# Extending tabletop application design to the classroom

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## ABSTRACT

While a number of guidelines exist for the design of learning applications that target a single group working around an interactive tabletop, the same cannot be said for the design of applications intended for use in multi-tabletops deployments in the classroom. Accordingly, a number of these guidelines for single-tabletop settings need to be extended to take account of both the distinctive qualities of the classroom and the particular challenges of having various groups using the same application on multiple tables simultaneously. This paper presents a synthesis of conclusions drawn from an empirical analysis of the effectiveness of designs for small-group multi-tabletop collaborative learning activities in the wild. We use distributed cognition as a framework to analyze the small number of authentic multi-tabletop deployments and help characterize the technological and educational ecology of these classroom settings. Based on previous research on single-tabletop collaboration, the concept of orchestration, and both first-hand experience and second-hand accounts of the few existing multiple-tabletop deployments to date, we develop a three-dimensional framework of design recommendations for multi-tabletop learning settings.

### Author Keywords

Multi-tabletop setting; guidelines; classroom; orchestration.

### ACM Classification Keywords

H5.2 Information interfaces and presentation: User interfaces, User-centered design.

## INTRODUCTION

Few teaching models have gained as wide acceptance and have proven as successful as collaborative learning [3, 15]. Learning in small groups has been shown to improve academic achievement, to support the development of higher order thinking skills, to realize academic heterogeneity in the classroom, to increase involvement in learning, and to have a number of social benefits such as promoting prosocial behavior and acceptance [3].

When it comes to the use of technology to enhance face-to-face collaborative learning, there is growing evidence that interactive tabletops are a technology of considerable promise. Interactive tabletops have the unique quality of providing the interactive capabilities of a digital technology while leveraging peoples' past experience of collaborating around tables. Consequently, there is growing research interest on how this technology can support collaborative learning [6, 12]; nevertheless, the majority of such investigations have taken the form of studies of groups in single-tabletop settings [16, 32, 33, 39]. In many cases, having multiple tabletops in the classroom has explicitly, or implicitly, been presented as a future vision of the use of such technology [16, 33]. However, deploying applications, that have been designed for and tested in a single-tabletop setting, in a multi-tabletop classroom environment is not a trivial exercise. Having multiple tables significantly changes the classroom dynamics [17].

Interactive tabletops, as with any other technology, do not necessarily enhance teachers' ability to manage the classroom or students' learning. If the design of multi-tabletop applications is not strongly grounded on theories of learning and practice, then these new technologies have the potential to unnecessarily increase the complexity of classroom management. Indeed, it has been shown that multi-tabletop deployments may raise several challenges. Teachers may have concerns about how to design learning activities [23], control the technology [17] and monitor what is happening in the classroom [25]. Accordingly, designers need to be aware of the principles on which to base extensions of single-tabletop systems to multi-tabletop settings, as well as the design requirements that specifically apply to classroom settings.

Based on a review of existing design guidelines, both for single and multiple tabletop settings, and our own experience in developing and deploying a number of single and multi- tabletop learning systems, we provide a set of *recommendations* for multi-tabletop learning systems for the classroom. We present these recommendations in relation to a new framework, based on the concepts of *distributed cognition*. The framework drives designers to consider how their multi-tabletop systems perform across the three dimensions of planes, space, and time.

## COLLABORATIVE LEARNING IN THE CLASSROOM

We address the specific context of a classroom in which a group of learners is divided into a number of small teams that work collaboratively using interactive tabletops. The types of group work we are particularly concerned with are 'formal cooperative learning' and 'academic controversy'.


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In formal cooperative learning, students work jointly in groups for one or more sessions towards shared learning goals. In academic controversy, a teacher allocates groups such that members of the same group hold incompatible opinions on a topic and the goal of the group work is to reach agreement. These are distinct from other types of cooperative learning such as when groups of students are formed on an ad-hoc basis to perform short (3-5 min) tasks; or when groups have a stable long-term membership with a view to members supporting each other [14].

## SINGLE-TABLETOP DESIGN PRINCIPLES

A number of researchers have provided guidelines for the design of single-tabletop applications. Scott et al. [35] made a number of general design recommendations that focused on supporting collaboration. Through a process of reflection on their own experiences, they identified a set of tabletop affordances relating to interpersonal interactions, transitions, the use of physical objects, access to shared objects, user arrangements and parallelism of activity.

Morris et al. [29] identified features of tabletop interfaces, including elements of the user interface, the nature of multi-user coordination, and insights from cognitive science, which can make an impact on group dynamics. In this vein, Kharrufa [16, 18, 20] also presented a number of design guidelines based on the development of a collaborative learning application aimed at developing higher level thinking skills, effective collaboration, and reflection. These latter guidelines proposed supporting the externalization of thinking; structuring the learning tasks; encouraging effective collaboration by using participation visualizations and switching between single and parallel input; and providing feedback prompts at stage boundaries.

