Object handover	
		Focuses on shared surface	[126]
		Short time taken to respond to a partner's action	[58]
	Awareness work	Verbal shadowing	[66]
		Raise voice and speak loud	[126]
		Body movements (turn to face to others; peer over shoulders; move to display)	
Questionnaire & Interview	How aware participants were of their partners' actions? How aware they felt their partners were of their own actions? How well the different techniques helped participants stay aware of others' actions?		[8] [115] [151] [159]

Table 3: Indicators for analyzing awareness

re-engage, reminding a group member to return to task. Table 4 shows the indicators that can be used for analyzing social regulation.

Categories		Indicators	Ref
Planning	Task	Agree to a plan; revisit the plan	[43] [125]
	Content	Evoke task relevant content knowledge to inform thoughtful task work	
Monitoring	Content	Explain, justify to enhance conceptual understanding	
	Plan	Clarify task, identify next steps, modify the plan	
	Progress	Identify accomplishments, recognize what remained to be completed	
Behavioral engagement		Make suggestions to involve group members in the task	

Table 4: Indicators for analyzing social regulation.

2.5.3 *Analyzing information sharing*

Information sharing aims to build a common ground and the mutual knowledge. The analysis of information sharing can focus on two aspects. One is verbal information sharing or narration, which means one passes unknown or unclear information to another verbally, such as reading out the contents on the device loudly. For example, Rogers and Lindley [126] observed that interactors sometimes read out information they had accessed from the displays to others.

The other aspect is linked to the digital environment, which is to study participants' interaction with devices when they want to share digital objects or contents with another. I cal this type on-device information sharing. We can analyze on-device sharing from participants' interaction with the devices and their position and body orientation. For example, Zagermann et al. [159] analyzed how participants share the digital documents when they have both shared and personal devices at hands by observing their manipulation on devices. Seifert et al. analyze how participants share information using devices for collaborative web searching [134]. They analyzed participants' body gestures for information sharing such as one turning the device towards the other, or one leaning over the other to share the device. Table 5 summarizes these two categories of information sharing and indicators for video analysis.

Categories	Indicators	Ref
Verbal sharing	Read out information to others	[126]
On-device sharing	Share/pass digital information/ document to others	[159]
	Turn the device towards the other; lean over the other to share the device	[134]

Table 5: Indicators for analyzing information sharing.

2.5.4 *Analyzing discussion*

Discussion analysis can indicate the distribution of each user's participation, the efficiency of the communication, and the productivity and the outcome of the task. As I stated in the former subsection (Section 2.4.2.4), I focus on the discussion which happens when people exchange ideas and reach a consensus based on the available information. The indicators of discussion are derived from Fleck et al.'s [46] when they analyzed children's collaboration around a multi-touch tabletop. Fleck et al. defined three types of collaborative discussion: *negotiating*, *making and accepting suggestions* and *maintaining joint attention and awareness*. In this dissertation, I take the first two types: negotiating, and making/accepting suggestions. The last one, maintaining joint attention and awareness, is already covered by awareness mechanism.

Researchers have used different methods to analyze discussion. To have an overview of participants' discussion, such as how many discussions are performed, one common method is to calculate the number or duration of utterances. For example, Rogers and Lindley's [126] counted the number of suggestions made per group during the task when they compare collaborative work between horizontal and vertical conditions. Seifert et al. [134] and Potvin et al. [118] calculated the duration of verbal utterance of each participant during the collaborative task.

Counting speaking turns and proportion can help understand verbal participation distribution. For example, Marshall et al. [101] counted the turn taken during the conversation of each participant when they compared equality of participation using different configurations of input around a tabletop. Potvin et al. [118] calculate the proportion of speaking time by the less talkative person to get the equality of verbal participation.

We can also link discussions with participation gestures and the way they use devices to better understand how the design of applications support group discussion. Fleck et al.'s [46] link both verbal and physical aspects to demonstrate how participants perform discussion around a tabletop. They provide several patterns when participants are discussing. For example, when a participant is making verbal suggestions and giving opinions, s/he may use gestures such as pointing at tabletop icons to ground talk, or demonstrate ideas by moving icons. Or when one is disagree with the other and tells the other to stop, s/he may knocking hands out the way, or shielding an area of the tabletop.

To sum up, discussion can be analyzed by calculating the duration or the number of utterances, the speaking turns, the proportion of speaking time, and also the gestures or interactions on devices participants are performing during the discussion, based on the aspects we are interested in. Table 6 shows indicators and methods for analyzing discussion.

Categories	Indicators	Ref
Nature of discussion	Negotiating	[46]
	Making/accepting/rejecting suggestions	
Acts of discussion	Number/duration of utterances	[118, 126, 134]
	Speaking turns	[101]
	Proportion of speaking time	[118]
	Gesture or interaction on devices	[46]

Table 6: Indicators for analyzing discussion.

2.5.5 *Analyzing collaborative position*

Groups can have different positions in MSE when using different configurations and performing different tasks. These positions, and also the transition between two positions can potentially influence users' collaboration. Analyzing groups' positions and movements during the collaborative activity is also an approach to understand their collaboration.

Proxemics [60] relates to the study of spatial relationships between people, and how physical positions and body movements shape human behavior. It is one of the seminal theories about people's perception and use of interpersonal distances to mediate the social interactions. Hall [60] defined four proxemic distances: intimate and personal distances within arm's reach, social and public distance beyond that. Proxemics is used as an analytical tool in HCI, and received renewed attention when considered as a tool to derive interaction heuristics for context awareness, or to inspire novel interaction techniques [99].

For instance, Prante et al. [119] defined three "zones of interaction" in front of wall displays, depending on the distance of users to the screens. These zones can be used to trigger or disable different types of interactions and display different information at different levels of detail. Another example is Vogel's public ambient display [149] which defined four zones with fluid inter-phased transitions to offer different interactions, from distant implicit public interaction to up-close explicit personal interaction: Ambient Display, Implicit Interaction, Subtile Interaction, and Personal Interaction (Figure 18).

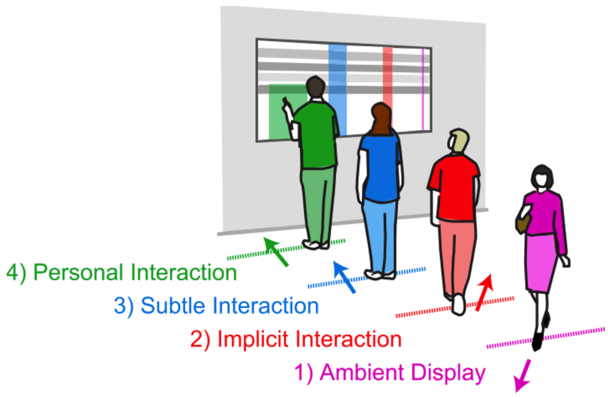


Figure 18: Vogel and Balakrishnan's four interaction phases based on the distance between the user and the wall display [149].

Proxemics primarily focuses on the impact of distance on the perceptions, such as the distance among people, or between devices. F-formations [78] further consider on a macro-level the physical arrangements that a small group adopt when they engage in a shared activity. It describes how people adjust their position and orientation to interact together and jointly manage their attention [78]. A typical F-formation arrangement is roughly circular and contains three concentric spatial domains (Figure 19-left). The innermost space, the o-space, is an internal interactional space where explicit actions are carried out and can be easily captured by participants. The p-space is the area occupied by the participants themselves. The r-space is the surrounding space outside of p-space, which can be considered as a kind of buffer between the group and the outside world. F-formation can be used as lens to analyze collaboration, such as which arrangement of F-formation is linked to which kind of collaboration mechanism, or in which space interaction happens shapes the F-formation and thus the interaction between participants.

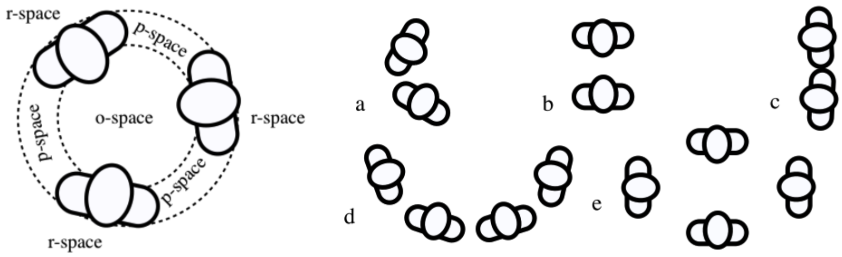


Figure 19: F-formation arrangements. Left: A circular three person F-formation. Right: some different F-formation configurations from Marshall et al. [100].

For instance, Marshall et al. [100] observe F-formation and social interactions inside a tourist information center (Figure 19). They come to the conclusion that discussions between more than two individuals were actually quite uncommon. Marquardt et al. [99] devised new multi-device interaction techniques for mobile devices based on preliminary laboratory studies of F-formation. They find out that in their design of task, participants usually stay in a side-by-side formation during the study, facing slightly inwards towards the o-space.

Tang et al. [144] study *collaborative coupling* over tabletop displays from the aspect of how collaborators are involved and occupied with each other's work. They identify six typical collaborative coupling styles based on the goal, space and view that participants are sharing: *same problem same area*, *view engaged: one working, another viewing in an engaged manner*, *same problem, different area*, *view: one working, another viewing*, *disengaged: one working, another disengaged*, and *different problems*. They investigate collaborators' F-formations around the table (Figure 20).

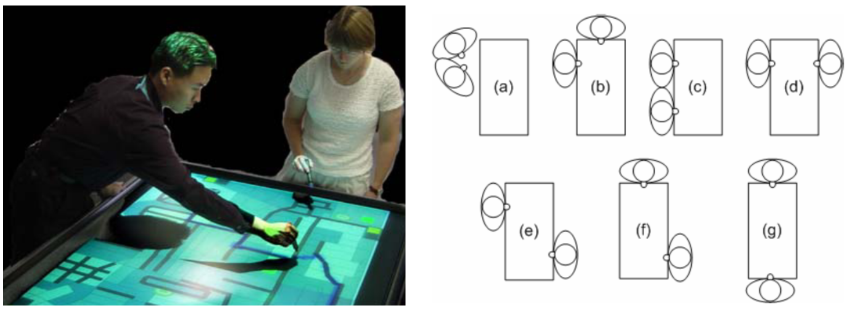


Figure 20: Users' position arrangements found around the tabletop (based on relative position): (a) together, (b) kitty corner, (c)side by side, (d)straight across, (e)angle cross, (f)end side, and (g)opposite ends.

AlTarawneh et al. [3] study collaborative position patterns for pairs of users working in a MSE which integrates a shared wall display and multiple mobile devices. They focus on their analysis on users' *eye contact*, *looking*, *talking*, and *talking & looking*, and identify six collaborating position patterns (Figure 21). They find out that participants preferably choose to stand faraway to maintain their own space, and pairs who were standing next to each other communicate more compared to those who were standing far from each other.

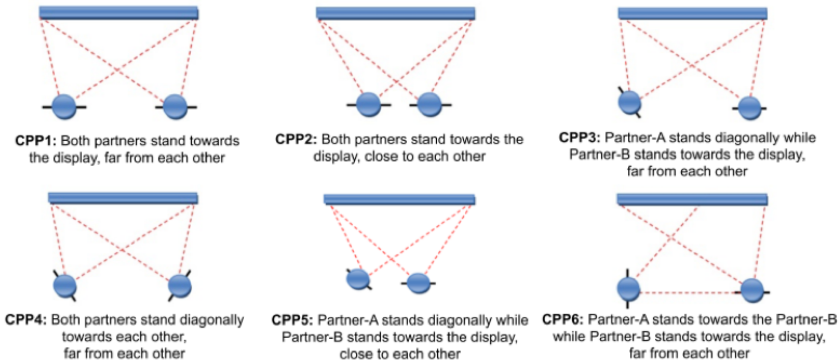


Figure 21: The six collaborating position patterns from AlTarawneh et al. [3].

2.6 POSITION OF THE WORK

2.6.1 *MSE configurations of interest*

In the beginning of this chapter, I presented MSE and introduced their possible configurations. I summarized three kinds configurations: shared surface with personal devices, multiple shared surfaces without personal devices, and multiple personal devices without a shared surface. Besides, devices used in MSE can also have different form factors, such as different size (big or small) and different orientation (horizontal or vertical). The first objective of this work is to study how the different configurations and form factors of devices shape users' collaboration, then provide design implications for collaborative activities in MSE.

Among these different kinds of configurations, I am interested in using the combination of shared surface and personal devices, and also using multiple personal devices without a shared surface. The first configuration can be used for indoor collaborative activities that requires both collaborative and personal tasks. I want to study how people behave when using the combination of shared and personal devices, and how the orientation of the shared surface impact their collaboration. The second configuration, using multiple personal devices, is more suited for outdoor collaborative activities. I want to understand how students perform tasks and collaborate in a highly mobile environment when using mobile devices. And in the end, based on these studies, to provide suggestions and design implication for collaborative activities in these two specific configurations of MSE.

2.6.2 *Collaborative activities of interest*

Various kinds of collaborative activities have been designed in MSE, from urban planning [143], to basin (oil/gas) exploration [135], to emergency response planning [22]. These collaborative activities frequently involve problem-solving and/or decision-making processes. Problem-solving is the process of *perceiving and resolving a gap between a present situation and a desired goal, with the path to the goal blocked by known or unknown obstacles* [69]. Decision-making is the process of gathering information, identifying and weighing alternatives, and selecting among various alternatives based on value judgments [146]. Sometimes, the steps in the process of both problem solving and decision making are similar and interchangeable. A problem-solving process may consist of a large number of smaller decision-making processes [84].

Educators have highlighted the importance of collaborative problem-solving and decision-making skills in education, especially in scientific courses. The process of critical analysis of information is helpful for the co-construction of knowledge [42, 52, 65]. Solving complex problems and making reasonable decisions in science courses involves many aspects of critical thinking, such as understanding procedures for rational analysis of a problem, gathering and using of available information, clarifying the concerns and values raised by the issues, coordinating hypotheses and evidence, evaluating the relevance and relativity of evidence, weighing multiple alternatives and making choices by considering and respecting different viewpoints [123, 139]. All these aspects can help students to increase understanding, learn to face problems and challenges, clarify issues, and identify solutions.

MSE appear particularly well suited for collaborative problem-solving and decision-making processes. Large surfaces can provide a high visual bandwidth for sorting and organizing notes, and support for cognitive offloading, increased shared awareness [76]. It can be used for prioritizing information, making comparisons, and structuring data that embodies the working hypotheses [151]. Personal devices can provide individual and mobile spaces, which are used to simultaneously control and exploit additional information [134].

With all these concerns, I choose collaborative problem-solving and decision-making activities as the focus of this work, especially decision-making activities for learning.

2.6.3 *Design and analysis of collaborative activities in MSE*

As I mentioned in the Chapter 1, my overarching research goal is to facilitate the design and development of collaborative activities in MSE. To do so, I need to understand how MSE can effectively support users' collaboration in general, and collaborative learning specifically. I studied how users collaborate in problem-solving and decision-making activities using the two MSE configurations of interest. I design two problem-solving activities: an outdoor orienteering learning game using multiple mobile devices (Chapter 3), and a trip planning activity using a shared surface and multiple tablets (Chapter 4). These two problem-solving activities also contain smaller decision-making process. Besides, I designed a decision-making learning activity using a shared surface with personal devices (Chapter 5).

In these activities, I studied users' collaborative behaviors by analyzing the four collaboration mechanisms that I synthesized in this chapter: *awareness, regulation, information sharing,* and *discussion*. I linked the analysis of these four mechanisms with the device usage and the application design in order to provide design implication for collaborative activities in MSE, such as how application design can raise group awareness, support social regulation, facilitate information sharing, and promote discussion. I also studied the relationship between F-formations and collaboration mechanisms in order to understand how collaborative behaviors shape group position and movement, which in turn impact collaboration per se.

Finally, as I mentioned in Section 2.3, designing and developing collaborative activities in MSE is quite complex and time consuming, especially for teachers who have no programming experiences. Therefore, I provide an authoring tool (Chapter 6) based on the experience of decision-making activity design and understandings of students' behaviors presented in Chapter 5, an in-depth analysis of decision-making models, and our discussions with teachers. This authoring tool can be used by people without programming experiences, such as teachers, to easily create collaborative decision-making activities in MSE.

3 MOBILE CONFIGURATION FOR COLLABORATION IN OUTDOOR MSE

This chapter focuses on the study of a collaborative problem-solving activity within multiple personal devices configuration. It describes the design of an orienteering mobile learning game which involves four groups of three students all equipped with tablets. It shows how students collaborate while using tablets. The data analysis deepens our understanding on students collaborative behaviors in an outdoor activity by demonstrating the relationship between group spatial configurations (F-formations), device usage and collaboration mechanisms. In the end, this chapter provides design implications for collaborative activities to better support collaboration, and how to analyze users' collaboration behaviors in a multiple mobile environment.

3.1 OVERVIEW AND OBJECTIVES

Personal devices, such as smartphones and tablets offer great opportunities in the field of collaborative learning. They are especially interesting in their ability to provide digital information while still supporting social interactions between group members. Early work have shown that mobile multi-player learning can be leveraged to minimize constraints of time and place in learning environments [70]. It can provide better context awareness and more situated learning, facilitate the organization of conceptual information, support the contextualization of the knowledge being developed, enhance students' social skills, and increase their self-efficacy, motivation and confidence [68, 70, 83, 147]. However, in truly mobile conditions, e.g. outdoors, the high variability of groups spatial configurations can potentially modify collaboration mechanisms. Not as in a fix classroom setting, students may apply different ways to maintain awareness, regulate behaviors, share information and discuss.

The objective of this chapter is to study how students use multiple personal devices to collaborate and accomplish problem-solving tasks. To achieve that objective, we design an outdoor collaborative learning game using multiple tablets, and conduct a study to understand students collaborative behaviors during the game. We analyze how the usage of personal devices and F-formations shape collaboration in highly mobile conditions. In the end, we provide design implications on multiple mobile activities for learning based on these understandings.

3.2 DESIGN OF AN ORIENTEERING GAME

To study how device usage and users' spatial arrangements shape collaboration in real condition, we design and develop an orienteering learning game for a high school from La Martellière (Voiron, France),

3.2.1 *Pedagogical objective*

We co-design the game with with a group of high school teachers (Figure 22). The pedagogical objective is to make students aware of sustainable development principles in a pluri-disciplinary approach. The game requires knowledge from biology, earth science, geography, chemistry, physics and information science. Through the game, students learn how to handle several measuring instruments (e.g. anemometer, luxmeter, thermometer and nitrite test strips), how to understand biotic characteristics of the environment and how to analyze geographical data (maps interpretation). In this context, mobility was important to support skill acquisition as it enables using contextual information and richer interactions among students.

Figure 22: Design process of the orienteering mobile learning game.

3.2.2 *Game play*

The game is a multi-player and multi-role game. It takes place in the Chartreuse Mountains (French Prealps), near the high school. Students have to discover four areas where to collect biotic data (magenta markers on the map Figure 23). To access to these locations, students have to solve scientific puzzles related to the areas identified previously (biology, geography, etc.). Several control points (orange markers on the map, Figure 1) are inserted between the four locations. Students are guided to these control points progressively. When they start the race, only the first control point is visible on the map. At each control point, participants have to find a QR code, which reveals the next control point location and gives students the opportunity to unlock clues by answering a puzzle covering one discipline.

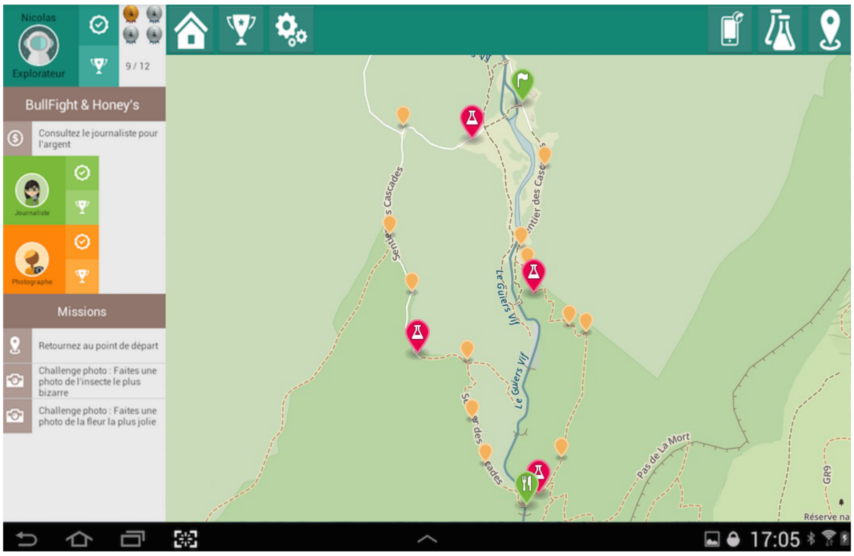


Figure 23: Game map on explorer's tablet (when all the locations are unlocked).

To favor rich interactions between group members, the game includes collective activities linked to data gathering skills. To encourage social interactions within groups when using measuring instruments, we introduced three levels of skills: novice, apprentice and expert. These levels are associated to each instrument and represented as badges in the game. At the beginning of the game, each student is considered expert on a specific measuring instrument (which they learned before in class). Hence, for each group, there is one expert on anemometer, one expert on luxmeter and one expert on both thermometer and nitrite test strips. During the game, each expert has to share his/her expertise to his/her group so that all the members can acquire knowledge (and badges) on all the measuring instruments and become expert by the end of the game.

We introduced a competition mechanism between groups through a scoring system. The groups earn points when they solve the puzzles. Answering correctly on the first try earns the group the maximum amount of points (500 points), a fewer amount (200 points) on the second try and finally a minimum amount (50 points) on the third or more tries. At the end of the game, the group with the highest total score wins the game. In addition, to maintain participants' engagement during the orienteering game, several "fun" challenges are added such as taking picture of the most beautiful flower and bizarre insects during the race. At the end of the game, back to school, students and teachers vote for the best pictures, and the winning group earns "best picture" rewards.

3.2.3 *Collaborative activities*

A group consists of three members. We defined three different roles for each group: the photographer, the explorer (Figure 23) and the reporter. The group should work together to reach a shared goal corresponding to the main mission and "fun" challenges. The main mission consists in finding out all the hidden locations, solving scientific puzzles and collecting data using the measuring instruments. Each role is associated to a specific measuring instrument and players have to perform specific actions that the others can't do. This pushes participants to cooperate and develop collaboration mechanisms during the orienteering race. The explorer is the one who is responsible for guiding her/his group. S/he has the map on her/his tablet. S/he is expert on the anemometer. The photographer can scan the QR codes unlocking the next step. S/he is also in charge of taking pictures. S/he is expert on the luxmeter. The reporter has to manage the puzzles and hints on her/his tablet. S/he is in charge of entering the answers and is the one aware of the team score. S/he is expert on both the thermometer and nitrite test strips.

3.2.4 *Synchronization flow*

Due to the lack of connectivity in the mountain, we didn't integrate data communication across devices, but preferred to develop a simple synchronization mechanism. Participants share verbally unlock codes that they get during the activity (scanning QR codes) in order to synchronize tablets and unlock parts of the game. At the beginning of the game, the reporter receives on his tablet the first puzzle and the explorer guides the group to the first control point to find a QR code (Figure 24, #1). When they find one, the photographer scans it to get an unlock code. S/he needs to pass the code to two others who will type the code into their tablets to update their missions (Figure 24, #2). Entering the code, the explorer gets coordinates of the next control point and the reporter receives a hint for the current puzzle. Once they get all the clues, they answer to the puzzle (Figure 24, #3). Once the reporter enters the right answer, the group earns a number of points, and the reporter also gets a code to update the tablets (Figure 24, #2). This unlock code will reveal the measuring location on the explorer's tablet which can guide them to this point. On the measuring area, students only need to perform the required measurements and collect biotic data (Figure 24, #4). After inputting data into their tablets, they can earn badges associated to their expertise on each measuring instruments responding to several quizzes. Then, their tablets are synchronized again (Figure 24, #2), the explorer getting the location of the next control point and the reporter the new puzzle to solve.

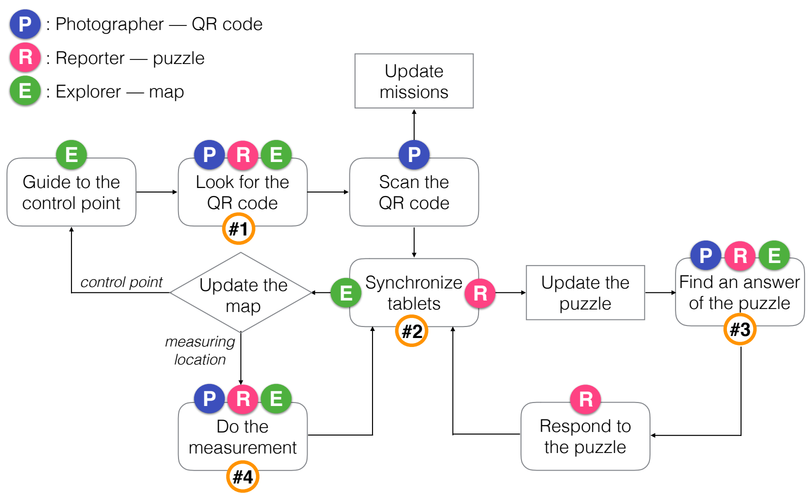


Figure 24: Game flow.

3.3 STUDY

We conducted the experiment in collaboration with a high school involved in the project.

3.3.1 *Participants*

We recruited four groups of three students, eight females and four males, aged from 16 to 17. The groups were already set before our experiment, which was part of a larger paper-based learning game. Participants were from the same class. Four teachers also participated to the outdoor activity as tutors and for safety reasons. Students knew each other and were comfortable working together. The teachers also knew the students.

3.3.2 *Training*

The afternoon before the orienteering session, we arranged a preparation session with all the participants. Students were already familiar with the game world from the larger paper-based game; so we mostly handed out tablets to let them become familiar with the game mechanics on the tablet, discover the different roles we introduced, and let students pick a role of their choice.

During the preparation phase, students conducted an informal mission in an open field on the campus. They learned how to use the measuring instrument related to their role in order to become "expert" in its use. Teachers gave them guidance on how to use these tools and explained them the principles behind the measures. Students were free to ask questions to their teachers. They also practiced inputting biotic data and synchronization codes on their tablets.

3.3.3 *Orienteering game*

We conducted the study itself following the game structure described in the previous section. Groups started the game ten minutes after the other to limit overlap in the activities. The whole session took about 2 hours and 40 minutes.

3.3.4 *Apparatus*

We used 12 Android tablets with protection cases, i.e. one per student. All had a resolution of 1280x800 pixels, 10 were 8″ Samsung Galaxy Note 8, and two were 10″ Acer Iconia Tablets. The two larger tablets were used by explorers.

3.3.5 *Recording*

During the experiment, one teacher and one person from our research team followed each group to supervise and film the group activity. The students and their legal tutors (i.e. parents) all agreed to the recording. The participants also filled in a survey back at the high school.

3.3.6 *Analysis method*

One researcher went through the video recordings of the four groups twice. In the first round, she browsed the videos to select segments containing collaborative behaviors. In the second round, she examined these segments in details, marking down when collaboration mechanisms took place. Overall the segments lasted 287 minutes (group 1: 86 min, group 2: 63 min, group 3: 75 min, group 4: 63 min). This first part of our analysis consisted in analyzing the collaboration mechanisms at play in the game. We analyzed students' gazes, gestures and conversations to classify these mechanisms according to the definitions presented in the related work, including regulation, awareness, information sharing, and discussion.

Once we had identified these mechanisms, we focused our analysis on whether some mechanisms led participants to position or orient themselves in specific arrangements; we also looked more precisely into tablet use and micro-mobility. To do so, two researchers scripted in detail one video segment to agree on a coding scheme, the relevant F-formations and the use of tablets (number of tablets used and their orientation according to users) for each identified mechanism. The main researcher also wrote a transcript of the verbal communication on the videotapes, proofread by the second.

3.4 RESULTS

3.4.1 *Observed F-formations*

Kendon [78] described three types of F-formation for groups of two persons: L-shaped, face-to-face and side-by-side (Figure 25, top), and he added a circular F-formation arrangement for groups of more than two persons. Marshall et al. [100] added two more arrangements for groups of four persons: semi-circular and rectangle.

In our study, the groups are composed of three students, we noticed three main types of F-formations arrangements: semi-circular, circular and triangular (Figure 25, bottom). These arrangements can be influenced by the on-going task, and also by environmental features. Given the mobile nature of the activity, compared to the F-formations described in the HCI literature, the F-formations we observed were highly dynamic. Both within the formation, for example students would keep their formation but move in the same direction, or all rotate at once; and also moving quickly from one formation to another. A transition from one formation to another often indicated a change of the focus in the on-going task.

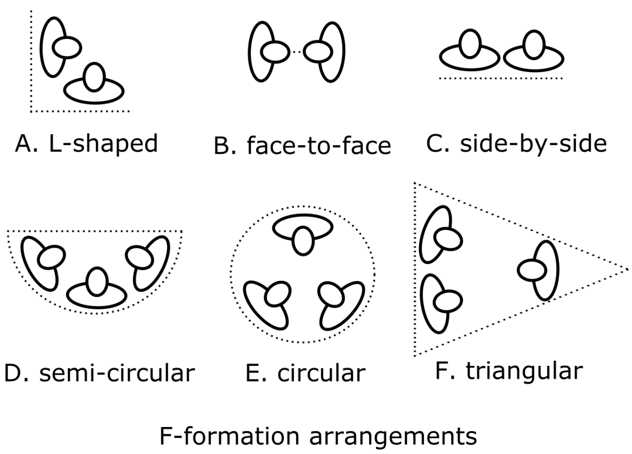


Figure 25: F-formation arrangements. A.L-shaped; B. face-to-face; C. side-by-side; D. semi-circular; E.circular; F. triangular.

The triangular arrangement happened when two students were standing close to each other on one side with a third student staying on the opposite side at some distance from the others. This arrangement is often caused by an unequal distribution of action. For example, when the photographer got an unlock code; s/he usually preferred to read it out to her/his group members before coming closer to them. S/he was standing alone, in control of the action, while facing the others. The triangular arrangement was rarely maintained for a long time. After giving the code to the others, the photographer would then move forward to form a circular arrangement. In the circular arrangement students are at a similar distance from each other, it appeared to be the most comfortable position to have a group talk. Most of the discussion we observed had taken place in this arrangement. The circular arrangement was the most stable formation we observed, and also the most frequent one. Finally, in the semi-circular arrangement, three students stay corner-to-corner, which let them easily share objects, such as a tablet or an instrument. We also observed this formation, less frequently than the circular one, when a discussion was happening.

3.4.2 *Collaboration mechanisms*

I now describe the various collaboration mechanisms and the F-formations associated to them and how students moved to reach them.

3.4.2.1 *Awareness*

To identify awareness, we used indicators such as students' gaze, body gesture and conversation analysis. Awareness is subtle and dynamic and often integrated in other aspects of participants' activity. The changes in awareness levels we observed were often due to the use of personal mobile devices and led to transformations in the F-formation. For example, when a student wanted to know what another was doing:

> [In group 2, Anna, the reporter, is inputting the unlock code. Two others, Sophie and David are looking at her (in a circular arrangement). As soon as Anna finished, Sophie and David step close to her to see her tablet for the puzzle (transform to the semi-circular arrangement).]

Awareness levels were also influenced by environmental constraints and mobility derived from the nature of the activity. These constraints may break the F-formation, which, consequently, led to issues related to maintaining awareness. For instance, when participants were walking, they could not see precisely what others were doing, nor the content of the tablets.

> [In group 3, after students got the right answer of a puzzle, they start to move forward. Ben, the reporter, is walking behind while looking at his tablet.]

> Ben: Eh guys, I think we get something new.
>
> [Two others, Zoe and Emma didn't hear him and keep walking.]
>
> Ben: Hey, wait, we have a new puzzle on my tablet!
>
> [Zoe and Emma stop and look at him.]

In this example, a group is walking in line. Two students in front are not aware of what Ben is doing, and cannot hear what he is saying. The speaker can only get the attention by speaking much louder.

3.4.2.2 *Regulation*

Regulation indicates that students are setting up strategies or goals, or monitoring and evaluating their task. For example, deciding on their next step could be regarded as a strategic action and asking for confirmation of a direction should be regarded as monitoring of regulation. Regulation also includes actions that students take to support each other to achieve a shared goal, such as one helping another to read out the data on the instrument.

In Figure 26 (left), the group is doing a measurement. Simon (white shirt) is measuring wind speed. He is holding an anemometer. Susan (the girl on the right side) finds out that Simon is measuring the wind in the wrong direction and points into the right direction. They two form a face-to-face F-formation. The student squatting in front is looking at another measuring instrument. He is in the r-space of the F-formation as he is not involved in the joint activity of the two others.

In Figure 26 (right), Susan, the photographer of the group, is trying to scan a QR code that is hung on a pillar. Simon is helping her by holding the QR code to make sure she can scan it at the right angle. They are forming a L-shaped formation.

Figure 26: Two examples of regulation.

We observed regulation behaviors in the form of mutual support, such as reading out data from a measuring instrument to another, or one helping another to check the answer to a puzzle. These regulation behaviors mostly happened within dyads. L-shaped or side-by-side arrangements were mostly used when participants needed to refer to devices, focusing in such cases on the same device or measuring instrument. Face-to-face f-formations were used when regulation mechanism did not require devices.

3.4.2.3 *Information sharing*

We observed two main forms of information sharing. The first one is verbal/in-air information sharing, which means passing information verbally without physically sharing devices; the other one is on-device information sharing, which means showing or passing devices to others. Verbal information sharing always happens when photographers pass codes to others, reporters read out puzzles, explorers give directions or when students share measurement data. For short information, such as the unlock code to synchronize tablets or a measurement to input, students always shared information verbally by reading it out. For example, the photographer always reads out the unlock code as soon as s/he gets it even s/he is far away from others (e.g. Figure 27-left). The explorer gives direction sometimes when the group is walking. When students are sharing information snippets like these, the arrangement of the F-formation depends on the former position. Figure 27 (left) shows the photographer (girl on the left side) standing on the slope where she had scanned the QR code as she gives the unlock code to her group. On the other hand, when students need to share more complex information, such as instructions or puzzles, they gather together to make sure everyone can hear clearly, a F-formation is consequently formed, for instance a circular arrangement, (e.g. Figure 27-right).

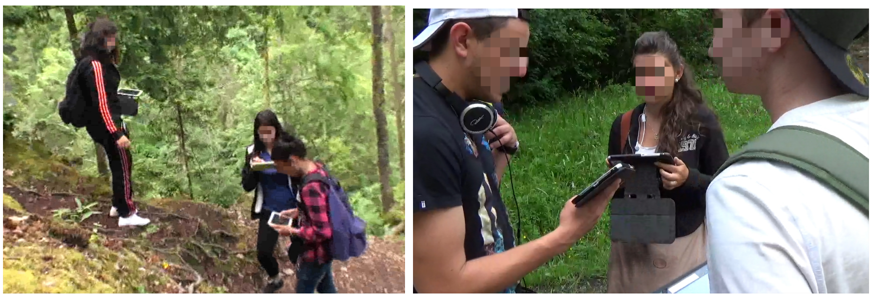


Figure 27: Verbal information sharing. Left: The photographer (on the left) is giving the unlock code to her team members; Right: The reporter is reading out a puzzle to others.

On-device information sharing happens when members need to share information that is difficult to share concisely, such as images, maps or blocks of texts. In such cases students feel the need to look at the tablet by themselves, the device is then always in the o-space and students position themselves around the tablet. With a group of three, there are three possible formations:

1. The owner is in the middle holding up the device (Figure 28-left);
2. The owner is on one side, tilting the tablet towards the others (Figure 28-right);
3. The group stands behind of the owner, looking at the tablet over the owner's shoulder (Figure 30-E).

Figure 28: On-device information sharing. Left: The owner is in the middle holding the tablet straightly; Right: The owner is on one side tilting the tablet towards the others.

We observed the semi-circular formation more regularly in these situations. When two students are sharing a tablet, they usually stand in an L-shaped formation. When the information on the tablet requires significant reading time, others would take the owner's tablet for a moment.

3.4.2.4 *Group Discussion*

We focus here on discussions to reach a consensus, such as when a group is figuring out the solution to a puzzle or discussing how to use a measuring instrument. This involves elements of suggestion and negotiation. From a F-formation perspective, we observed either discussions involving the whole group or a subgroup.

In group discussions, the three students are all involved in the joint activity. They are usually positioned in one of the two main F-formation arrangements: either the circular one or the semi-circular one. We observed the semi-circular arrangement when the discussion is based on the devices (Figure 29-left). Students talk to each other while checking the information on the tablets. The circular arrangement happens when students are discussing without using devices. In this situation, they are discussing face-to-face, and the circle becomes larger as discussion continues (Figure 29-right).

We observed students occasionally drifting a bit, or facing another direction while thinking. On other occasions, when they need to check something on a tablet, they would move towards the owner's tablet, the circle becoming smaller, and larger again once done checking.

Figure 29: Change of F-formation during a discussion. Left: Students are in semi-circular arrangement when the discussion is around a tablet; Right: The arrangement changes to circular when discussing face-to-face

Students tended to shift between these two F-formations while discussing.

The subgroup discussions happen mostly when students need to deal with simple problems, such as where to go next and how to use the measuring instrument. In subgroup discussions, we mostly observed face-to-face and L-shaped formations.

3.4.3 *Group dynamics*

Given the highly mobile nature of the activity, the structure of the formations changed rapidly. These dynamic transitions are particularly important in group work [11]. We present below the analysis of one sequence involving all the collaboration mechanisms described previously and the transition from one to the next. Figure 30 shows the most representative formations.

> [00:00] [In group 2, the group found a QR code. Sophie (the photographer) goes ahead to scan it. David flips the cover of the tablet. Anna takes her tablet out of her bag. Now both are ready to input the unlock code to synchronize their tablet. (Figure 30-A, awareness.)]

Here the group is in triangular F-formation. David and Anna are aware of Sophie's action because scanning the QR code is part of the task. They know what Sophie is doing without getting closer to her. Hence awareness can be maintained in a triangular formation even at several meters of distance.

> [00:06] [Sophie gets the unlock code. She turns back facing David and Anna, and reads out the code to them. (Figure 30-B, verbal information sharing)]
>
> [00:07] Sophie: The code is 8OE.

Figure 30: A sequence of collaborative behaviors and their corresponding F-formations. A: Sophie is scanning a QR code, David and Anna are watching (awareness); B: Sophie reads out code to others (verbal information sharing); C: David and Sophie move towards Anna to see her tablet (awareness & regulation); D: Sophie takes Anna's tablet (on-device information sharing); E: Sophie holds up her tablet showing it to the others (on-device information sharing); F: They are discussing the puzzle (discussion); G: David double checks the tablet (on-device information sharing); H: During the discussion, Anna suggests to move forward (discussion & regulation); I: Sophie asks David where to go next (regulation & on-device information sharing).

Sophie reads the unlock code to the others in a triangular formation. The information is concise and can easily be shared verbally; she does not have to get closer to the others.

> [00:09] [David and Anna input the unlock code in their tablets.]
>
> [00:13] Anna: It doesn't work.
>
> [00:27] [Sophie starts moving slowly toward the others]
>
> [00:34] David: We shouldn't enter a space after the code. [getting closer to Anna to see her tablet]
>
> [00:40] [Sophie goes down the slope to form a circle with David and Anna, then looks at Anna's tablet. (Figure 30-C, awareness & regulation)]
>
> [00:40] Sophie: 8OE. [repeating the code.]

David and Anna are initially in a side-by-side formation inputting the unlock code on their tablets. As Anna notices a problem, David moves towards Anna to see what is happening on her tablet and provides a suggestion. F-formation changes from side-by-side to L-shaped to maintain awareness and facilitate regulation inside the subgroup. The same situation happens to Sophie. She is not aware of what David and Anna are doing, so she moves towards them. The group F-formation changes from triangular to circular. As she notices that Anna has issues inputting code, she repeats the code. This is a sign of regulation taking place, i.e., monitoring the task and providing assistance.

> [00:42] [Anna enters the code again. It works this time.]
>
> [01:04] [After synchronizing the tablet, Anna (the reporter) reads out the puzzle to two others.]

When Anna is reading out the puzzle to the group, they stay in the circular F-formation shown in Figure 30-C; this F-formation being suited for sharing information verbally.

> [01:15] Sophie: Let me see. [she takes over Anna's tablet]
>
> [01:20] David: Is one of the answers correct? [leans forward Sophie to see the puzzle (Figure 30-D, on-device information sharing.)]
>
> [01:22] Sophie: It's what they say in the puzzle.

In this part, even though Anna reads out the puzzle to two others, Sophie still grabs the tablet to read the puzzle by herself. This is a sign of complex information where sharing verbally is not enough. The change in tablet possession leads to a transformation of the F-formation from circular to semi-circular.

> [01:28] Sophie: Yes, yes, this one is the answer. [turns back and holds up tablet to show it to two others. (Figure 30-E, on-device information sharing & discussion)]
>
> [Sophie discusses the puzzle in more details.]

In order to share the tablet with the group, Sophie turns back and holds the tablet like a shared vertical display. The group forms an F-formation that we only observed before in large shared display environments: everyone is facing the same direction and sharing common focus on the screen content.

> [01:32] [Sophie turns to face the others and returns the tablet to Anna asking her to input the answer.]
>
> [01:34] Sophie: Try it to see if it is correct.
>
> [01:39] [Anna inputs the answer; the two others are looking at her.]

This is a sign of regulation by monitoring other's action, in the classical circular arrangement.

> [01:43] [They got the right answer and unlock the next puzzle. Anna reads out the puzzle again. Then they begin to discuss. (Figure 30-F, discussion)]
>
> [02:02] David: Wait, what is the third clue?
>
> [02:04] [Anna tilts the tablet towards David and he reads out the puzzle. (Figure 30-G, on-device information sharing)]

David and Anna change F-formation to corner-to-corner, the group is still in roughly circular formation. The F-formation is changing based on the sharing of devices.

> [02:16] [Discussion keeps going. Now they don't need the tablet, the circular F-formation becomes larger. Sophie and David also exchange their position while they are discussing. (Figure 30-H, discussion)]

When students are suggesting ideas, discussing solutions, they do not stay in position, moving or turning a bit. The movement is always surrounding the o-space, and always coming back to a circular formation.

Table 7 and Table 8 present a synthetic view of the dynamic of F-formations, their occurrence, transition and duration for this particular sequence.

F-formation	Number	Duration	Percentage
L-shaped	3	25s	11.4%
Triangular	1	27s	12.3%
Circular	3	138s	62.7%
Corner-to-corner	2	30s	13.6%

Table 7: Comparison of the F-formations observed

Time	Sub-activity/action	F-formation	Duration
00:00	Sophie scans QR code	Triangular	27s
00:06	Manual synchronization		
00:27	Sophie moves towards two others	transition	
00:32	David moves towards Anna	transition	
00:34	David looks at Anna's tablet	Dyad L-shaped	6s
00:40	Sophie joins in two others	Circular	23s
01:04	Anna reads out the puzzle		
01:15	Sophie takes over tablet	transition	
01:20	Group discussion	Corner-to-corner	12s
01:28	Sophie turns back and holds up the tablet		
01:32	Sophie turns back and returns the tablet	transition	
01:39	Anna inputs the answer	Circular	23s
01:43	Anna reads out the new puzzle		
01:58	Group discussion		
02:02	David wants to check the puzzle	transition	
02:04	David and Anna are sharing the tablet	L-shaped in circular	12s
02:07	Group discussion		
02:16	Sophie start to move	transition	
02:22	Sophie stops; group is discussing	Corner-to-corner	18s
02:40	David starts to move	transition	
02:44	David stops; group is discussing	Circular	68s
03:49	Anna suggests to move forward, others agree		
03:52	Sophie wants to see the map on David's tablet	transition	
03:54	Sophie and David are sharing a tablet	Dyad L-shaped	7s
04:01	Group leaves the site		

Table 8: Timeline of the activity

3.5 DISCUSSION

Most mobile collaborative activities found in the literature focused on the design of activities. Barkhuus et al. [12] provided suggestions on supporting strategies in mobile games to enhance the game experience. Facer et al. [44] explored how to integrate physical interaction with mobile gaming to support learning. Huang et al. [68] provides instructors on designing mobile activities to facilitate learning in botany course. Even though all these studies involved collaboration, none of them provide design implications on how to support collaboration using mobiles. Nova et al.'s [112] study is one of the few focusing on mobile collaboration (in a remote context). They focused on task performance, communication among peers and task workload. They suggested that automatic location-awareness in a mobile activity do not promote collaboration. Our study focuses more on co-located collaboration in which students worked together and did not require location-awareness tools.

Besides, in a highly mobile condition, few studies focused on studying group arrangements and movements, and their relationships with collaboration. Marshall et al. [100] used F-formation to analyse the social interactions between visitors and staff in a tourist information centre. They described how the physical structures in the space encouraged and discouraged particular kinds of interactions, but there was no digital devices involved in their study. Marquardt et al. [99] used F-formation and micro-mobility lenses to explore cross-device interaction. But they did not show how different interaction techniques impact collaboration. In our study, we investigate the relationships between F-formation and collaboration.

Table 9 presents a comparison between related studies and ours on two main aspects: collaboration in mobile activity and group F-formation. Based on the comparison and our analysis of participants' behaviors, we derive design implications discussed below including how to better support different collaboration mechanisms and how F-formation system can be leveraged to analysis collaboration.

3.5.1 *Implications for supporting collaboration*

3.5.1.1 *Better support for awareness and regulation*

The various roles introduced in the application, with game content specific to each, had an impact on awareness with players needing to engage with others to get some specific information they did not have. Environmental constraints and the highly mobile nature of the game also influence level of awareness. Shared indicators of progress on group objectives, and of individual progress within the group, could have raise players' awareness, and eased coordination. For example, showing at which stage the whole group was could have helped play-

	Focus of the study	
	Collaboration in mobile activity	Group F-formation
Nova et al., 2005 [106]	Investigating how location cues influence collaboration concerning task performance and group communication.	-
Marshall et al., 2011 [94]	-	Using F-formation to analyze social interaction in a tourism center.
Marquardt et al, 2012 [93]	-	Using F-formation and mobility to design cross-device interaction.
Our study	Studying how students collaborate using mobile devices concerning four collaboration mechanisms	Analyzing group F-formation and participants dynamic movements.
	Investigating the relationship between collaboration and F-formation.	

Table 9: Comparison of our study with former related studies.

ers move to the next steps faster. Or showing the amount of earned badges could both improve self-esteem and encourage players in sharing and gaining expertise. But indicators supporting awareness and regulation should be designed with care not to decrease existing social interactions and engagement, as suggested by Nova et al. [112].

3.5.1.2 *Better support for complex information sharing*

While sharing snippets of information such as unlock codes or map positions was no problem. Sharing more complex information was challenging and frequently led to new group arrangements to cope with the lack of shared ground. In such situations three people focusing on a single tablet is burdensome and impedes collaboration. There is a need for tools enabling collaborative interaction with complex information in mobile conditions.

For instance, in semi-circular formations, we could use proximity to enable information transfers between tablets, as proposed by Marquadt [99]. We could also enable the duplication of screens for a moment, or enable a focused/zoomed-in mode so that information is more readily visible to people in a circle.

3.5.1.3 *Increasing participants' engagement*

We have shown that manual synchronization did not impact the activity performance. On the other hand, instead of taking manual synchronization as an annoying chore, students enjoyed sharing code. The code owner seemed to have a sense of achievement of passing code to others, and the two others were excited on what would happen after they inputted the code. Opposed to our expectations, the manual synchronization appeared to increase engagement and in the activity and let students have a stronger feeling of progress than they would have with automated synchronization. This indicates that automatically obtain information from partners may not always be helpful, which is consistent with Nova et al.'s [112] conclusion. Therefore, we encourage to use simply manual synchronization in mobile activities.

3.5.2 *Implications for leveraging F-formations*

3.5.3 *Focus on transitions between F-formations*

Group physical arrangements and collaborative behaviors are always linked. One F-formation can be related to several type of collaborated behaviors, and vice versa. For example, students could share information, regulate behaviors and discuss in circular formation. Marshall et al. [100] also demonstrated people's behaviors in different arrangements. However, not as Marshall et al.'s study in which people were gathered at a fixed information counter, more movements can be observed in mobile activities. Most of the arrangements were only stable for short amounts of time. Collaborative behaviors could cause changes in F-formations, such as transition from triangular to circular organization to start group discussion. Therefore, when designing tools to better support collaboration, rather than capturing given F-formations, emphasis should be given to changes between arrangements. For instance, the transition from one formation to another could be pro-actively managed on the devices by suggesting which device configuration would be most useful. Another possibility would be to let users to maintain the state of a previous configuration even though the arrangement has changed.