A number of other research projects have explored the use of tabletops in learning contexts (e.g. [9, 16, 32, 33, 36, 39]). Fleck et al. [9], explored the importance of analyzing student's actions to understand their strategies at the tabletop. Martinez-Maldonado et al. [22], proposed a set of recommendations to build systems able to capture these students' actions automatically. With these data, a tabletop can provide support in the form of visualizations, indicators of participation or adapted actions. Shaer et al. [36] showed the benefits of grounding the design of tabletop learning systems on principles of multiple representations and heterogeneous sources of knowledge.

This body of previous work proposes general design guidelines for single-tabletop environments. These have mostly been validated in either controlled settings or, at best, in settings that are not typical classroom environments.

## MULTI-TABLETOP ENVIRONMENTS

The recommendations proposed in this paper are based both on the literature of supporting collaboration in single-tabletop settings and previous work on multi-tabletops settings (SynergyNet and TinkerLamp). However, our recommendations primarily originate from the analysis of our multi-tabletop environments deployed in *authentic settings* (Tables in the wild and MTClassroom). As such, these are two of a very small number of multi-tabletop learning studies, but are distinctive in that they are studies that include a direct link to the regular curriculum, take place in actual classrooms and are led by the regular teacher for the class. Despite these similarities, they provide an interesting contrast with regard to their differing approaches to connectivity and teacher tools (see Table 1). Next, we described the four multi-tabletop classroom settings.

### SynergyNet

In the case of multi-tabletop environments, one of the most relevant projects is SynergyNet [2, 10, 27, 28]. This is a room with four tabletops, an interactive board, and a multi-touch control desk for the teacher. It was used to run experiments with elementary school students (10-11 years) engaged in extracurricular problem solving activities (e.g. Mysteries and mathematical exercises).

Direct observations, controlled interventions and qualitative analysis of video recordings were mostly used to study how tabletops can support students' interactions and the ways the teacher used the system. The work also focused on how the transitions between small group and classroom-level discussions influenced the conversation and interactions within the groups [27]. The analysis approach proposed by this project mostly focused on observing the strategies and patterns that can help describe how students learn and collaborate [28]. The analysis revealed a shift in students' reasoning to higher levels as a result of teacher lead interventions at the class-level [27].

Within the same project, AlAgha et al. [2] looked into providing tools for teacher's awareness. The system permitted the teacher to remotely control the classroom through a teacher's console. Using the console, the teacher could visualize, interact with and control each group's tabletop screen. It also allowed the teacher to display the work of the groups on a public display. This study, while focusing on the usability of the system, demonstrated the benefits of the non-interfering monitoring capabilities and the ability to show answers from tables on the public display. It also revealed that teachers avoided the use of features that allowed remote interventions in students' activities.

| System | Context | # Tables | Students per table | Orchestration tools | Data capture | Design analysis | Authentic cases |
|---|---|---|---|---|---|---|---|
| SynergyNet | Primary | 4 | 3 | ✓ | | | |
| TinkerLamp | Tertiary | 4 | 3-4 | ✓ | | ✓ | |
| Tables in the wild | Secondary | 7 | 3-4 | | ✓ | ✓ | ✓ |
| MTClassroom | Tertiary | 4 | 4-6 | ✓ | ✓ | | ✓ |

**Table 1. Comparison of the four multi-tabletop settings**

### TinkerLamp

In a similar study, Do-Lenh [8] described a classroom deployment of four tables (TinkerLamp's) that can track fiducial markers attached to objects located on the table's surface. The learning activity, which targeted vocational apprentices 17-20 years of age, involved the use of a simulation application for training logistics.

The approach used in this study was strongly influenced by the concept of classroom orchestration. It provided tools to help a teacher moderate the classroom activities of individual tables. It also included a wall display (TinkerBoard) that served as a classroom self-regulation tool used by students and the teacher. It supported teacher's debriefing and facilitated the continuity of learning by showing visualizations of the progress of each group or by comparing two groups' solutions.

The setup did not include a separate teacher control device; TinkerBoard played both the role of a public display and a teacher control space. This project also explored the possibility of providing students with multiple representations of the learning artifacts (tangibles and 2D objects). This was achieved by providing the means to save digital and paper versions of the layouts constructed by students to be used in further activities. The study focused on analyzing the usability and design aspects of the systems based on the principles of classroom orchestration. This study also explored scripting the activity into learning phases to support reflection.

### Tables in the wild

In our first study, seven interactive tables were deployed in a secondary school for six weeks [17] (Figure 1). The tables were used by two classes (an average of 24 students aged 12-13 years) for three subjects, with five teachers. The tasks covered full sessions and involved collaborative problem solving using Digital Mysteries [16] and collaborative writing [11].

At the classroom level, the setup followed the minimalism recommendation from the orchestration model [7] where a basic setup, with no interconnection between tables and a teacher's device, was used. The goal was to magnify the positive orchestration affordances inherit by the technology and to make evident any shortcomings in the system. This setup also aimed to closely mirror a traditional classroom with tables and students collaborating around tables without introducing new control, visualization, or monitoring tools for the teacher or the classroom. However, the applications used followed existing collaborative learning design guidelines for single-tabletop settings.