3.5.4 *Subtlety and control in proxemic interaction*

Leveraging proxemics to support users' interactions in context aware systems is promising [99]. However, in outdoor conditions, proxemics should be treated with care. The cost of implicit adaptations might not be worth the benefits. We observed many situations in which the arrangements of the participants were similar but the high level activity required different information and devices configurations. For example, in semi-circular formation, we observed two participants compared their tablets, or three participants were sharing the same tablet, or each of them was looking at his/her own device.

3.5.5 *Better representation of F-formations and their dynamics*

Throughout our analysis we struggled to find a way to systematically code and represent micro-mobile behaviors and the transitions between F-formations. Hall [60] provides a system for notating proxemic behaviors. Marshall et al. [100] also present several diagrams of F-formation in a tourism information center. However, these diagrams do not consider devices used in the environment. We introduced tablets in our diagrams of F-formation and small multiples (Figure 30) as a first step in improving the notation of F-formation and mobility.

We believe that progresses are needed in the development of a visual language describing device use in F-formation, and in transitions between them. This would enable more systematic annotations and the ability to quantify formations more easily. Elements whose representation would help analysis include:

- Device states (e.g. active, on-hold, folded away);
- Mobility within a group as people maintain the formation (e.g. rotation, shift, or expansion/reduction of the arrangement); or
- Transition from one arrangement to another.

Finding better ways to represent such dynamic behaviors would also help develop better models of collaboration, and create better computational representations of the activity, e.g., state machines of mobile collaboration.

3.6 CONCLUSION

This chapter describes the design of a collaborative learning game using multiple mobile devices. It shows how students behave and collaborate in a highly mobile environment using devices. I focused the analysis on the relationship between students' collaboration mechanisms (awareness, regulation, information sharing and discussion), F-formations, and the way they used their devices. The results demonstrate that students have very dynamic spatial arrangements during the outdoor learning activity, which shape the way they collaborate.

This chapter partially achieved my first research objective, which is understanding how the configuration and form factors of devices in MSE shape users' behaviors. We gained understandings on students collaboration when using multiple personal devices in MSE. We derived design implications from our study to better support collaboration in learning activities in mobile MSE configuration. We suggest that shared indicators are helpful on maintaining awareness and promoting regulation. Proxemic design should be used with care in a mobile context. And manual synchronization is possible in mobile activities as it can increase engagement and raise awareness.

To gain a better understanding of collaborative mobility, we suggest to develop more powerful tools to analyze F-formations in mobile situations. In the next chapter, I will focus on a more stable MSE configuration, combining a shared surface with multiple personal devices, where mobility has less importance.

4 SHARED SURFACE CONFIGURATIONS FOR COLLABORATION IN INDOOR MSE

In this chapter, I will study another common configuration of MSE for collaborative problem-solving activities: using a shared surface with multiple personal devices. The shared surface brings public spaces and personal devices can be used for personal workspace. I am interested in how the orientation of shared surface impacts users collaboration. Two conditions are compared: the horizontal surface versus the vertical surface. The results demonstrate that in a MSE setting, the orientation of a large surface has a different impact: (1) it nuances previous results showing that horizontal surfaces are better for collaboration. (2) it impacts the way activities are conducted. The horizontal condition leads to more implicit coordination and balanced interaction with the large display, but to less structured work, while in the vertical condition, group coordination is more explicit and is structured around one main interactor. Based on the results, I derive recommendations for MSE design.

4.1 OVERVIEW AND OBJECTIVES

As I mentioned in Chapter 2, using combination of a large shared surface with personal devices is a common setting in MSE. It can be used in different kinds of activities, such as urban planning [143], emergency planning [30], group meeting [13, 61], and also digital card games [133]. The large surface usually serves as a group space where users can perform collaborative actions such as pooling information or exchanging ideas. Personal devices can be used for achieving individual goals, such as doing personal evaluation or browsing information without being interrupted.

When building MSEs, decisions concerning the size, form and orientation of devices have to be made early on in the design process. These factors are often considered implicitly, or intuitively since data are scare in the domain. The complexity of changing form factors may explain why few papers discuss their impact on interaction, even though these factors profoundly shape the affordances of devices. Zagermann et al. [159] compared using different size of tabletops and showed that the size increases in a multi-surface environment, collaboration quality or sensemaking results decreases, since the larger screen diverts users' attention away from their collaborators and towards the shared display.

Closer to our concerns, Rogers and Lindley [126] showed that horizontal displays better at supporting collaboration compared to vertical ones. They promote more suggestions and idea generation, while also leading to more role switches and greater awareness of others' actions. The authors proposed two reasons (1) the input device, a mimio pen, was easier to pass among users over the horizontal table, and (2) it was harder to input data on the vertical display while standing. Inkpen et al. used a paper-based prototype to compare display orientation, size, and user arrangements [72]. They found that although participants felt the horizontal display was more natural and comfortable for collaboration, working with a vertical display tended to be more time-efficient. More recent work by Potvin el al. [118] comparing vertical and horizontal multi-touch displays found that the horizontal surface encouraged more equal physical interactions among participants with the shared display, as well as equal verbal participation, which differs from Rogers and Lindley's study.

All these previous studies focused on a single screen. These is no study on how the orientation of the shared surface impacts collaboration when using alongside with tablets. Since Rogers and Lindley's study in 2004, large multi-touch displays, smartphones and tablets have become pervasive, raising the question of how people behave and collaborate in such Multi-Surface Environments. Compared to previous work, devices like smartphones or tablets make input much more efficient, which should change collaboration by distributing control more evenly. The same applies to input on large devices which is now fast, reliable and multi-touch, meaning that anybody can take control of a shared screen without any limitation.

In this chapter, I investigate how the orientation of a large interactive surface combined with personal devices impacts collaboration. I study both low-level interaction aspects and high-level collaborative mechanisms that defined in chapter 2.

4.2 STUDY

We designed a application supporting problem-solving activities. A large surface can display the map, while tablets support information browsing, note taking and bookmarking favorite locations. For the experiment, I implemented a trip planning activity in the application.

4.2.1 *Pre-study*

In a preliminary study, we explored the impact of display orientation in MSE on individual and collaborative work. Our hypothesis was that the introduction of tablets would decrease the differences between horizontal and vertical conditions by enabling participants to carry out individual activities alongside. The study consisted of a collaborative problem-solving activity made up of an individual phase in which participants analyzed data on their tablets, followed by a collaborative phase in which participants discussed how to come to a collective decision.

The study lasted around 55 minutes. This included 5 minutes of task description and familiarization, 20 minutes for the task in one condition followed by a similar task in the other condition, and 10 minutes of debriefing at the end. We counterbalanced the orientation and the data presented to participants for the two conditions. Six groups of three people participated in the experiment. Within each group, participants knew each other.

4.2.1.1 *Lessons from pre-study*

We found that the horizontal condition seemed to better support collaboration among participants. Roles and tasks were most frequently distributed in this condition. Regarding individual tasks, participants inputted equal numbers of notes and arguments. However, the structured nature of the activity constrained what participants could do. In practice, everyone had to analyze the same data in order to move to the next phase. Moreover, we noticed variations between the two sessions in terms of time spent to complete the task and also in the level of the discussions. Participants spent more time in the first session (mean = 19m24s, SD = 3m54s) than in the second session (mean = 11m36s, SD = 4m24s) with a statistically significant difference ($t(5) = 7.19$, $p = 0.0008$). Besides time duration, we also observed that participants discussed task strategy only in the first session and continued to use the same strategy in the second session. Both phenomena made it difficult to compare group behaviors and draw reliable conclusions.

4.2.2 *Main study*

Based on the observations from the pre-study, we designed a task with fewer constraints and chose a between group experimental design. Our study configuration consisted of three participants, each with a tablet and sharing the multi-touch display. The collaborative activity, which consisted in planning a trip to New York, involved gathering information, analyzing it, and making group decisions.

4.2.2.1 *Hypotheses*

Based on the related work and our pre-study, we derived a set of hypotheses ranging from low-level interaction to high-level group organization. At a low-level, we focused on how people interact with devices in MSE while conducting collaborative activities, especially when creating and interacting with content. We hypothesized that:

H1 the horizontal condition would lead to more balanced physical interactions with the large display within groups;

H2 the difference in input levels (e.g., notes taken) between the two conditions would not be as pronounced as in prior work that did not include personal devices.

Our second set of hypotheses focused on higher-level activities related to group collaboration :

H3 the horizontal condition would support a higher level of awareness;

H4 the horizontal condition would support more efficient activity organization;

H5 the horizontal condition would encourage more communication and discussions.

4.2.2.2 *Task design*

The task consisted in planning a trip itinerary to New York with a limited budget, comparable to that used by Rogers and Lindley [126]. Such an activity is open-ended enough to enable various types of group organization. We chose New York as the degree of knowledge of its landmarks was relatively similar in our target population. Based on their budget, participants had to agree on: how many days they would stay in the city; which hotel they would stay at; which activities they would do; and their itinerary for each day. Once finished, participants had to present the day-to-day outline of their trip.

The shared screen displayed a map with markers for 15 tourist attractions and 8 hotels (Figure 31). Participants could push detailed information on their tablet by tapping their avatar on a marker (①). Information provided for each location included: description, price, rating, and feedback from other tourists (⑤). From their tablets, participants could individually add locations to their favorites (⑥) and take notes (⑦). A card per location showed its favorites and notes on the shared screen (②). Four filter buttons on the shared screen enabled to show/hide attractions, hotels, favorite locations, location cards (③). A timer in the top right corner reminded participants how much time was left (④). Two conditions used the same application. In the horizontal condition, the user interface orientated to the same direction, as the side-by-side position can encourage more discussion [118].

4.2.2.3 *Participants*

We recruited 12 groups of three participants. This amounted to 36 participants (24 males and 12 females). Participants were between 21

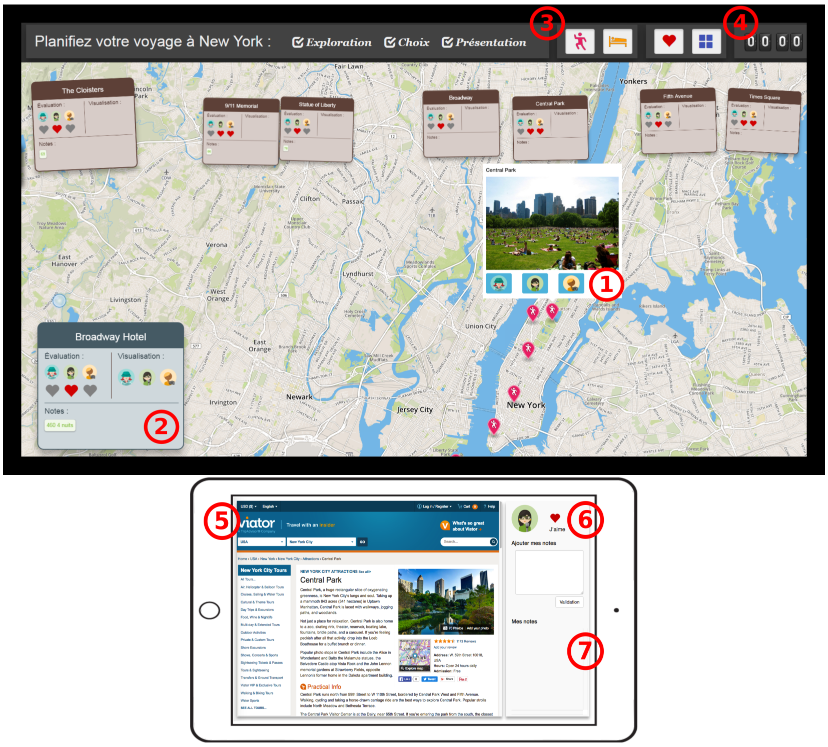


Figure 31: The application overview. Top: shared surface showing the map + favorite locations. Bottom: tablets content with details on an attraction.

and 31 years old (mean = 26.1; SD = 3.28). All of them were students at our university. Participants within a group knew each other.

4.2.2.4 *Apparatus*

We used a 55-inch multi-touch display with a resolution of 1920x1080 pixels to serve both in the vertical and horizontal condition. All the tablets were Samsung Galaxy Note 8 with protective covers. The devices were wirelessly connected to the network. The MSE application was built with Web technologies, and devices communicated via websockets.

4.2.2.5 *Procedure*

Based on the literature and our pre-study, we chose a between-group design with the shared display orientation as an independent variable with two horizontal or vertical conditions. In both conditions, participants were standing (Figure 32). In all we observed six groups of three participants in each condition, which is comparable to similar studies of collaborative work with tabletops [66, 159].

The experiment started with 5 minutes of task description and familiarization, and ended with 10 minutes of debriefs. The group had approximately 25 minutes to achieve the task, with a timer indicating the time left. However, the task instructions emphasized that the timer was an indication and that participants could spend more or less time depending on how the activity progressed.

Figure 32: Study setting, a shared interactive surface with multiple personal tablets. Top: large display in a horizontal condition. Bottom: large display in a vertical condition

4.2.2.6 *Data collection*

We collected behavioral data through videos and logs. We used two cameras to record the sessions: one was placed near the ceiling capturing from top to bottom to see the activity on the shared surface, while the other was placed beside the shared surface to capture the group. We logged interactions with the shared display and the tablets, such as touch events on UI elements, dragging/zooming the map, choosing a location, submitting a note, etc.

4.2.3 *Analysis method*

To analyze participants' behaviors, we defined a set of indicators detailed in Table 10. The indicators range from low-level actions, e.g. touch events, to higher-level collaboration mechanisms and group strategies.

<table>
<tr><th>Behaviors</th><th>Data source</th><th colspan="2">Indicators</th></tr>
<tr><td rowspan="2">Interaction with devices (H1 & H2)</td><td>Log</td><td colspan="2">Notes / Favorite locations / Total number of touch events</td></tr>
<tr><td>Video</td><td colspan="2">Touches on shared display per participant</td></tr>
<tr><td rowspan="3">Awareness (H3)</td><td rowspan="3">Video</td><td>Positive</td><td>Reaction without request / Complementary action</td></tr>
<tr><td>Negative</td><td>Interference / Verbal monitoring</td></tr>
<tr><td>Neutral</td><td>Verbal shadowing</td></tr>
<tr><td rowspan="2">Activity organization (H4)</td><td>Log</td><td colspan="2">Locations checked together at the same time /
Locations checked per person</td></tr>
<tr><td>Video</td><td colspan="2">Discussion on strategy / Duration of the whole task</td></tr>
<tr><td>Discussion (H5)</td><td>Video</td><td colspan="2">Discussion on hotels, attractions, budget and itinerary /
Sharing tablets for discussion</td></tr>
</table>

Table 10: Indicators used to analyze participants' behaviors.

4.2.3.1 *Interactions with devices*

To analyze low-level interaction, we used log data to count touch events, how many notes participants submitted during the activity and how many time they pressed the favorite button. We used video analysis to measure the number of touch events, e.g., tap, drag, or zoom, on UI elements of the shared display, in order to measure how active each participant was.

4.2.3.2 *Awareness*

To analyze group awareness, we drew indicators from Hornecker's et al. model [66]. As Hornecker et al. state, with a good level of awareness, little verbal communication is used in coordinating activity, and assistance and anticipation actions arise [66]. On the contrary, a lack of awareness can negatively impact coordination. Interferences, "unintended negative influence on another user's actions" according to Hornecker et al. [**12**], can arise with multi-user devices when two or more participants try to perform incompatible actions (e.g. attempt to drag the same object, or select two inconsistent features).

We took two positive indicators: reaction without explicit request and complementary action, which correspond to anticipation and assistance actions. Reaction without request is a proactive action that occurs when one participant reacts to, or helps, another without being explicitly asked. For instance, when a participant sends information about a location to his/her tablet and notices that another group member wants to check the same location, sending the information to him/her without being asked to is considered reaction without request. Complementary action occurred when participants were coordinating the task or distributing labor implicitly. We coded it when two or three participants were interacting together or alternately on the shared display without verbal coordination to achieve the same goal. For example, when two participants were sorting location cards together based on their itinerary, or when they were alternately dragging and zooming the map. These two indicators can be used to evaluate whether participants are aware of the on-going tasks taking place in the group.

We reused two negative indicators of awareness: interference and verbal monitoring. Interference occurs when participants unintendedly interrupt or impede another person's actions. For example, when one person wants to choose a location while another accidentally drags the map, or when two participants are reaching for the same location card. Verbal monitoring occurs when a participant is inquiring about other persons' behaviors. For example, when one person is asking the other: "Which location are you checking?"

Finally, we used verbal shadowing to measure and assess how participants' maintained awareness [66]. We coded it when one person was describing or giving a running commentary about who is doing or going to do what. For example, when one person is saying: "I'm writing down the price of that hotel" or "I'm going to like that location".

4.2.3.3 *Activity organization*

In HCI, regulation is observed in terms of activity organization (see Section 2.4.2.2). Studies analyze the way group members elaborate strategies [158], adopt roles and distribute or share labor [126] to understand this meta-level of coordination and how it relates to the overall activity. In this study, we analyzed activity organization in terms of group strategies, explicitly sharing labor, and roles taken by participants [126, 159], but also in terms of planning and monitoring [43]. We counted discussions related to activity organization when participants expressed strategies, such as deciding how to distribute labor, e.g. discussing the locations to explore. We also counted this indicator when participants were monitoring or planning these strategies. For example, when a group realized that nobody had favorited the locations explored, one participant stated: "one of us should 'like' the locations so we can filter the cards and find them easily", and another answered: "yeah, you're right, I'll do that". To observe how groups shared labor, we counted parallel interactions, which occurred when participants were interacting together on the large surface for a different purpose.

We were interested in measuring whether the task was more efficient in one condition rather than the other. Quality of results could not be a good efficiency indicator since we proposed an open problem. The different results proposed by the groups all met the budget requirements. Thus, to measure the efficiency of group works, we analyzed the activity in terms of duration and exploration. We used our logs to compute the number of locations explored together and by each person.

4.2.3.4 *Discussion*

To analyze participants' discussions, we marked in video each time that participants talked about locations. For example, when participants mentioned the price or room type of a hotel, places to visit, ticket prices, etc. We also noted discussions about budget and itinerary.

To analyze how participants used their tablets during discussions and how information was shared among the group, we captured each time that they shared their tablets with others. Using a qualitative approach, we observed participants' movements and deictic gestures when exchanging ideas, or arguments when discussing collective decisions.

4.2.3.5 *Video analysis process*

Two coders analyzed the videos. We conducted an inter-rater reliability test before starting the analysis. We chose one group from each condition to carry out the test and picked two segments in each group: one at the beginning of the activity when participants were browsing locations, and the other at the end when participants started to discuss their final plan. Each segment lasted 2 minutes. We went through the video twice. In the first round, we noted all the interactions, such as dragging the map, touching cards, tapping the filter buttons, and the complementary or parallel interactions. In the second round, we conducted the verbal analysis, considering the awareness indicators described above, the different types of discussion, etc. In the end, the analysis had 96.46% agreements (Cohen's Kappa $\kappa = 0.88$). After we had clarified coding differences and refined our coding scheme, we analyzed all the videos.

4.3 RESULTS

I present the results for each of the hypothesis and outline the main findings.

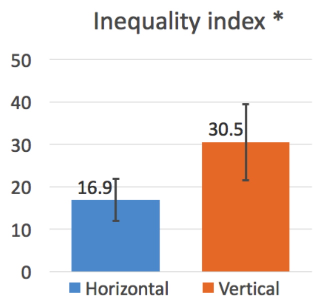
4.3.1 *Creating and interacting with content*

We analyzed collaboration among groups from a low-level perspective to determine whether the orientation of the shared display impacted users' interaction. We emitted the hypotheses that horizontal shared display would allow more balanced interaction (H1), whereas combining tablets with the shared display would reduce the differences between conditions in terms of content created or modified (H2).

4.3.1.1 ***H1**: More equality in physical interaction in the horizontal condition*

To test this hypothesis, we calculated the percentage of touch events (tap, drag, etc.) per person within each group. We then derived an inequality index from the standard deviation of the interaction percentage. This inequality index is smaller in the horizontal condition (mean = 16.9, SD = 6.26) than in the vertical one (mean = 30.5, SD = 11.2) with a statistically significant difference ($t(10) = -2.59$, $p = 0.03$) (Figure 33-right). In the horizontal condition, participants have more balanced interaction. On the other hand, in the vertical condition, groups were always organized around a main participant who had far more interactions than the others (Figure 33-left), even though everyone had access to the surface. When the main interactor was interacting, others pointed at the surface to give suggestions or asked the interactor to interact.

We observed behavioral differences on interacting with the large surface. Participants played with the display in the horizontal condition, such as zooming or dragging the map without a clear aim (something Zagermann et al. also noted in their study [159]). In contrast, in the vertical condition, interactions were goal-driven, with participants always touching the display for a specific purpose.



	P1	P2	P3
V-1	2.0%	19.1%	78.9%
V-2	8.1%	12.2%	79.7%
V-3	9.4%	14.6%	76.0%
V-4	13.8%	17.7%	68.5%
V-4	19.4%	21.3%	59.2%
V-6	24.4%	28.1%	47.5%

Figure 33: More inequality of physical interaction in the vertical condition. Left: Inequality index of physical interaction (means with 95% CI). Right: Percentage of touch events per person in the vertical condition.

Finding 1: these observations validate H1. Large horizontal surfaces support more equality in physical interaction, whereas vertical surfaces lead to the emergence of a main interactor.

4.3.1.2 *H2: Reduction of differences when creating and modifying content*

To test this hypothesis, we measured the number of notes and favorite locations that each group submitted. The results showed no significant difference between two conditions concerning the number of submitted notes (horizontal: mean = 16.3, SD = 6.62, vertical: mean = 11.3, SD = 8.66. t (10) = 1.12, p = 0.29). The usage of "Favorite" button also revealed no significant difference (horizontal: mean = 22.7, SD = 9.4, vertical: mean = 13.2, SD = 8.7. (t(10) = 1.81, p = 0.10). Unlike previous studies that did not include personal devices, we did not observe an effect of display orientation on content creation or interaction. Nevertheless, to validate statically this hypothesis, other experiments would need to be conducted with a 'no tablet' condition to compare against.

Finding 2: these observations are in favor of H2, although more work would be required to validate this hypothesis. Combining tablets with a shared surface could reduce the differences between horizontal and vertical conditions, especially in the creation of and interaction with content, a fact which was highlighted in previous studies [126].

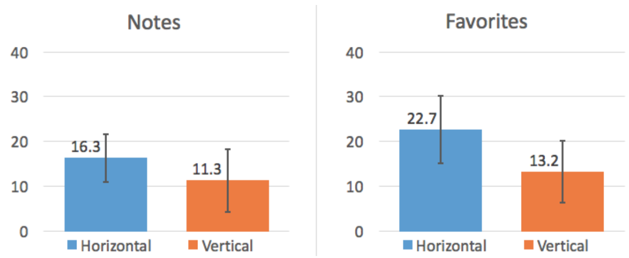


Figure 34: Average amount of *notes* and *favorites* per condition (means with 95% CI).

4.3.2 *Group collaboration*

To measure whether the orientation of the shared display impacts the way participants collaborate together from a meta-level, we analyzed group collaboration according to awareness (H3), activity organization and exploration efficiency (H4) and communication and discussions (H5).

4.3.2.1 ***H3**: Higher level of awareness in the horizontal condition*

To test this hypothesis, we looked at several awareness indicators. Verbal monitoring is considered as a negative indicator of awareness [**12**] and occurs when participants want to know the current situation of the on-going activity, such as what a collaborator is doing or what stage the group is in. We observed few instances of verbal monitoring either in the horizontal condition ($mean = 3$, $SD = 1.67$) or the vertical condition ($mean = 2.83$, $SD = 1.72$) (Figure 35-left). We observed significantly more verbal shadowing in the vertical condition (mean = 11.5, SD = 5.05) than in the horizontal condition ($mean = 6$, $SD = 3.1$; $t(10) = -2.27$, $p = 0.046$) Figure 35-right). In the vertical condition participants often gave cues to others, such as "I'm going to like that location", "I'll write down the price for that hotel", or "I'm going to look at this attraction to see if it's free".

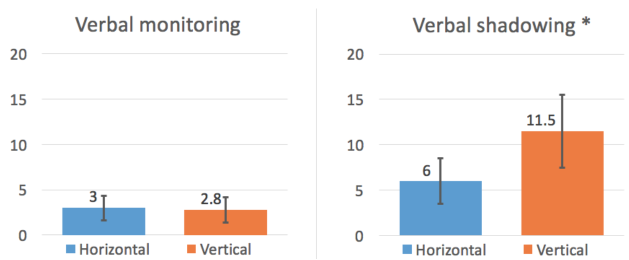


Figure 35: Average amount of *verbal monitoring* and *verbal shadowing* per condition (means with 95% CI).

In both conditions, groups maintained a good level of awareness, and participants did not feel the need to ask what the others were doing. However, in the vertical condition, participants had to make more efforts to maintain this high level of awareness, by explaining to the others what they were doing. This relates to *finding 1* and the presence of a main interactor, participants gave more verbal cues to each other to maintain awareness.

Regarding positive indicators of awareness, we observed more reaction without request in the horizontal condition (mean = 8, SD = 3.0) than in the vertical condition (mean = 3.5, SD = 2.1). The difference was statistically significant (t (10) = -3.01, p = 0.013) (Figure 36-left). Participants maintained a better awareness of others and offered help without being explicitly asked. For example, in a horizontal condition group, one participant said: "OK, now we can check attractions". Another person then used the filter buttons on the menu bar to hide hotels and show attractions. There were also far more complementary actions in the horizontal condition (mean = 30.8, SD = 10.2) than in the vertical condition (mean = 9.2, SD = 3.9) with a statistically significant difference (t (10) = 4.85, p = 0.0008) (Figure 36-middle). These actions could be, for example, handing over location cards or two participants dragging and zooming the map in turn. Complementary actions mostly occurred when participants were discussing the itinerary and sorting location cards according to their trip plan. More complementary actions suggest that participants were aware of the activity of other people anticipating actions and favoring higher implicit low-level coordination between people [**10**]. This finding is also related to the fact that there were more balanced interactions in the horizontal condition (Finding 1). As participants interacted equally, there were more chances of their having complementary actions.

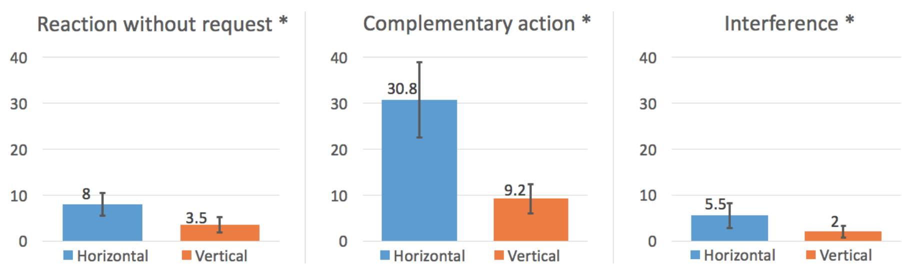


Figure 36: Average number of *reactions without request*, *complementary actions*, and *interferences* per condition (means with 95% CI).

We observed a side effect of these balanced interactions in the horizontal condition, there was more interferences in the horizontal condition (mean = 5.5, SD = 3.39) than in the vertical condition (mean = 2, SD = 1.67). The difference is statistically significant (t (10) = 2.27, p = 0.048) (Figure 36-right). As the horizontal condition fosters more balanced interaction, participants were all engaged in interacting, which can in turn cause more interferences: for example, when two participants wanted to drag the map or were reaching for the same location card. In the vertical condition, there was always one main interactor, a fact which prevented interference.

Finding 3: Groups maintained a good level of awareness in both conditions. In the vertical condition, even if participants made more efforts to maintain awareness, there was little occurrence of implicit coordination. This can be accounted for the emergence of one main interactor handling the large surface (Finding 1). With horizontal displays, participants are more likely to spontaneously help other group members or to finish the actions of others without verbal or explicit synchronization. Consequently, this can lead to more interference since participants interact more with the horizontal surface. Thus, our H3 hypothesis is partially validated. The horizontal condition offers a sufficiently good level of awareness for implicit coordination such as anticipation and assistance actions.

4.3.2.2 *H4: More efficient activity organization in the horizontal condition*

To test this hypothesis we observed how participants organized themselves and counted each time that they discussed good practices, exploration strategies or division of labor.

In both conditions, groups used explicit coordination to reach decisions about strategies or to organize work. We did not observe an impact of surface orientation on the number of discussions about strategies between the two conditions (horizontal: $mean = 11$, $SD = 3.52$; vertical: $mean = 7.67$, $SD = 4.08$; $t(10) = 1.51$, $p = 0.16$). However, we observed significantly more parallel actions in the horizontal condition ($mean = 11$, $SD = 6.8$) than in the vertical condition ($mean = 4.2$, $SD = 2.99$) ($t(10) = 2.24$, $p = 0.048$) (Figure 37-first). For instance, in the horizontal condition, we observed several times a participant organizing the location cards while another person was checking the map. This result can be related to our previous findings about balanced interaction (Finding 1) and awareness (Finding 3). Interestingly, in the vertical condition, the effort of maintaining a good level of awareness combined with the emergence of one main interactor for the shared surface did not do away with the need for explicit coordination among participants for strategy and activity organization. Moreover, the main interactor always took control of the activity, thus reducing the potential for parallel actions. In contrast, in the horizontal condition, participants interacted equally and needed to agree explicitly on the activity organization and their strategies. In this condition, more parallel actions were performed on the shared surface.

Regarding exploration strategies and task efficiency, in the horizontal condition, participants preferred to check the same location together (5 out of 6 groups), while in the vertical condition, they distributed labor (5 out of 6 groups). Only one group in each condition did it in the opposite way. Excluding these two opposite groups, the number of location explored simultaneously in the horizontal condition is significantly higher than in the vertical condition. (respectively mean = 20.6, SD = 6.84, and mean = 7.6, SD = 3.29), (t(10) = 4.20, p = 0.005) (Figure 37-second). The simultaneous exploration of locations in the horizontal condition led to significantly (t (34) = 2.53, p = 0.016) more locations explored per person in the horizontal condition (mean = 21.6, SD = 6.84) than in the vertical condition (mean = 15.6, SD = 7.4) (Figure 37-third).

Finally, even though groups had different exploration strategies in the two conditions, we did not observe a significant difference regarding the time spent on the activity (in horizontal: mean = 28m06s, SD = 3m; in vertical: mean = 25m24s, SD = 5m48s; t (10) = 0.98 p = 0.35) (Figure 37-fourth). This suggests that, in the horizontal condition, exploration of location was not as efficient as we expected. Even if participants checked more locations in this condition, they did not reach an agreement on their trip any quicker than in the vertical condition.

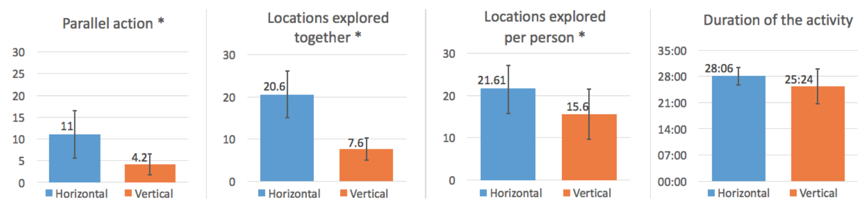


Figure 37: Average number of *parallel actions*, *locations explored together* (excluding two opposite groups), *locations explored per person*, and *duration of the activity* per condition (means with 95% CI).

Finding 4: Our observations do not validate H4. Participants tended to use two different strategies in the two conditions. In the horizontal condition, groups explored the locations together and checked more locations. While in the vertical condition, participants distributed labor and each person explored fewer locations. In the end, the task duration was similar in both conditions. One strategy was not necessarily more efficient than the other.

4.3.2.3 *H5: More discussions in the horizontal condition*

To test this hypothesis, we analyzed how groups conducted discussions, how people shared information, the devices they used to support the discussion, etc. We analyzed both verbal cues and participants' formations.

The number of discussions that participants had about hotels, attractions, budget and itinerary were similar in both conditions (horizontal: mean = 48.8, SD = 11.3, vertical: mean = 45.7, SD = 13.5). We initially thought that the design of the activity might have led to this similar number of discussions, and that this number was linked to the number of locations to check. However, participants explored different numbers of locations and adopted different strategies for exploration. Overall, orientation does not seem to influence group discussions.

When discussing a location, participants always used a device - either the shared display or a tablet - to support the discussion and bring in new information. When using the shared display, participants stood close to the screen and pointed at elements such as a marker on the map or a location card. In the vertical condition, participants faced the shared display in a line formation, while in the horizontal condition, they kept the same position throughout the activity. In five out of six groups, two participants stood on the long side and one stood on the short side. In the last group, all participants stood on one long side of the display.

Participants leveraged tablets to introduce new elements into the discussion. In the horizontal condition, probably due to their standing positions around the table, we mostly observed tablet sharing between two participants, such as one person holding his/her tablet towards another, or one person looking over the shoulder of the tablet's owner. We only observed once three participants sharing the same tablet. In the vertical condition, we observed more often three participants sharing the same tablet. Nevertheless, we found no significant difference in the number of times participants shared a tablet (horizontal: mean = 7.17, SD = 3.31, vertical: mean = 4.5, SD = 4.23; t (10) = 1.22, p = 0.25).

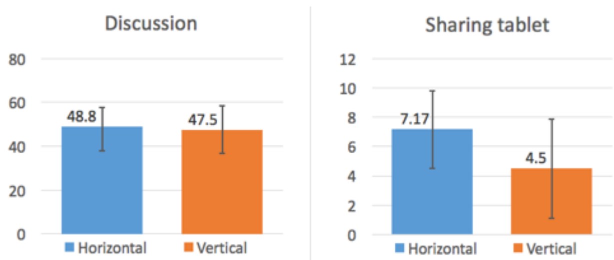


Figure 38: Average amount of *overall discussion* and *sharing tablet* per condition (means with 95% CI).

When the discussion did not rely on the shared surface, such as when participants calculated the cost of their trip, participants in the vertical condition always changed their position to a circular arrangement to maintain face-to-face discussion. Either the participant in the middle would step back, or the two participants on the side would step forward. In the horizontal condition, only the group with three participants standing in line changed its position, with the person in the middle stepping back a slightly. Other groups kept their former positions during the discussion.

Finding 5: We did not find a significant difference between the two conditions in the number of discussions within groups. This invalidates our hypothesis of discussions being better supported in the horizontal condition. In both conditions, participants used tablets for sharing information or individually exploring information, to bring arguments into the discussion. Furthermore, unlike in previous work [3], we observed participants re-arranging their formation, and forming more triad formations in the vertical condition.

4.4 DISCUSSION

Building on our results and contrasting them to previous work, we now look at how display orientation shaped collaboration. Table 11 shows a comparison of findings from former studies with ours. From the table we can see that we are the first to explore the implications of MSE, as former studies used either paper whiteboards [72, 118], or a single interactive surface (tabletop or vertical-screen) [126].

We compare findings on two levels. Low-level interaction consists of physical interaction on the shared surface, and content creation (e.g. comments participants submitted). And high-level group collaboration, which consists of different collaboration mechanisms we defined earlier, including awareness, activity organization (regulation) and discussion (also refers communication in former studies). We now draw recommendations for the design of MSEs based on these two levels.

	Apparatus	Interaction (low-level)		Group coordination (high-level)		
		Physical interaction	Content creation	Awareness	Activity organization	Discussion/ communication
Roger and Lindley, 2004 [119]	Interactive tabletop and wall-display	H: greater equality; V: main interactor	H: more notes; V: difficulty to write	H: higher level	V: the main interaction organize the task	H: more suggestions
Inkpen et al., 2005 [69]	Paper whiteboard	V: more body movements	V: more difficult to write	-	V: more focused on completing tasks	H: more on-task communication
Potvin et al., 2012 [112]	Paper whiteboard	H: slightly greater equality	-	-	-	H&V: similar amount of discussion. V: slightly greater equality
Our study	Multi-surface environment	H: greater equality; V: main interactor	Reduction of difference between H&V	H&V: similar level. H: implicit coordination (assistance & anticipation); V: more efforts on maintaining awareness	H: parallel work; V: more structured & distributed work	H&V: similar amount of discussion

Table 11: Comparison of findings from former studies with ours. H and V respectively stand for horizontal and vertical conditions.

4.4.1 *Low-level interactions*

Our study confirms previous results on the impact of display orientation on interaction [118, 126]. In the horizontal condition, physical interaction with the surface was more equally distributed among group members. The use of tablets does not seem to significantly impact direct interaction with the large surface. However, when looking at interactions that involved inputting information, tablets proved to be particularly beneficial in the vertical condition as it was more difficult to write compared to the horizontal condition [72, 126]. On a qualitative level, participants valued more the introduction of tablets in the vertical condition than in the horizontal condition. This suggests that MSE reduces differences previously observed in single shared display set-ups.

Recommendation: if individual content creation is part of the activity, then introducing handheld devices in the MSE should enable more balanced contributions among participants. If a vertical configuration is chosen for an activity that requires equity of participation, visual feedback should be implemented on the shared display to encourage participants to regulate their activity and participate more equally.

4.4.2 *High-level group collaboration*

4.4.2.1 *Similar levels of awareness*

Unlike in previous studies [126], participants managed to maintain a good level of awareness in both conditions, as the low number of verbal monitoring suggests. However, in the vertical condition, this awareness came at a cost, as participants used far more verbal shadowing, i.e., announcing what they do. Moreover, they kept moving backward to observe the situation, before moving forward to analyze information on the shared display.

Recommendation: incorporating awareness or change indicators on the shared surface or the handheld devices, could help decrease the amount of monitoring required.

4.4.2.2 *Activity organization*

We observed more signs of implicit and explicit coordination in the horizontal condition. Participants were more inclined to anticipate the actions of others and to share and agree on strategies or good practices to conduct the task. The activity seemed to run far more naturally, as participants took upon themselves to visit locations and to support each other. However, participants had to make more efforts to ensure that they were in sync. In contrast, distribution of work seemed more efficient in the vertical condition, which is consistent with Inkpen et al's [72] results that vertical condition more focused on completing tasks. The person who interacted most with the display also distributed labor and sent information to others. This was similar to Roger and Linkdley [126] results that there was a main interactor organized the task in the vertical condition. Even if participants took collective decisions all the same, the activity seemed more structured, with less interference than in the horizontal condition.

Recommendation: horizontal surfaces seem to support more cohesive collaborative activities where participants go through the task together. This kind of behavior is particularly interesting for collaborative learning where participants have to acquire the same skills and knowledge [8, 28]. Vertical surfaces seem better suited to cooperative situations in which one person drives an activity and distributes tasks to others.

4.4.2.3 *Similar number of discussions*

Former work have different results on the total number of discussion in each condition. Roger and Lindley [126] and Inkpen et al. [72] show that horizontal condition encourages more discussions, while Potvin et al. [118] and our study hold the same result that two conditions have similar number of discussion.

Our MSE set-up shaped how participants positioned themselves during discussion. In the horizontal condition, participants mostly maintained their formation, merely tilting their tablets to show their content to another participant. On the other hand, in the vertical condition, tablet sharing led to changes in position (often semi-circular or side-by-side formation). This suggests that bringing tablets could introduce freedom in group activities. Participants would have a personal workspace to conduct individual exploration, and join group discussions when needed.

Recommendation: there is no strong evidence on whether the orientation have an impact the the number of discussions. If the MSE is built for an activity involving discussion of rich content or data, cross-device interaction should support micro-mobile behaviors and support exchange of complex information across devices.

4.5 CONCLUSION

The chapter presents a study of users' collaborative behaviors in one of the MSE configurations: using the combination of a large shared surface with multiple personal devices. This configuration is particularly suited to support collaborative activities, enabling group activities on large shared surfaces and individual activities on personal devices. Although there is a wealth of application examples in this configuration, the study clarifies the underlying collaborative dynamics.

We compared two orientations of the shared surface in the study: horizontal versus vertical. Our results show that the orientation of a shared surface in a MSE shapes group coordination. MSE reduces differences between the horizontal and vertical conditions when it comes to create and interact with content. More importantly, it profoundly shapes the way collaborative activities are conducted: using a horizontal surface will lead to better equity of interaction and more cohesive activities. On the other hand, group coordination is more structured and is organized around a main interactor when a vertical display is used.

Based on this study, we have gained a better understanding on how people perform problem-solving activity in a shared surface configuration of MSE. In the next chapter, I will focus on the decision-making process and study how students collaborate using MSE in a real classroom situation.

5 DECISION-MAKING ACTIVITIES FOR MSE CLASSROOMS

This chapter presents the design of Pickit, a MSE tool supporting collaborative decision-making activities for high school students. It shows how Pickit is used by four groups of high school students as part of a learning activity. We analyze student' interactions patterns with digital devices that are related to given phases of the decision making process. The results show that Pickit is a useful tool for learning activities as it enables to balance personal and group work. The introduction of personal devices (tablets) makes free riding more difficult, while enabling the formation of subgroups in a highly dynamic manner. By using Pickit, students successfully made their decisions and better knew about the decision-making process.

5.1 BACKGROUND

Decision-making is a process of gathering information, identifying and weighing alternatives, and selecting among various alternatives based on value judgments [146], as presented in chapter 2 (Section 2.6.2). Educators have highlighted the importance of collaborative decision-making skills in scientific education [42, 52, 123], as it can help students to obtain knowledge. Several models of decision-making processes have been introduced in the learning literature over the past years [2, 74, 85, 123]. These models differ mostly in how they scope the decision-making process. They define however similar stages and all underline the non-linear nature of the process. The most generic model, proposed by Ratcliffe [123], draws upon common elements in normative and descriptive decision-making models [74]. This decision-making process consists of 6 stages that can be intertwined: 1) Listing options; 2) Identifying criteria; 3) Clarifying information; 4) Evaluating the advantages and disadvantages of each option according to the criteria previously identified; 5) Choosing an option based on the analysis undertaken; 6) Evaluating the decision-making process, and identifying any possible improvements.

This process of critical analysis of information is widely used in basic scientific education and is well suited to the co-construction of knowledge [42, 52, 65]. Making complex decisions in science courses involves many aspects of critical thinking, such as understanding procedures for rational analysis of a problem, gathering and using of available information, clarifying the concerns and values raised by the issues, or coordinating hypotheses and evidence [123, 139]. Students evaluate the relevance and relativity of evidence and make choices by considering and respecting different viewpoints. Whenever a group makes a collective decision, each member of the group should reach the same decision individually [25]. Students should develop their own judgment and understanding on the problem, and exchange opinions with the group.

To improve students' ability to make decisions, it is necessary not only to focus on the result of their discussions but also on how the students carry out the decision-making process, such as how they are able to evaluate and take into account the available information individually [146]. Learning environments supporting decision-making processes should enable both collective and individual activities, including exploring and analyzing data, modeling, voting, or analyzing decisions.

In the meantime, the former works [22, 135] and our experiments confirm that MSE is suited to support decision-making and problem solving activities. Large shared displays are excellent at providing an overview of information. In most cases, they are used for supporting groups in prioritizing information, making comparisons, and structuring data that embodies the working hypotheses [151]. Personal devices support individual activities and enable participants to conduct analytical tasks, control and exploit additional information in parallel [134].

Former work in decision-making support with tabletops and MSE focused mostly on the system design and collaboration results. The objective of this chapter is to study how students pursue decision-making learning activities by using the combination of devices, and provide implications on designing collaborative decision-making activities in MSE. I show the design of Pickit, a MSE learning tool that enables students to explore various locations on a map on a shared display and decide which is the most appropriate by analyzing their characteristics on personal devices. I also demonstrate how students interact with personal and shared devices, and how collaboration mechanisms are performed in such an environment.

5.2 APPLICATION DESIGN

5.2.1 *Decision-making behaviors supported*

To understand teachers' requirements and expectations regarding the design of an environment for learning decision-making processes, we organized several workshops with four teachers from a vocational high school. Based on the discussions and workshops, we found that the decision-making process was often too complex for our target students.

Our exchanges with teachers strengthed by the literature [42, 52, 123] emphasize students' struggle with such complex process, especially with multi-dimensional analyses. The underlying problems lie in difficulties to: become familiar with the material, evaluate choices and reach a decision together, follow a process, know what others are doing and adjust behavior accordingly. Considering Ratcliffe's model [123], three stages (stage 3, 4 and 5) were particularly relevant to teachers' pedagogical concerns. These concerns are strengthening students' abilities to analyze and evaluate different options, weighing the benefits and drawbacks, expressing their own reasoning, considering others' opinions, and reaching group decisions. Other stages of the decision-making process such as defining criteria or searching for options [139] are not the main focus for the targeted learners. The knowledge about the activity, including the options, criteria and context would be developed in previous classes. Teachers would prepare these supporting material beforehand.

Our proposition thus focuses on supporting the analytical process in decision-making activities. In order to structure the design and evaluate the activity, we identified four broad categories of behaviors relevant to decision-making activities based on the literature (presented in Table 2, chapter 2) and the discussions with the teachers:

1. Exploring content;
2. Discussing options;
3. Maintaining group and activity awareness;
4. Regulating the activity.

Exploring is mostly an individual behavior, with which students can develop their own opinions. Exploring consists of browsing content, running simulations or conducting data analyses. It corresponds to behaviors linked to clarifying information and surveying described in several models [74, 123].

Discussing is the main collaborative mechanism involved in the decision-making process (Section 2.4.2.4). It happens when students are talking about and exchanging their ideas. According to the different models [2, 85, 123], this behavior occurs when participants are building common ground [23] on the options and collectively evaluating them. Ratcliffe identified several subcategories when analyzing discussing including *discussing options*, *discussing criteria*, *discussing information*, *comparing options*, and *choosing with reasoning*.

Awareness as defined in chapter 2 (Section 2.4.2.1), is necessary for collaborative activities to enable participants to adjust to the group progression. It involves monitoring the activity as it unfolds, its progress, what other people are doing and how the group is behaving as a whole [38].

Regulation refers to shared social regulation mechanism (Section 2.4.2.2). It is important in the context of collaborative decision-making, and even more so in a learning context in which students are still in the process of developing collaboration skills [59]. In a classroom environment, regulation can come from the teachers or the students themselves.

5.2.2 *Scenario*

The decision-making activity is part of a larger paper-based learning game focusing on a non-determinist and pluri-disciplinary pedagogical situation. The goal of the game is to set up a sustainable company breeding and selling insects. Students are split into groups of three people and must choose one kind of renewable energy and the family of insect to breed and sell.

Our application focuses on the selection of the best location to establish the insect farm. Students must analyze the geographical and abiotic data of four optional locations and decide which location is best. To do so, they should consider the breeding and living conditions of their insects, logistics requirements, and sustainable development principles. Teachers defined six criteria before the session for students to help them analyze: 1) moisture for breeding the insect; 2) temperature for breeding the insect; 3) feasibility of using wind energy; 4) feasibility of using solar energy; 5) accessibility (transport, communication routes); and 6) neighborhood.

To support students' progress throughout the activity, but also to monitor and evaluate the analytical process, we decided to structure the activity around three steps:

1. *Survey*: students explore, analyze the data and rate the four locations before they can move to the next step. We merge *clarifying information* (stage 3) and *evaluating option* (stage 4) of Ratcliffe's model into this step because of the close relation between these two stages and the non-linear nature of the process.

2. *Choice*: students decide which location to choose. Once a location is picked, they can move to the final step. This step is based on *choosing an option* (stage 5) of Ratcliffe's model.

3. *Justification*: students produce an explanation of their choice, explaining how the location meets their requirements based on the criteria. This step is essentially required by the teachers for the evaluation of students analytical skills.

5.2.3 *Application*

Pickit, the application developed, uses the combination of a tabletop and tablets to support analytical decision-making process (Figure 39). The tabletop is mostly dedicated to viewing the decision-making context and the tablets are dedicated for browsing the data about each location, i.e. the options in the decision-making model.

The tabletop displays a large map with four markers corresponding to the four locations to consider. To get the information about a location on their tablets, students need to tap a marker on the map, then tap their avatars in the pop-up box. An information button in the menu bar in the top left corner lets students get information about the energy and the insect they chose.

On their tablets, students can then see data about light intensity, wind strength, soil temperature, and humidity. The students can analyze each location based on six criteria defined by the teachers. Students must rate each location based on these criteria on a scale from one star to five stars. While exploring, they can also submit comments about the locations to help them build an argument and support later discussions. Such arguments can also be recorded to build a justification of the final decision. Each student has an individual color for their comments.

These evaluations appear as four cards representing the four locations to support group discussion (brown cards in Figure 39). On these cards, students can see each other's comments. When all the group members finish their rating, they can get the average of the group rating results on the cards. These cards can be dragged and scaled, which allows students to organize and compare different options when discussing. It also allows students to orient cards easily when sitting on the side of the tabletop.

We introduced several features to foster awareness and facilitate group regulation. For example, when a student picks a location to explore, the background color of his/her avatar on that option card will change on tablets in order to indicate who is exploring which location. Once a student has finished rating a location, a green checkmark appears on that option card next to his/her avatar as a sign of completion. On the menu bar, there are rating progress bars for each student and step-lists with the current step highlighted, to help students understand their progress and the ongoing task. Table 12 shows the functionalities of the application that support these decision-making behaviors.

We used AngularJS to develop a Web application running on tabletops and tablets. All the devices connect wirelessly to an external server hosted on Heroku, and they communicate via Web sockets.

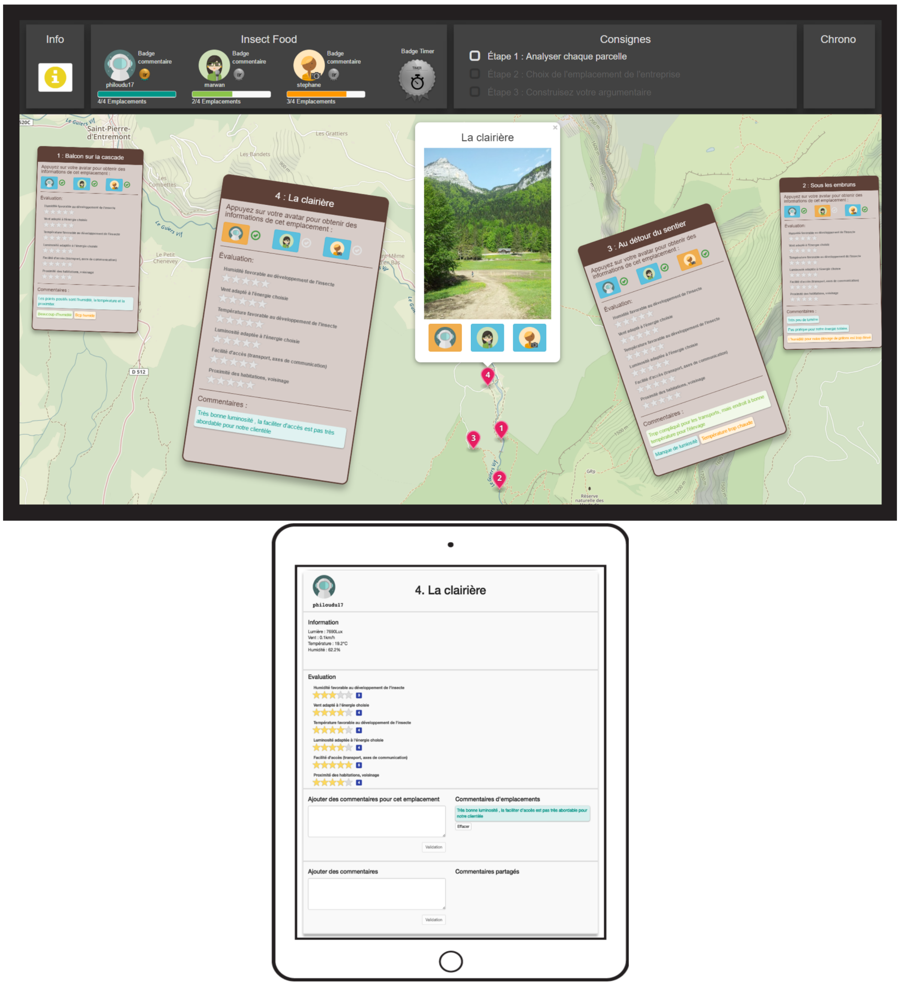


Figure 39: Pickit application. Top: A screenshot of the survey stage on tabletop. Bottom: Pickit on one student's tablet, from the top to bottom showing the location title, location information, rating, comment for the location, and comment in general.

5.3 STUDY

We conducted the activity described above in the high school to study whether and how our application supported the four categories of behaviors that were defined before, and how the devices were used when students were performing those behaviors.

5.3.1 *Participants*

Four groups of three students from the same high school class took part in the activity (12 in total). The students were between 16 and 19 years old (mean: 17.5, SD: 0.78), including seven females and five males. They knew each other well and had already worked together as groups in their former classes. Two teachers joined us to follow

Behaviors	Functionalities
Exploring (tabletop)	- Information button to show the decision making context (energy and insect) - Map to show the geographical condition of locations
Exploring (tablet)	- Showing data of locations - Rating tool based on criteria provided - Writing comments and arguments
Discussing (tabletop)	- Sharing everyone's comments - Providing average of the group's rating result - Showing location cards for comparison
Awareness & Regulation (tabletop)	- Showing who is exploring what - Progress bars for the rating processes - Check marker for the location that has been rated - List of steps in the menu bar

Table 12: Functionalities of the application to support decision-making behavior

groups and gave instructions on task. Teachers underlined that it was challenging for students from this class to collaborate.

5.3.2 *Apparatus*

Each group had a capacitive 27-inch horizontal touch screen with a resolution of 1920x1080 pixels, and a tablet per student (Galaxy Note 8 with protective covers). The touch-screens were positioned on round tables. Students all sat on the same side of the table and could rest the tablets on the table in front of the touch-screen (see Figure 40). All the devices were wirelessly connected to the network.

5.3.3 *Task organization*

Each session lasted about 30 minutes. The study took place in the high school library. Two groups performed the task at the same time. A teacher followed each group to give instructions. Before the task, the teacher explained the application to the students, and let them play with the application to familiarize themselves with all the functionalities. Several bookshelves isolated the two groups, to avoid any external influence during the task. Competition or collaboration between groups was neither encouraged nor discouraged.

Figure 40: Students in a decision-making activity using tablets and a horizontal surface.

5.3.4 *Data collection / Recording*

We used one camera set in front of the table to record the tabletop screen, students' interactions, gestures, and postures. We also collected logs to quantify interactions on the tabletop and tablets and complement the videos, e.g. know what was displayed on the tablets of the participants. After the experiment, students were asked to fill in a questionnaire containing 5-point Likert-scale and free-form questions about their perception of learning and their feelings on using the combination of devices to carry out the activity.

5.3.5 *Analysis method*

We focused our analysis on the four behaviors identified earlier. We used two type of data sources, the recorded videos, and logs. The goal of the analysis was not to provide quantitative data of the activity but to give qualitative insights on how students behaved and collaborated in MSE. We tried to understand how the design of our application impacted activity and device usage, and contributed to the decision-making process. To do so, we defined a coding scheme for the analysis of videos based on the literature presented previously.

Two coders analyzed the videos independently on different samples. They did an inter-rater reliability test with the result of 85% agreement. Then one researcher analyzed three groups and the other analyzed one group. Both of them went though the videos twice. The first time, they used the coding scheme and the second time, they noted down devices usage (for instance who was interacting on the shared display or how students used their tablets and the tabletop to discuss a specific option).

5.3.5.1 *Video coding scheme*

For exploring behaviors, we noted the sequence of exploring options of each student on a timeline. This timeline is used to analyse how students chose the options to explore, how long they spent on each option, and whether their exploration strategies were influenced by others.

To analyse discussing behaviors, we used the categories defined by Ratcliffe's [123]:

D-O. *discussing options*;

D-C. *discussing criteria*;

D-I. *discussing context (background knowledge or information)*;

D-CMP. *discussing benefits and drawback of options (comparing)*;

D-R. *choosing with reasoning*.

We coded awareness behaviors when they were directly linked to the MSE configuration and to the distribution of the interface among the different devices, for instance when someone was looking or taking a glance at one another to check what others are doing [126]:

AW. *looking what others are doing*.

We split regulation between group regulation (RG) and teachers initiating group regulation (RT). We coded regulation when observing monitoring and planning of the task, as in [125].

RG-1. *one group member reminds others of the time or the task progression*;

RG-2. *one group member offers help to others*;

RT. *teacher gives instructions on how to use the application or provides instruction/information to help students understand the decision they should make*.

5.3.5.2 *Pattern of device usage*

We analyzed the usage pattern from two dimensions: 1. The number of students involved in the activity; and 2. The devices students focused on. Table 13 outlines all the possible patterns that may happen. The categories Group of 3 and Group of 2 are the moments when the group activity is happening, such as discussion or regulation. The characters with dashed lines represent people conducting their own individual activity without involving others. They can either be interacting with a tabletop or a tablet. In all the patterns, the positions of characters are interchangeable. For example, in pattern 3-H1, the person focusing on the tabletop could also be positioned on the left or right side.

5.3.5.3 *Log analysis*

We focused our log analysis on the number of actions on the large display including zooming and dragging the map or the location card, pressing buttons, selecting avatars, etc. We computed students' ratings to see whether their final choice was the location for which they gave the highest score. We also gathered the number of comments and justifications of each student.

5.4 RESULTS

We now describe how the different groups performed the decision-making activity, focusing on the behaviors defined previously.

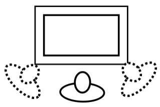
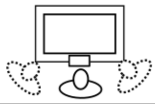
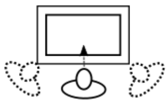
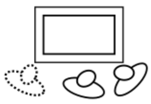
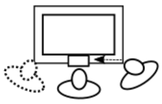
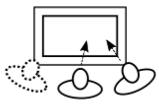
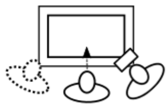
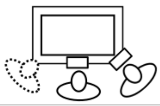
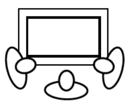
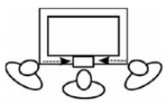
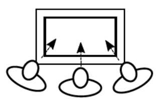
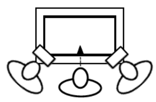
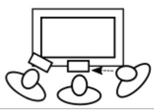
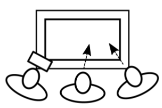
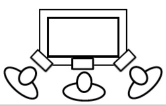
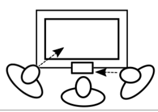
	Free focus	Tablet focus	Display focus	Hybrid focus
Individual	1-F 	1-T 	1-D 	-
Group of 2	2-F 	2-T1 	2-D 	2-H 
		2-T2 		
Group of 3	3-F 	3-T1 	3-D 	3-H1 
		3-T2 		3-H2 
		3-T3 		3-H3 

Table 13: Patterns of device usage.

5.4.1 *Overview of the activity*

Table 14 shows the overview of the activity, computed from the logs. We were interested in observing how groups structured the analytical process and which behaviors were involved in the different steps. We observed that three groups (G1, G2 and G3) explored options and began to discuss and compare them at the same time, during the *survey* step. Discussions always happened when one student finished browsing an option and wanted to exchange ideas with others. Such discussions only happened when students were checking or had already checked the location. But if other students did not check the location yet, the discussion would not be initiated.

Group 4 acted differently. The students explored options individually and did not discuss during the *survey* step, which made it much shorter. In this step, we observed fewer interactions on the shared display but a higher amount of individual comments for each location in comparison to the other groups. Discussions on the various options only happened in the *choice* step, which was longer than for the other groups.

G1, G2 and G3 spent a little time on the *choice* step as they already had discussions and changed their ideas in the former step. On the contrary, G4 began to discuss various options in the *choice* step, using the individual comments written on the previous step. Consequently, this step was longer than for the other groups.

		Group 1	Group 2	Group 3	Group 4
Step 1 *Survey*	Duration	25m15s	19m55s	24m43s	12m52s
	Interaction on large display	102	156	50	35
	Comments	14	15	16	26
Step 2 *Choice*	Duration	36s	1m40s	59s	3m20s
	Interaction on large display	8	10	2	25
Step 3 *Justification*	Duration	12m38s	4m2s	5m51s	7m8s
	Interaction on large display	7	30	2	8
	Arguments	3	3	3	3

Table 14: An overview of the activity of each group

5.4.2 *Exploration*

Exploration happened mostly during the *survey* step. Students checked the information about breeding requirements of their insects, their chosen energy and geography of locations on the shared surface, and browsed each option and criteria (such as the temperature for breeding the insect or the feasibility of using wind energy) on their tablet. In G1, G2 and G3, students did not double check options in the last two steps, which indicated they knew well about these options after the *survey* step. Only G4, who did not discuss during the *survey* step, re-visited some locations in the *choice* step.

During the exploration, students acted individually when choosing a location to analyze on the map. We observed nevertheless implicit coordination in the choice of locations. From the Figure 41 we can see that three groups (G2, G3 and G4) started the exploration with the same location. When a participant selected another location, s/he was later followed by the two others. According to the speed of exploration of each student, we can observe adjustments and switches in the exploration sequences. For instance, in G3, after the second location visited, students 2 and 3 broke the order chosen by student 1, who is quicker than the other two. They chose the location that student 1 was exploring at this moment so they could discuss together.

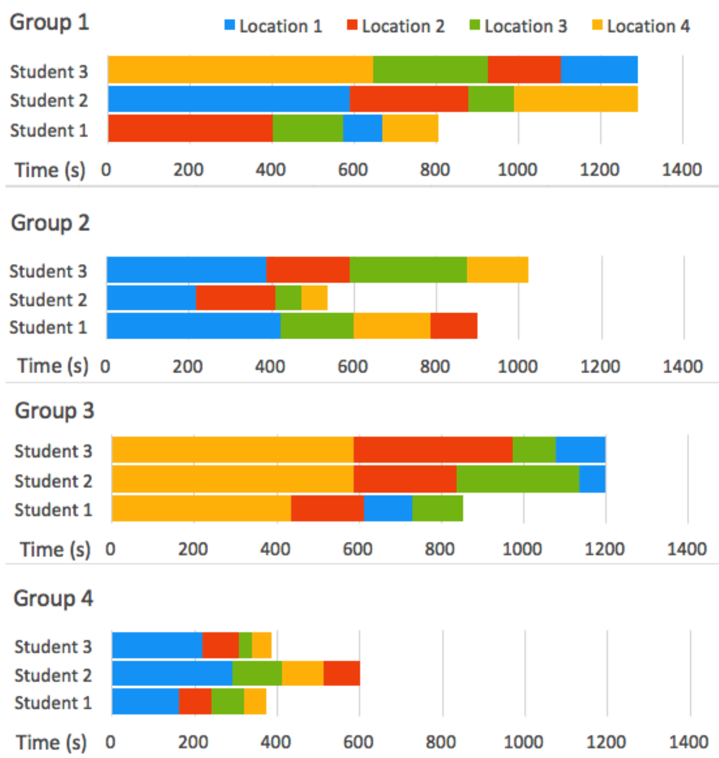


Figure 41: Location analysis sequence of each student based on the timeline. Four colors represent four locations.

Student A and B have the same location on their tablets: - A: “What do you think about the humidity?" (A looks at B.) - B: “It’s too humid." (B looks at his own tablet.) - A:“Too humid? What about the wind speed?" (A takes a look at her tablet, then looks at B.) - B: “We don’t care about wind, we use solar energy." (B looks at A.) - A: “Yes, but the light intensity is also not good enough." (A looks again at her tablet, then looks at B.) - B: “No, it only has 1017 lux." (B looks at his tablet.)

Table 15: Extract of G3 discussion on a specific option

We can find several periods in these three groups when students were checking the same location together. One reason for this could be they were influenced by the interface, choosing the marker that showed up on the display. The other reason could be that students wanted to evaluate together the same locations so they could discuss and share opinions. Only students of G1 adopted a different strategy. They chose different locations to explore on purpose during the whole survey.

5.4.3 *Discussion among group*

5.4.3.1 *Discussion in survey*

We counted the number of discursive acts in the *survey* step and the patterns used during these discussions from which we present only the most frequent, those which appeared in summation more than 80% of the time (Table 16). During this step, the most common pattern was two participants focusing on one tablet (2-T1), followed by two or three students focusing on the shared display (2-D and 3-D) and hybrid chat using both shared display and tablet (2-H). Students had most discussions dyadically and used tablets to discuss, especially when the discussions were related to options and criteria. In such cases, students used tablets to check a specific option, analyzing the data together according to the criteria, exchanging ideas and preferences (example of discussion in Table 4). Group 3 also used tablet focus dyads to synchronize the comments they were writing. When they discussed about the context and their preferences, the shared display was used more frequently (2-D and 3-D). Regarding group coordination, groups that tended to explore the same options in parallel on their tablets (G2 and G3) preferred to discuss using their tablets. Group 1, where students explored the location independently on their tablets, used mostly the tabletop to discuss.

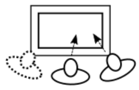
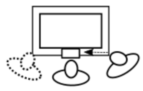
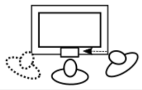
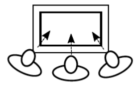
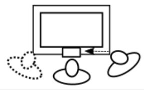
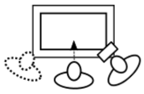
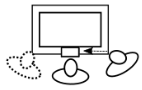
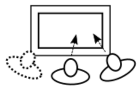
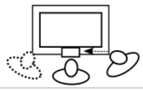
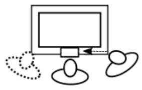
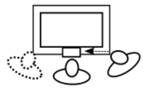
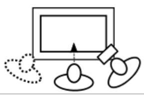
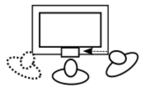
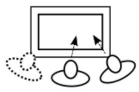
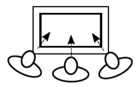
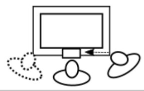
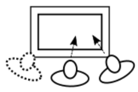
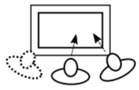
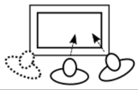
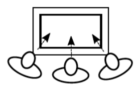
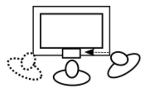
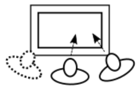
Discussion	Group 1		Group 2		Group 3		Mostly happened
	N	>80% pattern	N	>80% pattern	N	>80% pattern	
Option	12	2-D  2-T1 	8	2-T1  3-D 	14	2-T1  2-H 	2-T1 
Criteria	5	2-D  2-T1 	3	2-T1 	10	2-T1  2-H 	2-T1 
Context	6	2-D 	1	3-D 	2	2-T1 	2-D 
Comparing options	1	2-D 	3	2-D  3-D 	1	2-T1 	2-D 

Table 16: *Survey* step - The number of discussions (about option, criteria, content and comparing options) and the most common patterns.

5.4.3.2 *Discussion in choice and justification*

Discussions in the *choice* and *justification* steps were more concentrated in comparison to the *survey* step where they were fragmented. Therefore, we considered discussion durations instead of counting occurrences in our analysis (Table 17). Group 4 spent more time in these steps compared with other groups since they did not discuss during the *survey*. All the groups discussed in the 3-D pattern (discussing around tabletop). This indicates that the shared display supported groups in synchronizing opinions and reaching a decision. Group 4 also exhibited pattern 3-H1 (one student looking at the tabletop while two others looked at their tablets), when they had difficulty deciding which option was better and needed to check the data on their tablets again. This indicates that tablets served as supportive tools for debating during discussion when more information was needed.

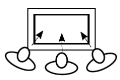
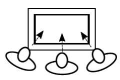
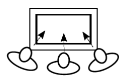
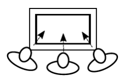
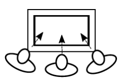
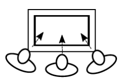
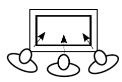
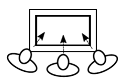
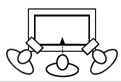
Discussion	Group 1		Group 2		Group 3		Group 4	
	Time (s)	>80% pattern	Time (s)	>80% pattern	Time (s)	>80% pattern	Time (s)	>80% pattern
Comparing options	142	3-D 	20	3-D 	37	3-D 	184	3-D 
Choosing with reasoning	12	3-D 	16	3-D 	11	3-D 	53	3-D  3-H1 

Table 17: *Choice* & *justification* step - The number of discussions (about comparing options and choosing with reasoning), and the most common patterns.

Location cards played an important role during the discussion. The ratings on the cards helped students to quickly find the options with the highest scores. Students could zoom out and put aside the options with lower scores and only focus on the best ones. We observed several times students were organizing the cards on the shared display together to compare options. The comments they added to the cards also reminded them of their reasoning and supported them in building justifications. In the end, each student submitted his/her justifications through his/her tablet. We observed two ways students used for submitting their justifications. In two groups, students submitted the group justification that they discussed and agreed upon. In two other groups, students distributed their justifications, each one submitting the justifications that concerned some specific aspect. From the logs, we saw that members of a group did not always have the same preferences, but all groups chose the option that had the highest average score.

5.4.4 *Awareness and regulation*

Awareness and regulation behaviors happened mainly in the *survey* step, when students were individually exploring options. The maintenance of awareness was subtle. For example, when one student chose an option on the tabletop, other students working on their tablets would take a glance at the tabletop. This slight head movement indicated that students could be aware of others actions on the tabletop. In group 2 and 3, although we did not observe students explicitly looking at each other, they still knew which option their partners were exploring and talked with them about that option. Awareness was mainly maintained through the patterns 2-D (one student looking at another's interaction on the tabletop) and 2-T1 (one student looks at another's tablet).

We did not observe many regulation behaviors in which students reminded others of their progress or time (RG-1) (mean = 1.25, SD = 0.96). In contrast, regulation in the form of supporting one another (RG-2) happened more frequently (mean = 17, SD = 10.7). For example, in group 1, student A was looking at the location card on the tabletop and saw student B dragging the map looking for the next location to explore. A pointed at a location card and said to B: "*This one you haven't evaluated.*" Such behaviors happened mostly over the tabletop (pattern 2-D) when they were tapping avatars for others, showing others the picture of a location on the map, or passing location cards. At a more minor level we also observed regulation behavior while students shared a tablet (pattern 2-T1).

Teachers intervened mostly at the beginning of each step to regulate the activity. It mainly involved explaining the task and the application functionalities. They also answered students' questions about the criteria and the decision-making context, ensuring relevance of students' analysis.

5.4.5 *Learning experience*

After the activity, we gathered students' feedback (Figure 42). They were all positive about their learning experience and the skills developed during the activity. In particular, they felt more competent in collaborating with others, analyzing problems and taking reasonable decisions at the end of the activity. Besides that, they were also enjoyed in the activity (see Figure 43). Most of them thought using a personal tablet with a shared display helped them collaborating.

We also interviewed teachers after the activity. They were all satisfied with the activity progress. Teachers were positively surprised to see that students collaborated well and could listen to others opinions as they used to have problems on collaborating.

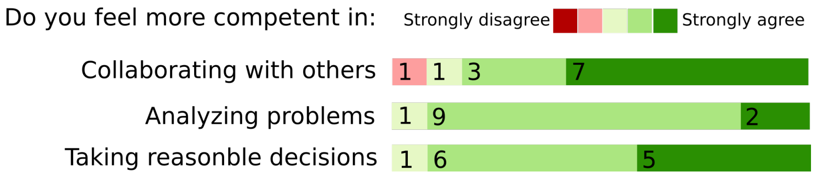


Figure 42: 5-point Likert questionnaires on learning results: *do you feel more competent in collaborating with others* (top), *analyzing problems* (middle), and *taking reasonable decisions* (bottom).

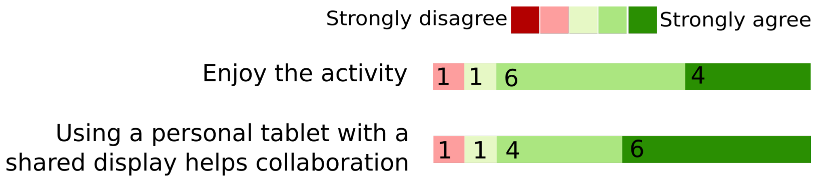


Figure 43: 5-point Likert questionnaires on learning experience: *enjoy the activity* (top) and *using a personal tablet with a shared display helps collaboration* (bottom).

5.5 DISCUSSION

We compare Pickit to former systems supporting decision-making (Table 18). Among this past work, only Convince me [139] and Argue-WISE [42] aimed at learning, and both used PCs. Convince me [139] only supported individual decision-making, and it ignored collaboration. Argue-WISE [42] was mainly focusing on building arguments. The two systems that used tabletop, T-vote [105] and Finger Talk [127], did not support analytical processes. None of these systems supported the full process of decision-making.

Caretta [143] and ePlan [22] supported problem-solving activities that involved decision-making processes. But they did not provide a clear decision-making flow, and they focused on analysis rather than taking decisions. Our study was the first one that used MSE for analytical decision-making with a defined flow, as well as collaborative learning.

5.5.1 *Main findings*

Our study showed that the analytical process conducted during decision making activities in classrooms can benefit from MSE properties. The combination of devices enabled tightly-coupled collaboration and loosely-coupled parallel work in the decision-making process, avoiding free-riding situations. The shared display seemed to increase students' awareness of the ongoing activity, and led students to explore the same option synchronously, but with a high level of freedom and without interfering with each other. In this sense, the tablets improved independent exploration of options within groups. Students were able to develop their own judgments on the various options using criteria, and hence increased their understanding. During discussions, the shared display supported students in synchronizing opinions and reaching a decision whereas tablets served as supportive tools for debating when more information was needed.

From an educational point of view, according to teachers, students all succeeded in making reasonable decisions and providing justifications to support their decisions. Students learned to argue and better structure a decision-making activity. Teachers also underlined the positive effects of the application on students' cross-disciplinary skills. They were more inclined to collaborate with others even though they usually have great difficulties to listen to others and consider other opinions. Former studies have demonstrated that prior friendship had a significant, large negative impact on group performance [97].

Systems	Device	Application context	Stages of decision-making supported and associated functionalities						Summary
			1) Listing options	2) Identifying criteria	3) Clarifying information	4) Evaluating options	5) Choosing an option	6) Evaluating decision	
Convince me [132]	PC	Science and sustainability issues	Listing options and evidences	-	Linking hypotheses and evidence	Evaluating evidence and belief	-	Obtaining feedback of evaluation	Making individual decisions, no collaboration
Argue-WISE [39]	PC	Socioscientific issues	-	-	Browsing information	Writing arguments	-	Writing arguments	Mainly focusing on building arguments
T-vote [99]	Tabletop	Finding a shared topic of interest in a Museum	-	-	-	Voting for topics		-	Not supporting the analytical process
Finger talk [120]	Tabletop	Calendar design	-	-	-	Browsing images	Choosing images	-	Not supporting the analytical process
Caretta [136]	MSE	Urban planning	-	-	Browsing information (individual)	Simulating plans (individual)	Agreement button (shared)	Backtracking (shared)	No clear decision-making flow
ePlan [20]	MSE	Emergency response planning	-	-	Browsing / sharing information (shared); annotating (individual)		-	-	Focusing on analysis rather than taking decisions
Pickit (our study)	MSE	Pluri-disciplinary sustainability issues	-	-	Browsing information (shared & individual); writing notes (individual)	Rating options based on criteria (individual)	Rating averages, validation (shared)	Writing arguments (individual)	Focusing on the analytical process and collaboration in a decision-making activity with a defined flow

Table 18: Comparison of Pickit with other systems supporting decision-making.

Our findings did not show that friendship had negative impact on collaboration.

5.5.2 *Implication for design*

5.5.2.1 *Structuring decision-making applications and taking advantages of MSE*

The design of decision-making activities should take into account the properties of MSE to balance individual and collaborative work, and to help students in structuring their analytical process.

As underlined by previous literature, we observed that depending on the groups, the stages of the analytical process could be more or less intertwined. Many times students were discussing during the individual exploration, building gradually their choice. The structure promoted more independent analytical work nonetheless. Students rated their options independently and were able to construct personal opinions. We did not observe free-riding behaviors in a class that was prone to it according to the teachers. We attribute this partly to the design of the application: the analysis being connected to each participant through their tablets, it made everyone accountable in a way.

In addition, distributing content on tablets led to less conflicts in viewing and analyzing, especially in our case where the information was abundant and challenging to display at once.

5.5.2.2 *Better supporting discussion*

On the whole, tablets supported well discussions, serving as supportive tools for debating. It also enabled students to freely analyze options at their own pace. Such a case of students evaluating different options at the same time tended to impede discussion. We observed in group 3 how confusion could arise from students discussion about specific criteria until they realized they were not exploring the same location, which led to an abrupt end to the discussion. We also hypothesize that group 4, which did not discuss at all in the survey stage, because one student did not let others look at her tablet. We assume that letting students going through options together may promote more discussions.

Moreover, giving an overview of analysis elements on the shared surface can support students in comparing options. We observed several times that students were organizing the cards according to the scores of options to debate. The comments added during the survey and displayed on the cards also supported students in building justifications.

5.5.2.3 *Better supporting awareness*

In our application, we distributed the controls between the shared display and tablets. For instance, in order to control what was displayed on their tablet, students needed to use the tabletop. An alternative could have been to offer tabs on the tablets so that all the locations would be directly available. However, we noticed that our strategy led to a good awareness of students' actions, status and progress. Students could notice when their partners finished one location and switched to the next. In addition, the features designed in the application, such as avatars showing who is exploring which option, progress bars and step-list, contributed to maintaining a good level of awareness.

5.5.3 *Limitations*

The design of Pickit was focused on the analytical process in decision-making activities. In agreement with the teachers, we decided to not support several aspects of the process, such as searching for options, and identifying criteria. We assume that more features would be required in the application when supporting the whole process of decision-making. Also, we should investigate deeper whether the design of the application could influence or introduce some bias in the behaviors we analyzed. In particular, it remains difficult to establish if the sequences of location explored during the survey followed a specific strategy or if it was a consequence of the interface, displaying the last location chosen by someone.

5.6 CONCLUSION

This chapter presents Pickit, a system supporting decision-making process in MSE. Our application design is grounded in workshops with teachers and an in-depth analysis of the literature on decision-making process and collaborative behaviors. Based on these dual requirements from teachers and the literature, we focused on the analytical process of the decision-making activity, which involves four broad categories of decision-making behaviors: exploring, discussing, awareness and regulation.

We conducted a study with 12 high school students to understand how our application would support in a complex decision-making scenario, involving the consideration of multiple options, criteria and background information. A second purpose of the study was to understand how students interact with personal and shared devices in such an environment. Our results show that Pickit is supportive for the analytical decision-making process. It helps students develop their own ideas and makes free-riding more difficult. Students were all succeed in making reasonable decisions and providing justifications to support their decisions. Our experience indicates that the design of decision-making learning activities in MSE is complex and time-consuming. In the next chapter, I will provide an authoring tool that can make the creation of decision-making activities in MSE faster and easier.

6 DECIMAKE: AN AUTHORING TOOL FOR CREATING DECISION-MAKING ACTIVITIES IN MSE

Chapter 5 presents the design of a decision-making learning activity in MSE and how students perform the activity using the combination of devices. This chapter presents the design of an authoring tool named Decimake. My goal is to support users in creating custom decision-making activities in MSE. The design of Decimake is based on the literature review of decision-making models and an analysis of teachers' needs. It can be used by teachers to generate decision-making learning activities in MSE. Teachers can prepare the decision-making context, including alternatives, criteria, and related information.

6.1 BACKGROUND

The former chapter shows the importance of decision-making in scientific education. Making complex decisions in science courses involves many aspects of critical thinking that can help students increase scientific understanding, learn to face problems and challenges, clarify issues, and identify solutions [42, 52, 65]. MSE can be suited for collaborative decision-making activities, especially for activities that require both collaborative and individual tasks [143].

However, in MSE the design of decision-making learning activities is quite complex and time-consuming. From our experience, co-designing the decision-making activity presented in Chapter 5 with a group of teachers, the design session lasted for more than a half year and it took several iterations until we all agreed on the final version and began the implementation. We organized several workshops with teachers to learn about their teaching requirements and discuss about the learning contexts for the application. This long process can be shorter and simpler if teachers could create and modify decision-making applications. They would have more freedom to adjust the applications based on their teaching goals, while meeting their students' skills and abilities.

As we mentioned in chapter 2 (Section 2.3), there are frameworks that focus on addressing the technical issues in MSE, such as the distribution of interface and interaction [82, 109]. However, these frameworks do not support scripting and orchestrating learning scenarios. Some authoring tools have also been developed to help educators create learning activities. For example, StoryTec [51] supports the creation of digital storytelling learning games which can be published both on PCs and smartphones. Digital Mysteries[1] [80] offers an authoring tool that allows teachers to create mysteries from scratch or edit existing mysteries for PCs or stand-alone tabletops. However, these authoring tools can only help users create learning activities in in single device environment, such as on tablets, PCs or tabletops. They do not consider the condition where there are multiple devices in the environment, neither support distributing interaction and interface between devices.

This chapter presents the design of Decimake, an authoring tool that addresses both the technical and teaching issues. Authoring tools are systems that aim to "reduce the development cost and to allow practicing educators to become more involve in their creation" [106]. They allow people with no particular programming skills to design, configure and run learning activities. The programming features are built in but hidden, so the author does not need to know how to program. The goal of our authoring tool, Decimake, is to allow teachers or researchers to rapidly create decision-making learning activities in MSE and encourage them to test ideas and find better ways for teaching.

6.2 DECISION-MAKING PROCESS MODEL

The complexities of decision-making process are acknowledged [123]. To help students understand and learn how to make decision, it is important to create the applications that follow or enclose the decision-making process. Over the past years, various models of decision-making processes have been proposed in different domains. For instance, in the psychology domain, the seminal work of Janis and Mann provide a theory that outlines five stages of effective decision-making [74]:

1. Appraising the challenge;
2. Surveying alternatives;
3. Weighing alternatives;
4. Deliberating about commitment;
5. Adhering to the decision.

Their theory provides a comprehensive and descriptive model of decision-making. However, it emphasizes individual-level properties and provides suggestions on how individuals should make decisions. Hirokawa et al. [64] attempt to integrate concepts from various disciplines, such as communication, engineering, psychology and sociology, to provide a theoretical model for group decision-making:

1 http://www.reflectivethinking.com/digitalmysteries

1. *Individual decision-making.* At the early stages of the decision-making process, group members function as individual decision makers and respond to the task in terms of their own cognitive schema.

2. *Group communication.* Group members begin to communicate with others members to integrate various elements into their own cognitive scheme.

3. *Form decisional preferences.* As the communication continues, group members begin to form decisional preferences. Group members tends to justify positions and have persuasive communication.

This model provides an overview on decision-making processes from the individual-level to the group-level. However, these is still a lack of concerns on organizing decision-making activity for teaching. Beyth-Marom et al. [18] offer normative principles when teaching decision-making to adolescents:

1. Distinguishing between decision calling for different decision-making models (e.g., decisions under certainty, risk, and uncertainty).

2. Identifying and defining a decision-making situation.

3. Listing action alternatives.

4. Identifying criteria for comparing the alternatives and the possible consequences of each alternative.

5. Assessing the probability of possible consequences (when necessary).

6. Evaluating each alternative in terms of its attractiveness and probability.

7. Assessing the value of collecting additional information.

8. Evaluating the decision-making process.

In this normative model, Beyth-Marom et al. clarify the steps of decision-making precisely. They emphasize the importance of students' understanding, such as what they know already and how they intuitively approach decision-making tasks. Ratcliffe [123] draws upon elements from former works [18, 64, 74] and proposes a decision-making structure for students within the science curriculum consisting of 6 stages:

1. *Options*. List or identify the possible alternative courses of action in considering the problem or issue.

2. *Criteria*. Develop or identify suitable criteria for comparing these alternative courses of action. The nature of these criteria is left open to discussion.

3. *Information*. Clarify the information known about possible alternatives, with particular reference to the criteria identified and to any scientific knowledge or evidence.

4. *Survey*. Evaluate the advantages and disadvantages of each alternative against the criteria identified.

5. *Review*. Evaluate the decision-making process undertaken, identifying any possible improvements.

Ratcliffe's model provides a structure that can be used in scientific curriculum to guide students on taking decisions and organizing group discussions. The six steps have encouraged a particular logic which focus on both knowledge building and group collaboration. We thus build our work upon Ratcliffe's model, meanwhile introducing a little modification to answer teachers' specific needs we observed.

As we mentioned in chapter 5, teachers highly emphasize the problems that students have in the analytical process, especially with multi-dimensional analyses. The underlying problems lie in difficulties to: 1) become familiar with the decision-making context, 2) evaluate options and 3) reach a decision together.

Not as in former models that regard "listing options" as a main stage, we chose to eliminate this stage as the process of listing options is still quite difficult for students. Teachers also suggest to prepare the options for students. By doing so, they can have more control on the scope of the learning and can let students step into the analytical process in a more straightforward manner. Identifying criteria should also be an optional stage, depending on the difficulty level of the learning context. By combining the suggestions from teachers and former models, we propose a decision-making model for designing the application as follow:

1. **Identifying criteria**. This is an optional stage in the application that is decided by teachers. Teachers can decide to prepare criteria for their students. Or they can let students define criteria by themselves.

2. **Analyzing and evaluating options**. In this stage, students need to analyze and evaluate the advantages and disadvantages of options according to the criteria previously identified. Depending on teachers' educational purpose, this stage can be designed as an individual task, to ask each student do his/her own analysis and evaluation, or let group of students do it collaboratively.

3. **Comparing options and making decisions**. After understanding all the options, students now need to compare and choose an option based on the analysis undertaken. This stage should be performed collaboratively, students present their preferences on each option, persuade or argue with each other, and reach the final decision together.

4. **Justification**. This stage is also an optional one that is sometime required by teachers. In this stage, students provide and present the justifications of their choice to teachers. Teacher will give instructions on their decision and help students identify any possible improvements.

Our model, as well as the former models, are presented as linear. However, the decision-making processes rarely flow in a linear sequence [64, 124]. The stage 2, *analyzing and evaluating options*, and stage 3, *comparing options and making decision* are sometimes intertwined, especially in a single activity that requires taking a sequence of decisions. Students can behave differently according to their preferences. They may prefer to analyze all the options before making a decision, or make the choice while analyzing. For example, in a trip planning activity which involves making decisions on attractions, hotels and itineraries, students can firstly browse all the attractions and hotels then plan the itinerary in the end, or they can decide which attractions to visit while planing their itinerary. Therefore, the decision-making application should be based on the nature of the activity. It can force students to strictly follow the decision-making process, or give them the freedom to perform the tasks based on their preferences.

6.3 DECIMAKE: AN AUTHORING TOOL

Our goal is to provide an authoring tool to create decision-making learning activities in MSE, which we call it "Decimake". Decimake follows our proposed model to build the main structure of the decision-making activities. It is also equipped with more features to ensure the adaptation to the digital environment and also meet the teaching requirements, including the devices' roles in MSE, gamification elements and group settings.

6.3.1 *Role of devices*

Decimake should be able to assign the role of devices that are available in the environment. We have highlighted in the former chapters that different types of surfaces in MSE are suited for different kinds of activities. The large surface are well suited for group activities, such as sharing information, exchanging ideas, discussing and negotiating. While mobile devices are often regarded as personal devices for performing the individual activities, such as browsing detailed information, providing personal opinions and individual evaluating. The role of devices will follow the principles. The shared surface can be used to display the whole context of decision-making, list options, and show the comments of students. The decision-making context can be presented on the shared surface in different forms depending on the nature of the activity, such as a map on the background for geographical applications, or digital cards showing the options and relevant information. On the other hand, the mobile devices will be used for individuals to analyze detailed information of options, provide evaluation and take notes.

However, this principle is only suited for the MSE that have both shared surface and mobile devices. We also consider another configuration of MSE: only large surfaces. Teachers can choose the configuration of MSE using Decimake based on the devices they have at hands. When only having large surfaces, it is no longer a MSE. Decimake will create the decision-making activity which is totally collaborative with no individual tasks. Students go through the process together. There is not private space for individual analyzing and evaluating.

6.3.2 *Gamification elements*

Gamification, defined by Deterding et al. [26], means *the use of game design elements in non-game contexts*. It has been used in learning activities to improve the learning experience and gain engagement [27]. In our decision-making activity presented in chapter 5, several gamification elements and indicators are used to motivate and encourage students, including the progress bar and check markers for evaluating the options, and badges for submitting enough comments or finishing the activity in time. These elements add entertainment and motivation to the activity while encouraging students to regulate their behaviors. Decimake will provide these gamification elements to teachers, let them choose which elements they want to add to the activity and configure these elements.

6.3.3 *Class setting*

When conducting a decision-making activity in a real class situation, students will be divided into several groups and all the groups will perform the activity. The digital contents students created, such as comments for options and evaluating results, can be stored in a database for teachers to review after the class. Therefore, we should give each student a recognizable identity in the application, such as his/her name, to store their data. Due to the limited time on a class, it would be better to prepare the class settings for the application instead of letting students create their accounts on the spot. Decimake will allow teachers to define and store class setting for the application, including groups' names, the size of a group, and each student name in a group.

6.3.4 *Activities covered by Decimake*

Decimake was initially designed for the teachers from the agricultural vocational school that we have collaboration with. According to the teachers, analyzing environmental conditions plays an important role in their classes. Therefore, we implemented Decimake which aims to create geographic decision-making learning applications. The geographic decision-making application is a specific type of application that has a map in the background while containing all the functionalities that a normal decision-making application requires, including the decision-making context and options. In a geographic decision-making application, the options are related to different locations, and the goal is analyzing different locations according to the criteria, then choosing one or several appropriate locations.

6.3.5 *Technological choices*

The growing popularity and cross-platform support of web and hybrid applications [156] make web programming language the ideal choice for our authoring tool. We used Javascript, Html and AngularJS for implementing Decimake which is hosted on Heroku. The created applications will have the similar layout and mechanisms with Pickit (the application that presented in chapter 5, Figure 39).

6.4 CREATING A DECISION-MAKING ACTIVITY WITH DECIMAKE

Creating a decision-making activity using Decimake consists of two main parts: 1) configuring the decision-making application and 2) configuring the class. Figure 44 shows the home page of the Decimake. By configuring the application and class separately, teachers can choose to run the same application for several classes, and vice versa.

6.4.1 *Configuring an application*

Part 1 on the homepage is to configure the application. It shows all the existing applications (if there is any). Teachers can edit, delete and also add applications. We offer two options for teachers to create a new application: 1) Create based on an existing application (Fig-

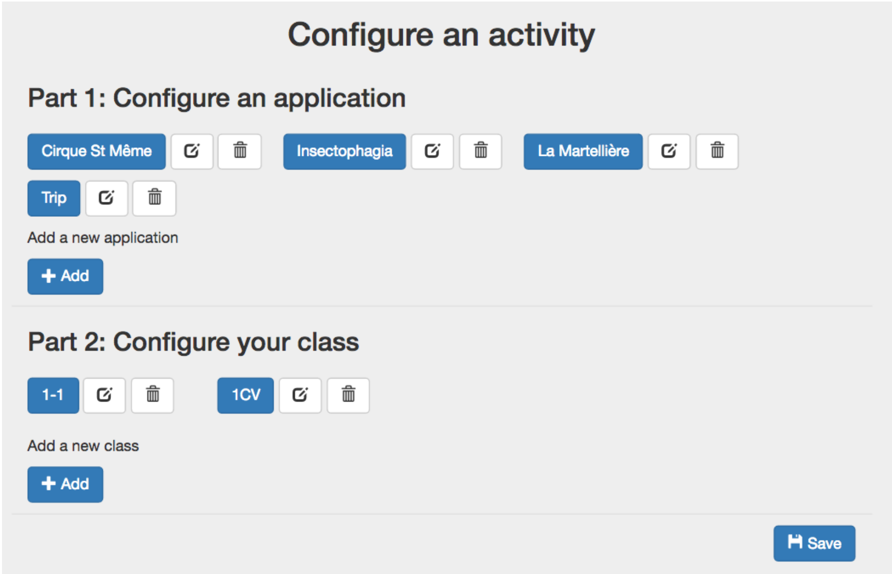


Figure 44: The homepage of Decimake

ure 45-top). This option will generate a copy of an existing application which they can modify based on their new requirements. This option is better suited for creating a similar application as former ones. 2) Create a new application (Figure 45-bottom). When teachers choose this option, they will create a totally new application. They need to define the type of the application. We offer two application types: "map" and "other". "Map" is to create geographic applications that have a map on the background on the shared surface. Other type represents more general applications, which do not have to rely on geographic information. In the current version, we only offer the "map" type. Once teachers choose to create an application, they will jump to the next page to configure the application.

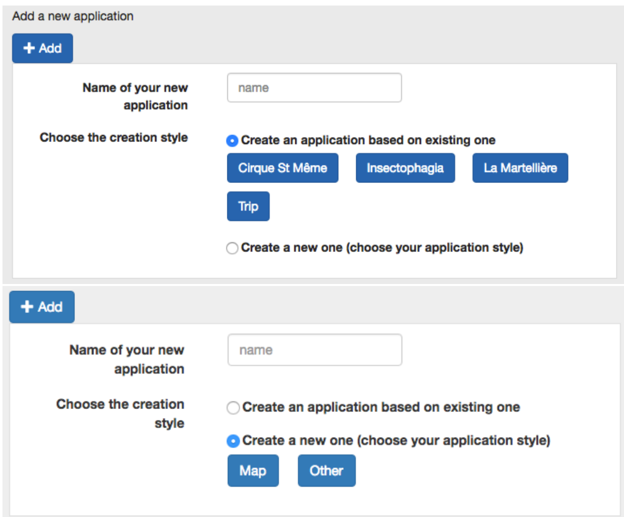


Figure 45: Two options for creating a new application.

Creating a geographic decision-making application using the Decimake only contains of three main steps: 1) define the nature of decision-making, 2) define the application flow, and 3) adding the indicators and gamification elements.

6.4.1.1 *Step 1: define the nature of decision-making*

In this step, teachers need to clarify the nature of the decision that must be taken by students, including the context of the decision-making and the options (Figure 46).

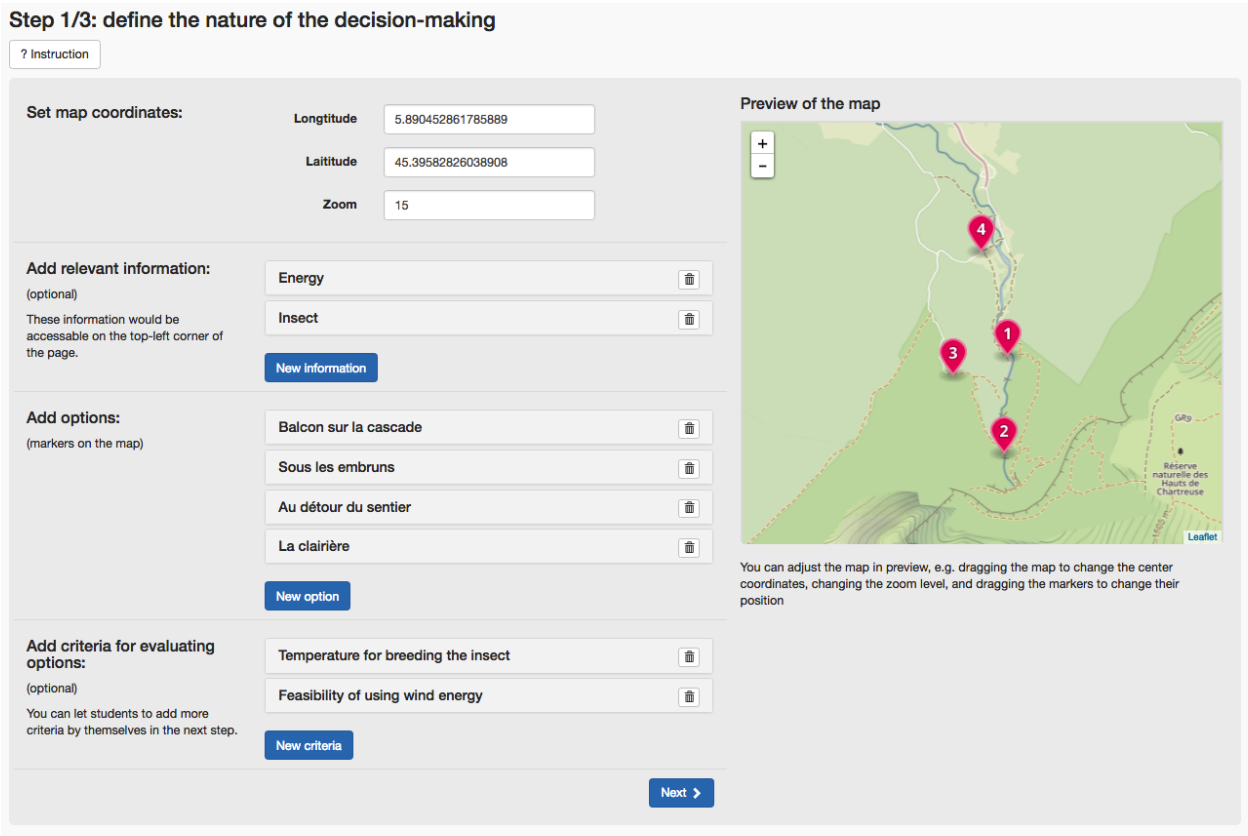


Figure 46: Decimake: step 1 - define the nature of decision-making.

1) Set map coordinates. Teachers need to set the map coordinates for the application in order to reveal the locations they concern. For example, in Pickit the coordinates should be the location of the mountain. Teachers can input the coordinates and the zoom level directly in the form or they can drag and zoom the thumbnail map on the right side to adjust the map.

2) Add relevant information. Teachers can add information that are relevant to the activity to help students making decision reasonable. The information can take different forms including images, texts, or external links. For example, the relevant information we added in Pickit were concerning the reusable energy and insects.

3) Add options. Teachers need to add all the options that they want students to evaluate. In a map-based activity, the options are usually locations. Each location will be presented as a marker on the map. Teachers need to provide the necessary information in order to create an option, including name, marker symbol, coordinates, and detailed data that require to be analyzed. They can also adjust the coordinates of locations by dragging them on the thumbnail map. Besides the markers on the map, option will also be presented as a card on the shared surface with students' avatars on it. Students can choose their avatars on an option card to get its detailed data on their tablets.

4) Add criteria. This is an optional choice. Teachers can choose to define criteria for their students to help them evaluate options, or they can let students define criteria by themselves. For example, in Pickit, the criteria were defined by teachers including *temperature for breeding the insect*, *feasibility of using wind energy*, and *accessibility (transport, communication routes)*. When the criteria are defined, students need to evaluate options based on the criteria. Each criteria is presented as a rating tool on students tablets. Students need to rate the options based on each criteria. The shared surface will show the average rating when a group finishes their rating. Teachers can also add no criteria for the application, or add the "identify criteria" step in the following setting to let students define criteria by themselves.

6.4.1.2 *Step 2: define the flow of the application*

As we defined in the proposed decision-making model, the stage 2 (analyzing and evaluating options) and stage 3 (comparing options and making decision) are sometimes intertwined, or even mixed, depending on the nature of the activity and students behaviors. In this step, we offer two options for teachers to structure the activity: the unrestricted and the restricted sequence.

2) Unrestricted sequence (see Figure 47)

Stage 1 (identify criteria) is an optional stage which can be enabled or disabled. If it is enabled, students will be asked to define the criteria at the beginning of the activity. They can add criteria by using their tablets. A new criteria must be agreed upon by all the group members to finally appear on the devices.

In the unrestricted sequence, stage 2 and stage 3 in the model are mixed which are named together stage 2. Students can make decisions while they are analyzing and evaluating options. The final choice in this sequence is not limited to only one option. Students can choose multiple options without evaluating all of them. Besides, teachers also need to identify the scale of the rating system for the evaluation. We use a star rating system for the evaluation, more stars means the options is more fitting the criteria. The scale of the stars depends on how precisely teachers want students to do the evaluation.

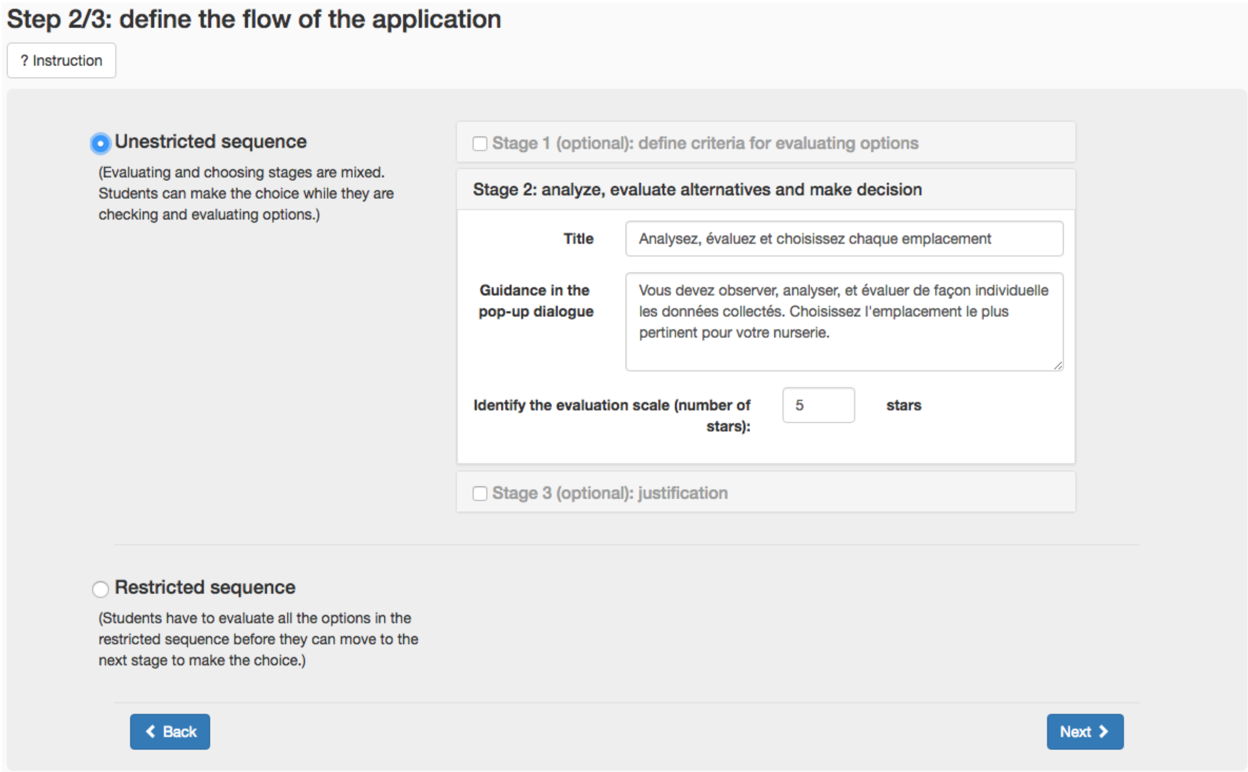


Figure 47: Decimake: step 2- unrestricted sequence.

Stage 3 (former stage 4, justification) is also optional. Teachers need to choose whether to enable this stage to let students provide justification for their choice.

Within the sequence, teachers need to configure each stage in detail, including the title and description of each step. The description will be shown in a pop-up dialog on the shared surface to give students instruction when they move to a new stage. We offer teachers a default example of title and description of each step. The unrestricted sequence is more suitable for a casual and open ended activity.

2) Restricted sequence (see Figure 47)

In the restricted sequence, students need to strictly follow the decision-making model step by step, which means they have to evaluate all the options before they can step to the next stage to make the choice. This sequence is suited for an activity that requires students to analyze all the options and develop their individual analytical skills.

The stage 2 requires students to finish evaluating all the options before they can move to the step 3. There are two ways for finishing the evaluation: 1) each student needs to evaluate all the options, and 2) a group needs to evaluate all the options by sharing the work. The first way will turn the step 2 to an individual task as each student need to do his/her own analysis. Teachers can choose this one if they want to strengthen students' individual analytical skill. The second way allows students in a group to distribute the evaluation

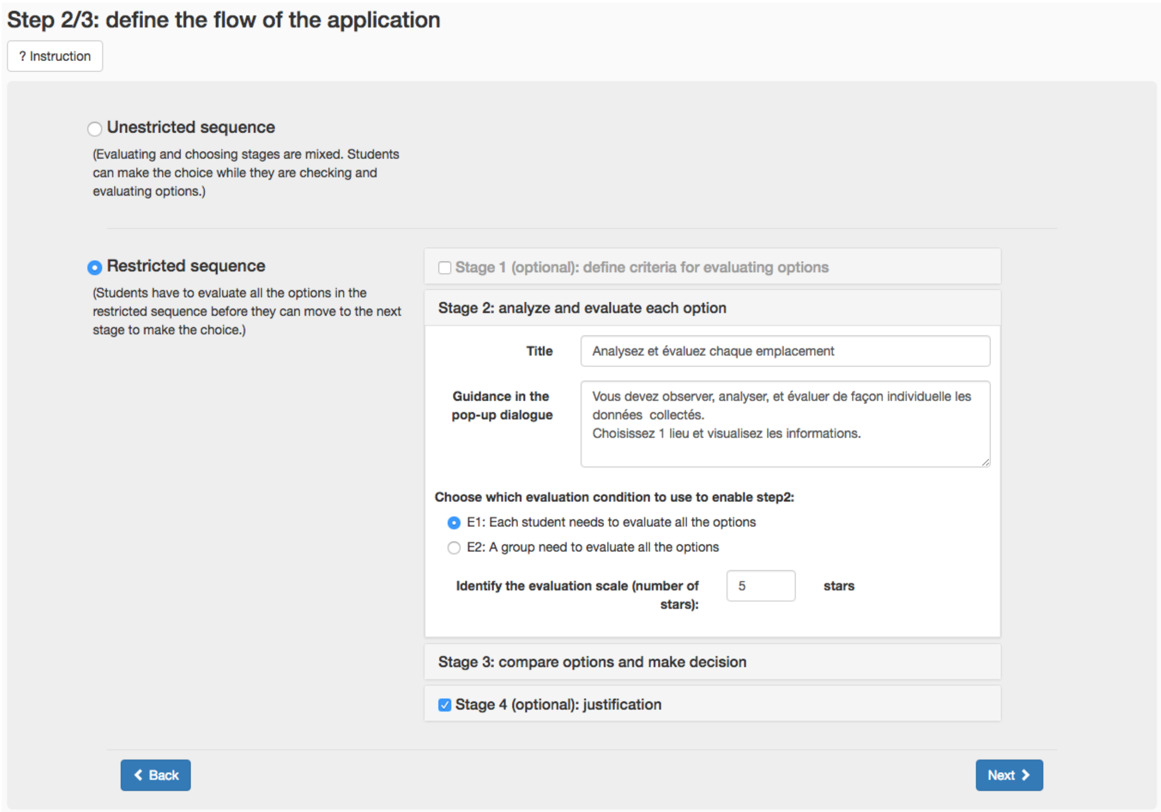


Figure 48: Decimake: step 2- restricted sequence.

task. More collaborative behaviors are favoured when choosing this way. Teachers should also identify the evaluation scale as explained in the unrestricted sequence.

In the stage 3, students will obtain the rating results. In this stage, they need to compare different options and make their final decision. Teachers can decide how many options they want students to choose in the end, one or multiple.

As in the unrestricted sequence, stage 1 (criteria) and stage 4 (justification) are still optional. Teachers also need to configure the title and description of each stage.

6.4.1.3 *Step 3: add indicators and gamification elements*

In this step, teachers will choose which indicators and gamification elements they want to add to the activity. These features would help students to be aware of their progress, encourage them to regulate their behaviors, and motivate and stimulate them to finish their tasks.

The progress bar can only be seen when teachers have chosen restricted sequence Figure 49. As the restricted sequence asks students to finish all the evaluation before they can step into stage 3, the progress bar can then indicate how many options left to be evaluated, to help students being aware of their progression. We also offer two

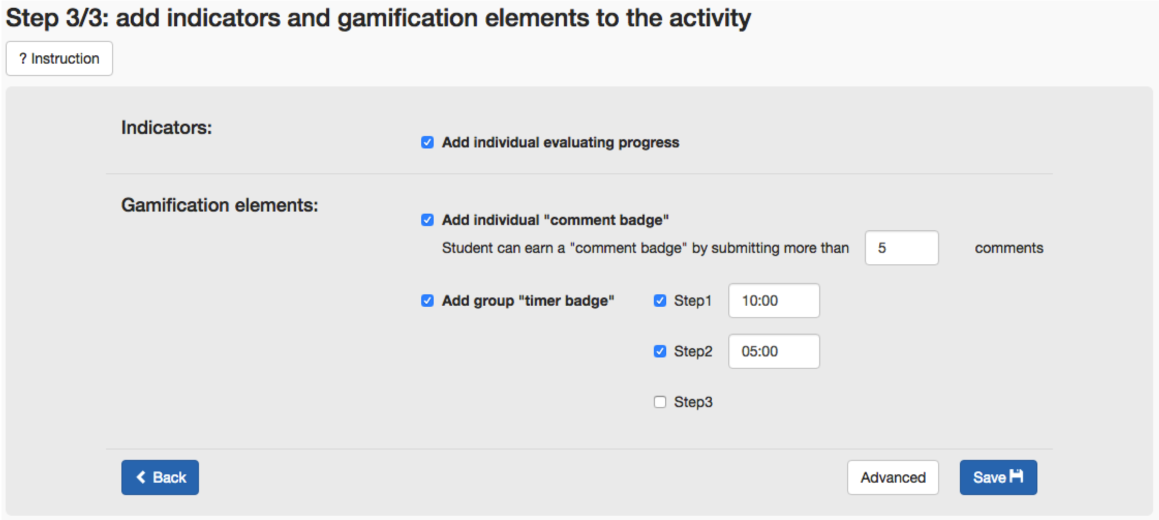


Figure 49: Decimake: step 3 - add gamification elements.

gamification elements: the "comment badge" and the "timer badge". The “comment badge” is an individual reward. Student can win it by submitting more than a specific number of comments. Teachers need to give the minimum number of the comments. The “timer badge” is a group reward. It will award the group which finish tasks within a limited time. Teachers can add the "timer badge" to each stage they choose in the former step, and set the limited time.

These is also an advanced feature in the step. Teacher can define the devices configuration in MSE. The default setting is using a large display as the shared surface and tablets as personal devices. Teachers can change this to the configuration of only using a shared surface.

6.4.2 *Configuring the class*

After teachers finish configuring the decision-making application, they will move to the part 2 to configure the class. They can add their class including setting the class name, adding all the groups of the class, and adding students in each group. They can also modify or delete the existing classes. Teachers can set each group from two to four students as we focus on small group size concerning the ergonomic difficulty, as former studies did for the shared surface collaborative activity [6, 80, 143]. Figure 50 shows the information teachers need to provide for a class.

6.4.3 *Operationalizing the activity*

Once finished configuring the application and class, the final step is to publish the activity on a Heroku server. Teachers need to choose the application then want to run and also their class. Then they can

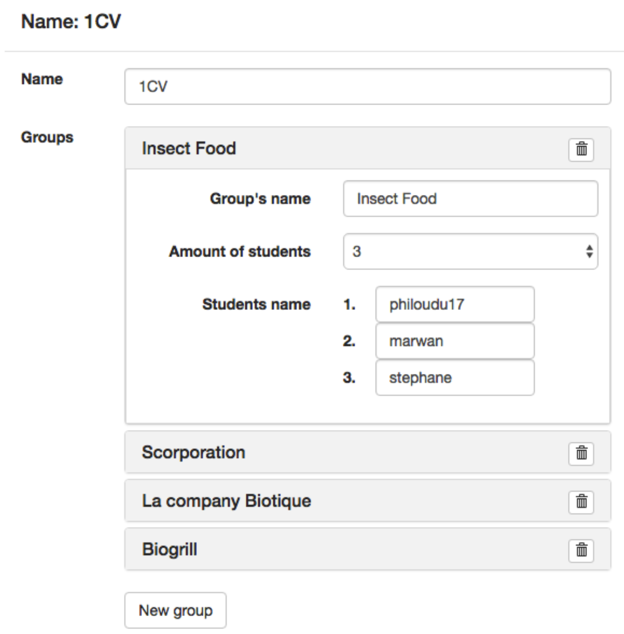


Figure 50: Decimake: configure class.

get access to the application by copying the url. Figure 51 shows that the application "Insectophagia" and class "1CV" is chosen for the activity. Figure 52 shows the final application that we just created with students' information in it.

6.5 USER TEST

We invited a teacher from the vocational school to create a new application using Decimake. We firstly showed Cerise, the teacher, how to use Decimake. I created a simple application with a trip-planning scenario, and explained her the links between the created application and Decimake, such as which part of the application was created by which step in Decimake. The introduction lasted for ten minutes.

After the introduction, we asked Cerise to create a decision-making application based on an experiment students did near their school. In the experiment, four groups of students collected data of three locations, including soil temperature, light intensity, wind speed and nitrate. Their following task was to compare these environmental conditions of three locations and choose the most suitable location in concern of raising insects and using sustainable energy. Cerise needed to use Decimake to create an application that implemented these functionalities, including setting the map coordinates, adding three locations and the data of each location, choosing the decision-making sequence, etc.

We did not set limitations on time. Cerise could spend as much time as she wanted to be familiar with Decimake and create the ap-

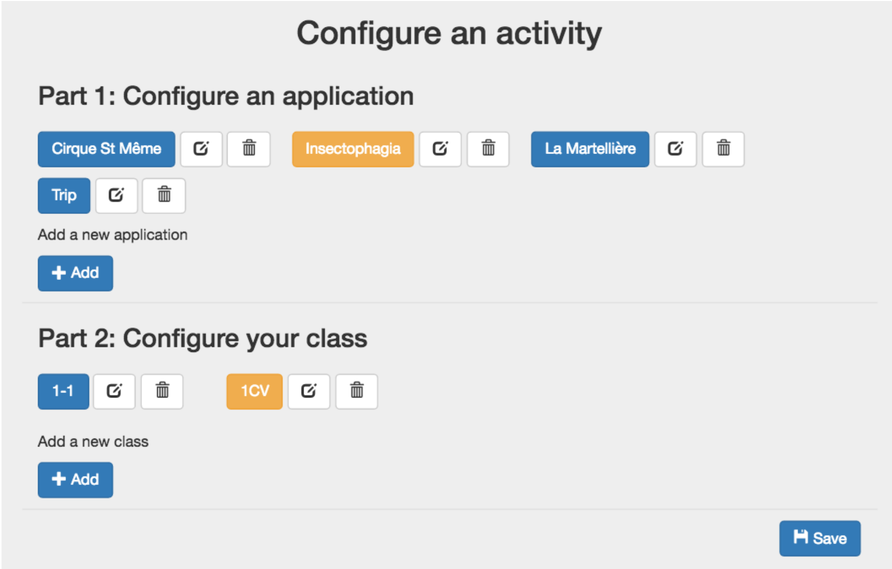


Figure 51: Decimake: deploy the activity.

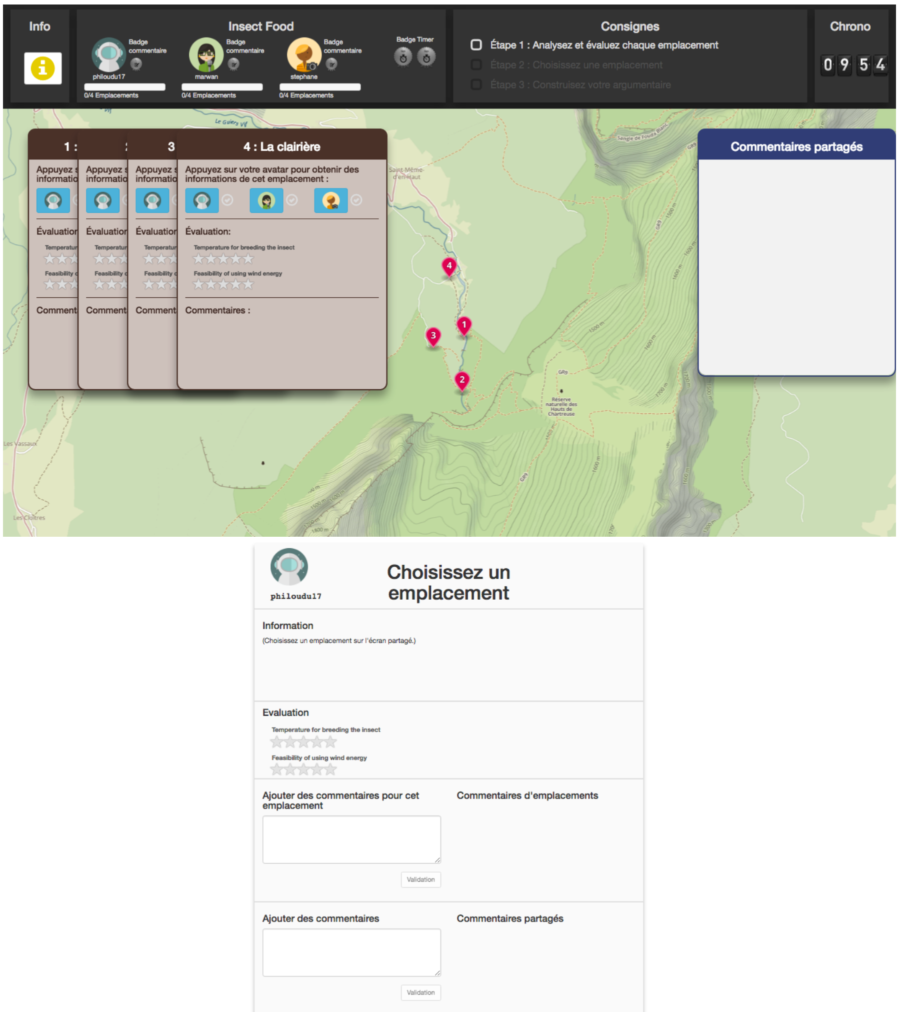


Figure 52: Final application. Top: application on the shared surface. Bottom: application on the one student's device.

plication. We were there to offer help, but we encouraged her to finish the creation by herself. She could feel free to ask about translation of the interface, as it was written in English (she speaks French). We also recorded the screen during the test.

Cerise successfully created a decision-making application with little help. Most of the time, Cerise could understand what she should do in each step. The only thing she was confused about was the flow of activity, and which sequence to choose. After we explained it to her, she immediately knew what to do. The rest of the instructions we gave were about the translation of the interface. During the test, she made a mistake when configuring relevant information. She only provided the title of the information she wanted to add, but did not provide the context. We reminded it to her after the test. The screen record showed that she spent 32m29s for the whole test, including 12m50s on defining the nature of decision-making application (step 1), 11m46s on defining the flow of application (step 2), 1m07s on adding gamification elements (step 3), and 6m46s for inputting class information.

After the test, we had an informal interview asking Cerise about the experience of using Decimake. Cerise was quite satisfied with Decimake. She said that Decimake is *easy to use*. After creating an application, she understood the functionalities. She was very confident that she could redo it again by herself in a shorter time. She also provided us some useful suggestions, such as how it would be better to see the preview of the application when she modified the parameters. These suggestions will be updated in the next version of Decimake.

After the test, Cerise created another application totally by herself and used it in her class. Students successfully performed that decision-making activity.

6.6 LIMITATIONS AND FUTURE WORK

The main goal of Decimake is to help teachers to easily create decision-making activities in MSE. Even though the examples given in this chapter were always related to learning, Decimake can also be used to create other kinds of decision-making activities to study participants' collaboration. We have used Decimake to create a trip planning activity which required participants to plan itinerary to Paris within the fix budget. The shared surface shows a map of Paris, and options are attractions and hotels that located around Paris. Each option has detailed information, such as location, price, and visitor comments. The decisions are about which locations to visit, which hotel to stay in, and how to plan the travelling days. By using Decimake, the application was rapidly created in dozens of minutes when all the required information were prepared at hands.

The decision-making model we proposed in the chapter is based on our discussion with teachers and former models. It is mainly focusing on the analytical process which contains four stages. However, the literature review also indicates other stages in the decision-making process, such as identifying options and weighting criteria. Besides, our current version of Decimake only supports the creation of geographic decision-making applications, which means the nature of created applications should be based on a map. But, we expect Decimake to be a more general tool to create various types of decision-making applications. Therefore, my future work includes studying how to support the design of the other stages of decision-making process, meanwhile expanding the existing features of Decimake to make it more adaptable and flexible to create other type of decision-making activities.

Moreover, Decimake is mainly focusing on creating the applications for the MSE that has one shared surface with or without multiple personal devices, as these two are the most common configurations for collaborative learning activities in class [80, 143]. The configuration of using multiple personal devices without a shared surface is also under construction. However, when designing decision-making within other situations, such as for emergency planning, other types of configurations in MSE could be used, such as using multiple shared surfaces [22]. Therefore, the future work will consider other types of configurations in MSE, studying the role of devices and distribution of interface within these configurations.

6.7 CONCLUSION

This chapter presents Decimake, an authoring tool for creating decision-making activities in MSE. The design of Decimake is based on the literature review and our discussion with teachers. A model of decision-making process was purposed which serves as the main structure of the created application. By using Decimake, users can easily define the nature of application, structure the decision-making process, and add indicators and gamification elements into the application. Decimake also allows teachers to configure the class setting for the activity.

The current version of Decimake was tested by a teacher from the vocational school. The teacher successfully created a decision-making activity based on her teaching materials and requirements within 30 minutes. The activity created by the teacher was later used by her students in a real class situation. The future work includes expanding the functionalities of Decimake, to make it a more general tool for creating various types of decision-making activities in different configurations of MSE.

7 CONCLUSION

The overarching focus of this research has been on understanding collaboration in MSE, in order to facilitate the design and development of collaborative activities. Towards this goal, I defined two specific objectives as stated in Chapter 1 including studying how the configuration and form factors of MSE influence and shape users' behaviors, and supporting the design of collaborative applications in MSE, especially the decision-making applications for learning. In this conclusion chapter, I review how work addressed these two objectives, summarize my contributions, and provide directions to future research.

7.1 THESIS REVIEW

Multi-surface environments (MSE) combine different type of surfaces in a variety of physical arrangements. The large-scale MSE have shown their benefits for supporting co-located activities, especially the ones involving rich data exploration, such as complex collaborative decision-making activities. However, the diversity of MSE also raises questions since different configuration and devices factors of MSE can be suited for different kinds of activities. In addition, designing and developing collaborative activities in MSE remains complex.

The first broad research objective is to study how configuration and form factors of MSE influence and shape users' behaviors, then provide recommendations for the design of collaborative activities in MSE. The field study in Chapter 3 shows how students performed a collaborative learning game in highly mobile conditions using mobile configuration in outdoor MSE. The results demonstrate that students have very dynamic spatial arrangements during the outdoor learning activity, which shape the way they collaborate. The study in Chapter 4 presents how participants collaborate in a trip planning activity using shared surface configuration in indoor MSE. In these two studies, we focused our analysis on the relationship between participants' collaboration mechanisms, the way they used devices, and their physical positions. We provide design implications on collaborative activities for both of these two configurations.

The second objective of this thesis is to support the design of collaborative applications in MSE. I chose to focus on decision-making applications in classroom settings. Chapter 5 presents the design of Pickit, an application supporting decision-making process in MSE using share surface with multiple personal devices configuration. Based on observation and analysis of students collaborative behaviors using Pickit, I provide design implications on decision-making activities in MSE. Based on the experience from former studies and the literature review, I propose an authoring tool named Decimake presented in Chapter 6. Decimake is a tool for creating collaborative decision-making activities in MSE which is based on the synthesis of former decision-making models, our discussion with teachers, and experiences from our former studies. Decimake can be used by teachers who want to design decision-making learning activities in MSE. It can also be used by researchers to explore ideas, develop rapid prototypes and conduct user studies in MSE.

7.2 CONTRIBUTIONS

This dissertation explores people' collaborative behaviors in MSE. It provides insight and implications for designing collaborative activities in MSE. Table 19 summarizes the design implications that derived from the studies presented in this dissertation for supporting collaboration mechanisms. By combining the theoretical perspectives and empirical findings, this dissertation provides contributions on the following three aspects.

	Design implications
Awareness & Regulation	- Adding shared indicators and visual feedback, such as individual progress bars, step-list for group objectives, and reflections of partners' actions (e.g. showing who is checking which option during decision-making) - Enabling manual synchronization (**mobile configuration**). - Using tabletop to partially control tablets (**shared surface configuration**).
Information sharing & Discussion	- Enabling cross-device interaction and exchange of complex information: duplication of screens for a moment, or a focused/zoomed-in mode. - Leveraging proxemic design, but with care (**mobile configuration**) - Letting students go through options together (**decision-making**). - Showing individual comments on the shared surface (**shared surface configuration**) - Providing an overview of analysis elements on shared surface (**shared surface configuration)**

Table 19: Design implications for supporting collaboration mechanisms in MSE.

7.2.1 *Design implications for supporting awareness and regulation*

In both mobile and shared surface configurations, adding shared indicators and visual feedback are helpful for maintaining awareness and promoting regulation. Indicators can be shown on mobiles and/or shared surface, such as progress bars of individuals within the group, a step-list for group objectives, and reflections of partners' actions. In mobile configurations, enabling manual synchronization, such as letting participants update their missions by verbally sharing a simple code, would be positive on maintaining awareness and can provide a stronger feeling of progress comparing to only using automatic synchronization. In shared surface configuration, using tabletop to control tablets can raise awareness of partners' actions, status and progress, and encourage students to regulate their own behaviors. Besides, for designing cooperative activities in which one person mainly control and regulate the task, we suggest to choose vertical surfaces. When designing collaborative activities which require participants to have equal regulation and acquire same skills, such as collaborative learning, horizontal surfaces are more suited.

7.2.2 *Design implications for supporting information sharing and discussion*

We encourage designers to use cross-device interaction for information sharing. Enabling exchange of complex information could promote discussions about rich contents or data. Proxemic interaction can be leveraged to facilitate information sharing, such as duplicating screes for a moment, or enabling a focused/zoomed-in mode. However, in mobile configurations, proxemic design should be dealt with care. Users' spatial arrangements are quite dynamic in mobile configurations and can shape their collaboration. The same low-level group spatial arrangements may require different high-level information and devices configurations. When designing decision-making activities in MSE, letting students go through options together had positive impacts on numbers of discussion. Providing an overview of analysis elements, showing individual comments on the shared surface can also support students in comparing options and building justifications.

7.2.3 *Supporting creation of decision-making learning activities*

I presented the design of Pickit and analyzed how students followed the decision-making process using Pickit to make collective decisions. Based on the experiences of Pickit, I proposed Decimake, an authoring tool to create decision-making applications in MSE. The process model implemented in Decimake was build on an in-depth analysis of the literature of decision-making process and our discussions with teachers. Decimake can help people who do not have programming experience, such as teachers, to rapidly create collaborative decision-making learning activities without concerning the technical issues. Using Decimake, teachers can define the context of decision-making, add options, criteria, and also gamification elements to the application. They can also set their classes in the application. The effectiveness of Decimake has been tested by teachers by creating a decision-making application that has been successfully used in a real classroom activity.

7.2.4 *Collaboration analytical grid in MSE*

The analytical grid of collaboration in MSE is another contribution of this dissertation. In Chapter 2, I derived four collaboration mechanisms from a literature review including awareness, regulation, information sharing and discussion. I synthesized how these mechanisms were analyzed in the related works. I listed the indicators of each mechanism. Based on the synthesis, I proposed an analytical grid to study collaboration in MSE. Table 20 presents the indicators that I used to analyze collaboration in different studies. It is categorized by different studies, and the four collaboration mechanisms.

	MSE configurations		
	Mobile & Outdoor	Shared surface & Indoor	
	Chapter 3	Chapter 4	Chapter 5 (Classroom)
Awareness	- Looking or moving toward to others to see what others are doing	- Reaction without request - Complementary action - Interference - Verbal monitoring	- Looking at what others are doing
Regulation	- Setting up strategies or goals - Monitoring the task - Evaluating the task	- Discussion on strategy - Duration of the whole task	- Reminding others of the time or the task progression - Offering help to others - Teacher providing instructions
Information sharing	- Passing information verbally to others - Showing or passing devices to others	- Sharing tablets for discussion	-
Discussion	- Figuring out the solution to a puzzle - Discussing how to use a measuring instrument	- Discussions on hotels - Discussions on attractions - Discussions on budget - Discussions on itinerary	- Discussions on options - Discussions on criteria - Discussions on context - Discussions on comparison - Discussions on choice

Table 20: Analytical grids used in different studies.

7.3 PERSPECTIVES

In this section, I discuss possible research directions to extend the work presented in this dissertation.

7.3.1 *More device configurations and form actors*

Two configurations (mobile and shared surface), and different device form factors (orientation, size, etc.) of MSE have been discussed in this thesis. They are just few instances within the much wider space of MSE which serve as an initial step in studying how the configurations and form factors influence collaboration. However, MSE have more possibilities, combining various types and different amounts of devices.

Further studies are needed to build a solid body of knowledge on users' collaboration using other possible devices configurations, and form factors, such as different size, angle, as well as unconventional form factors (e.g. curved or shape changing surface). For example, instead of using tablets in the mobile configuration, as we did in chapter 3, we can also choose to use smartphones which are easier to take, but with smaller screens. Students' collaborative behaviors might be changed as small screens will impede a group of three students looking at the screen at the same time.

Besides, in the shared surface configuration, we can have more than one shared surface for a classroom setting, such as a tabletop for students' group discussion, and a wall display for presenting and demonstrating. When shared surfaces are not available, we may also use tablets to replace shared surfaces, and regard smartphones as personal devices. When the configuration changes, users' collaboration patterns will be changed accordingly.

Future work should focus on analyzing other configurations and form factors of MSE, provide implications on designing activities to better support collaboration in different MSE, meanwhile give suggestions on which configuration and form factor is suited for which type of activities.

7.3.2 *Dynamic MSE*

Most of the MSE we have seen have fixed configurations and different devices are assigned with specific roles. It is difficult to add or remove devices from the environment or change the roles of devices during the activity. Future work can explore more dynamic MSE, which would allow users to add or remove the devices from a workspace, or even adjust the device role according to the task. When the task requires dealing with a large number of information, users can add more devices to the environment, or adapt personal devices to be shared surfaces to have larger display spaces. On the contrary, users can remove extra devices and have a compact view. For example, our studies in chapter 3 and chapter 5 were connected. Students firstly used tablets performing an outdoor activity, then they came back to classroom to carry on decision-making using a shared surface and tablets. The data of decision-making were obtained from the experiments students did in the outdoor activity. In this situation, the learning activity is firstly hosted on multiple mobiles, then transform to a shared surface configuration. We did a semi-manual sync to transfer data from tablets to the shared surface. Future studies should provide features to redefine MSE configurations and assign new roles to devices. Once a device role is reset, the application should obtain the relevant data and adjust its UI automatically.

When discovering devices, the first problems are often at the infrastructure level. Universal Plug and Play[1], and Bonjour[2], are two examples of existing technologies making device discovery and pairing easier. However security constrains and practical networking often hinder the wide use of these technology. Our experiment presented in chapter 5 was failed in the first year due to network problems in the school. We did it again in the second year.

Proxemic interaction has been leveraged for improving device discovery and cross-device interaction. In the Appendix A, I present an infrastructure which allows dynamic reconfiguration of the interactive space by grouping different devices together using proxemic. Users can extend and create their own interactive surface during the task by bringing their personal devices close to any side of a interactive tabletop. However, this infrastructure has its own limitations. It requires magnets that sticking on the sides of devices for detecting nearby devices. Futures study should consider to make the infrastructure more convenient without using extra auxiliary tools. Besides, as I have shown in chapter 3, proxemics should be used with care, especially in a highly mobile condition. More work are required to design ergonomic proxemic interaction, such as excluding meaningless behaviours or repairing wrong interactions during task, investigating the impacts of activity nature, as well as users' nationalities, age and gender on the proxemic behaviors, and providing annotating tools for analyzing group proxemics and f-formation.

7.3.3 *General authoring tool for MSE*

As MSE technology matures and becomes increasingly available and affordable, it is important that the scope of research broadens to include the general impact of MSE on classroom environments. More works are required on studying how students collaborate and ac-

1 https://en.wikipedia.org/wiki/Universal_Plug_and_Play
2 https://support.apple.com/bonjour

quire knowledge in MSE, and how the learning activities should be designed in MSE to reinforce knowledge building. As designing cross-device learning applications is still quite challenging. In order to maximize the opportunities MSE offer on collaborative learning, more attention should be paid to help teachers or people without programming experiences to create learning applications in MSE by themselves.

The authoring tool (Decimake) I proposed in this dissertation was only focusing on decision-making learning which supported parts of decision-making process. More work are needed to extend the features of Decimake. The next generation of Decimake will firstly focus on extending the scope of activities which will not be only limited to geographic applications, and then supporting the whole decision-making process including searching for and identifying options. Additionally, adaptation to different MSE configuration at hands is also an objective of future work for Decimake.

Besides decision-making, other types of collaborative learning activities should also be considered, such as problem-solving for learning. Overall, future study should consider to design and develop more general authoring tools that can create different type of collaborative activities for MSE.

7.4 CLOSING REMARKS

Multi-Surface Environments provide more possibilities for enriching and strengthening learning experiences. Mobile devices break the constraints of traditional classrooms and allow students to go outside and get closer to their topic of study, such as to museums, zoos, and mountains as we did. Large surfaces provide shared spaces for information sharing, discussing, demonstrating and brainstorming. However, these advances are not always the end. Upcoming technologies are on their way to change our everyday lives as well as our learning activities. Wearable devices (e.g. watches, glasses) could make outdoor learning easier and more convenient, with no need to carry mobile devices.

Thinking about the popular mobile game Pokémon Go which has attracted numbers of young people, it would be interesting to see what will happen if we bring such elements to our learning environments and enrich the learning experience. As technologies continue to mature, future work should consider how such developments can be utilized to improve our learning situation, and also step back to see how our teaching methods can evolve to incorporate them more fully.

Part II

APPENDIX

A

INTERACTIVE SURFACE COMPOSITION

A.1 BACKGROUND

Discovery and pairing of devices is often complex in MSE, either requiring all the devices to be connected to the same local network or involving technologies such as NFC, Bluetooth, or other ad-hoc solution working across limited distances, and still requiring manual pairing. I am interested in providing generic and low cost solutions for the dynamic management of MSE.

In this appendix, I introduce an infrastructure based on an Web server (nodejs), and websockets to develop applications for MSE. I tested this approach with rolling standing desks and tables that can be recombined at will. In order to handle spatial relationships, I used a simple solution based on magnetic sensing. Users can extend and create their own interactive surface dynamically during the task by bringing their personal devices close to any side of interactive tabletop. The manipulation of objects in and cross displays is based on drag and drops.

A.2 PROTOTYPE

In this prototype, I designed a simple collaborative web-based game on a multi-touch device (tabletop or tablet) where users can control the sprite, letting it jump, run to collect starts. Figure 53 shows the screen-shots of the initial game world. This world has brick walls on its both left and right side and will be extended when users bring other devices close to it. According to the position of the added device, the brick wall on the corresponding side will be killed and the corresponding scene appears on the device. Figure 54 shows a game world that is extended on three sides (left, right and up side).

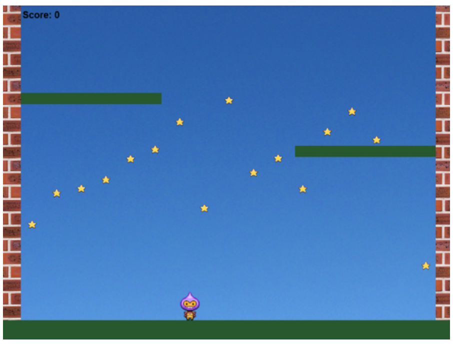


Figure 53: Initial game word

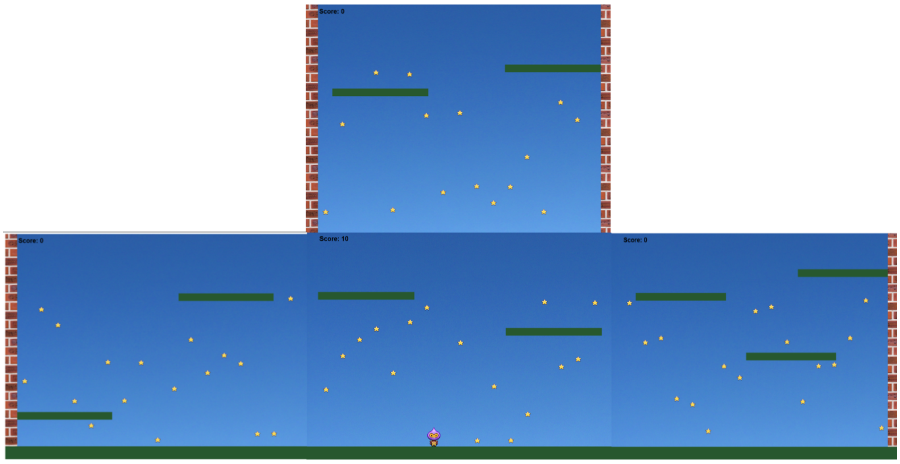


Figure 54: Game word extended on three sides

I present now a scenario that highlights the dynamic construction of the game world by connecting different devices during the game.

A.2.1 *Scenario of interactive surface composition*

In the beginning of the game, only one tabletop is active (Figure 55, tabletop A). Tabletop B (on the left side) is placed next to tabletop A. In order to bring tabletop B into the game, users simply need to push it and align it with tabletop A. When tabletop B is connected (Figure 56), the left side brick wall of the initial game world disappears. The world is extended on the two tabletops. Users can pass the little sprite to tabletop B just by making it run across the left border. When it reaches tabletop B, it keeps the same velocity and relative Y position. User B can also pass the sprite back to tabletop A in the same way.

Now, another user who holds a tablet also wants to join in the game. Here are two options for him. Firstly, he could place tablet on the right side of tabletop A, by which means the game world would be extended to right side. He could also put tablet on the top side of tabletops A and make the up side world extended (Figure 57). After the tablet joins in the game, users could control the sprite to jump and run through these three displays.

A.2.2 *Technical Aspects*

Our http server is based on nodejs, any device willing to become part of the MDE has to connect to a given IP address via a Web browser. The devices can thus be connected to any network Wi-Fi, wired or 3G. The server is set to listen to "connection" and "information exchange" messages, and sends feedback according to the message it receives. The physical detection in this prototype is based magnetic switches

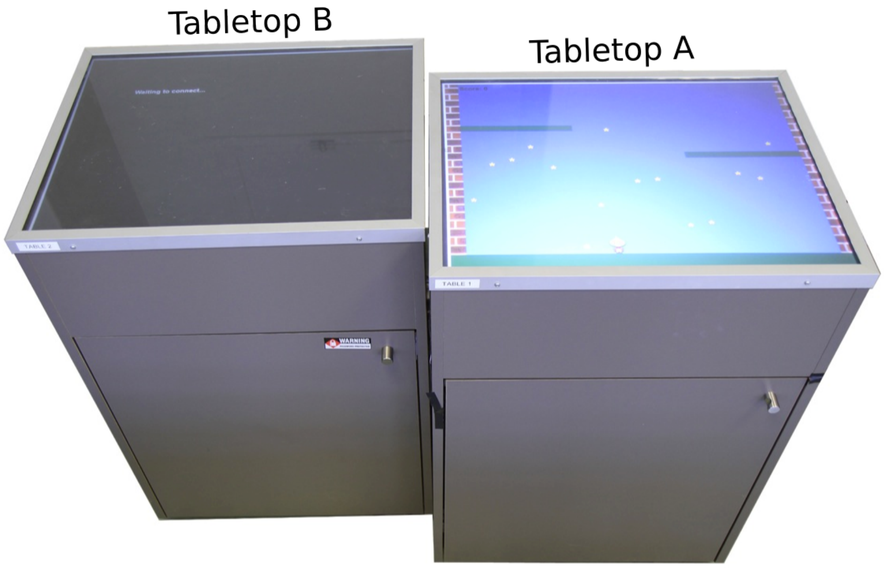


Figure 55: Before connecting

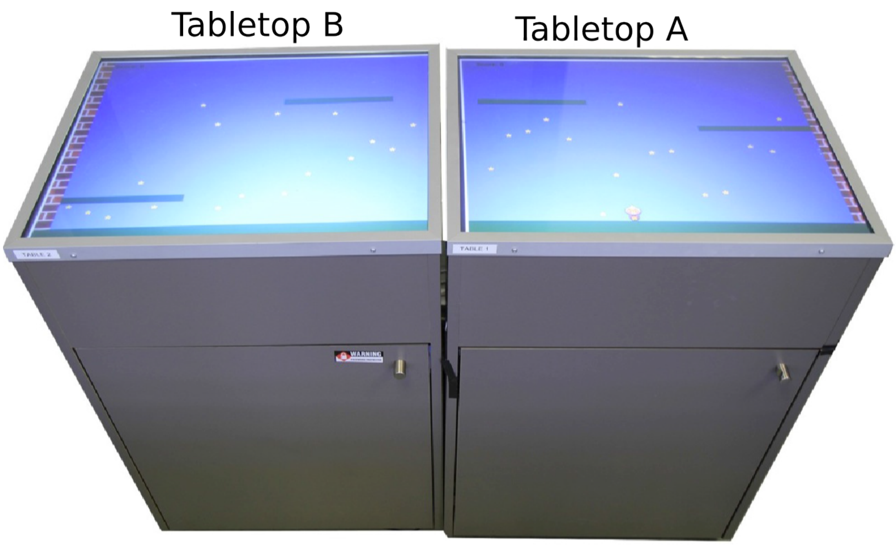


Figure 56: Add tabletop B into game

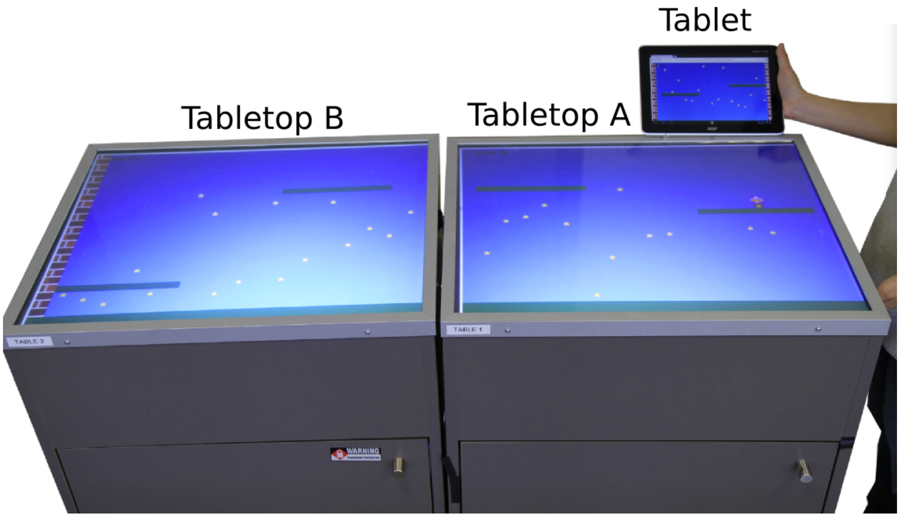


Figure 57: Add tablet into game

and an arduino board programmed with noduino for maintaining javascript as the unique programming language of our environment.

To detect devices relative to each other, we arranged three magnetic switches on the edges of left, right and top side of tabletop A (Figure 58). These switches are parts of the circuit of Arduino board which is also connected to the server. Magnets are attached to the edges of tabletop B, tabletop C and a tablet. When they are brought close to tabletop A, they will turn on the nearest magnet switch. The circuit board will pass the "connection" message to the server including the ID of switch. As soon as the server gets the message, it obtains the position of the nearby display and sends a command to the display to let it join in the game and spontaneously makes the corresponding scene appear on the screen. Meanwhile, tabletop A also receives the command. It destroys the brick wall on the corresponding side to enable the sprite to go out of the world.

For example, when user C wants to play game on the right side of tabletop A. He brings the tablet next to tabletop A, the magnetic switch on the right side is connected. The circuit board passes the "connection" message to the server. The server knows that the right side switch is connected, it sends message through Wi-Fi to make the tablet show the right side extended world. At the same time, tabletop A also receives the message, it kills the right side brick wall. Now the game world is extended on tablet, sprite can go to tablet through the right border of tabletop A. It can also return to tabletop A through the left border of tablet.

The information exchange part is also based on the Web server and websockets. If we control the sprite to go from tabletop A to tabletop B, the server records the attributes of the sprite when it reaches the border of tabletop A and sends this information to tabletop B. Then

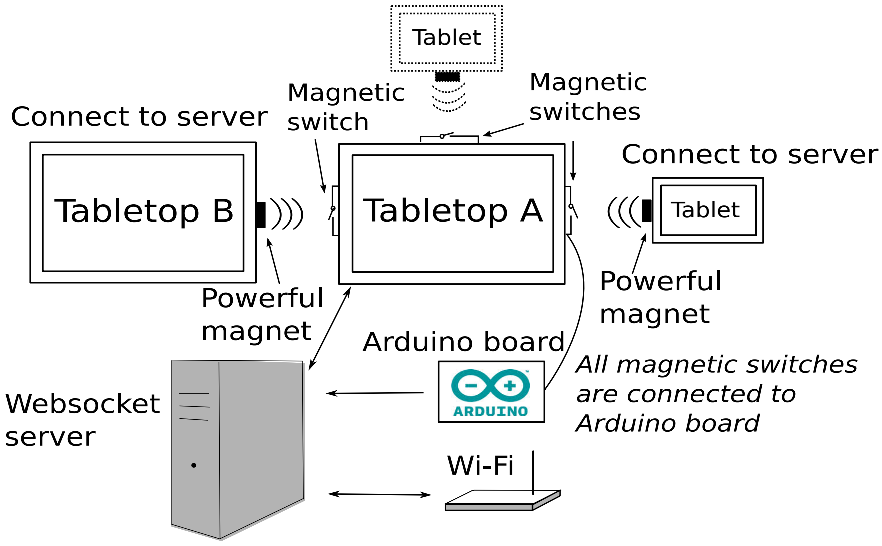


Figure 58: Layout of devices

the sprite appears on the right side of tabletop B with all its former attributes.

This new method embodies spatial relationship in devices' connection which makes the interaction easy to learn. Users can clearly know which part of the game world they hold based on their spatial position. For information exchange, users just need to pass digital objects over the border to the target world. There is no need to have physical contact for each exchange. The transfer is via Wi-Fi which enables its fast speed and provides the potentiality to transform high resolution images. The pair of magnetic switch is cheap (less than 1 euro/pair) and reusable. Each switch's installation on circuit board and programming only cost several minutes. The switches can be equipped on the side of tabletop display, which do not interfere on-going task and others' views when the connection happens. The amounts and positions of switches can be rearranged based on different tasks' requirements.

The software architecture of this work is mainly written on JavaScript. We used CCV (Community Core Vision) to track touch events, and TUIO protocol to collect these events. The communication between different displays is done via web sockets. We used Phaser[1] as the framework of the game.

1 http://phaser.io/

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