The study was analyzed using the orchestration framework with specific emphasis on the orchestration factors of awareness, flexibility, linearity, leadership, control, and cross-plane integration [5, 7]. Many of the issues identified were a direct consequence of the real-world qualities of the study. The study stated a number of points to consider from the perspective of designers seeking to realize multi-tabletop integration of their applications. These points focused on cross-plane interactions/transitions within the lesson and on supporting better integration of the task in the learning process in general and in the classroom session in specific (a time perspective). The former required designing for improved awareness (mainly for the teachers) of the state and progress of the groups and the individuals when possible. It also required providing tools to support transitions between the individual, group, and classroom levels.

From a time perspective, the study emphasized the need to use the technology as part of the classroom activity rather than considering it as 'the' classroom activity with the goal of extending its impact beyond the limitations of the classroom session. It also required providing tools to monitor progress and maintain, more or less, synchronized progress through the task.

### MTClassroom

Our second multi-tabletop classroom environment is designed to capture interactions of students working in small groups (Figure 2). This provided the teacher with the infrastructure to design, control, monitor and assess collaborative activities [23, 25, 26]. The design of MTClassroom was strongly grounded on a data-driven approach and principles of collaborative learning and orchestration. This environment focused on empowering teachers' classroom control and awareness.

Tutorials in this setting were taught in two teaching periods for two university level subjects (376 students aged 18-22 years). The MTClassroom consists of four interactive

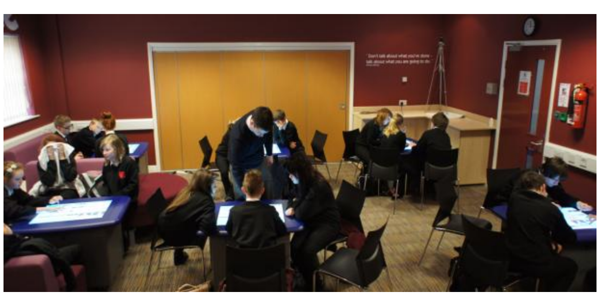

**Figure 1. The school multi-tabletop classroom [17], featuring 6-7 SMART tables used in multiple sessions for different activities by two year 8 classes.**

**Figure 2. The university multi-tabletop classroom setting [25], featuring 4 interconnected tabletops, an unobtrusive data capture system and a teacher's orchestration dashboard.**

tabletops, one or more vertical public displays and a teacher's dashboard. The tabletops are connected to a centralized sensing system which can unobtrusively capture students and classroom data. All the devices that are part of this ecology can log students and the teacher's actions to a common data repository. Teachers can prepare learning material that is loaded to the tabletops to help students scaffold their group activity. For example, if the activity consists in building a concept map, the teacher can introduce a list of suggested words, a scaffolding map and a master map that the system can use to compare with each group's map in real-time.

The teacher's dashboard allows controlling the class script and all the other devices. The dashboard shows a number of simple visualizations of groups' collaboration and progress. Showing real-time indicators of each group performance has proven effective in helping teachers decide which group may need attention [25]. The data captured by the MTClassroom can help teachers to assess how effective their design was during the real tutorials by analyzing the time spent on each activity, if the students accomplished the task or if they participated evenly [23]. These data can also be analyzed to discover patterns of interaction automatically using data mining techniques [26].

## THEORETICAL FRAMEWORK

Designing for, and analyzing the use of, collaborative technology in the classroom is not a trivial endeavor. Many social, pedagogical and technological factors need to be considered. Appropriate theoretical frameworks are required to guide both the design and the analysis of such technological interventions.

Our concern here is for the aspects that are under the direct control of the *technology designer*, as distinct from the factors that relate to what educators can (or should) do. Both theory of *distributed cognition* and the *orchestration model* provided us with frameworks and a terminology for the presentation and discussion of our design recommendations (Figure 3).

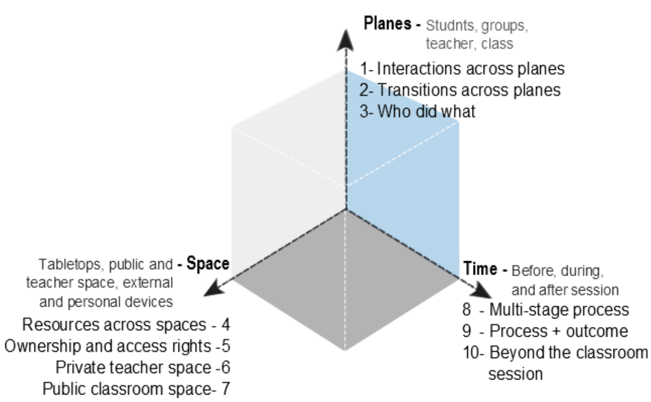


**Figure 3. Designing classroom collaborative technology from the perspectives of distribution across planes, space, and time.**

### Distributed cognition

Distributed cognition [13, 31] has been used to guide the analysis and design of general collaborative environments [34], learning environments [4] and, more specifically, learning applications for single-tabletop settings [18, 19]. While a detailed discussion of its use to inform collaborative learning classroom is beyond the scope of this account, the use of the concepts of distribution of cognition among learners, devices and time; and the concept of representation states, help in framing the existing work on collaborative learning around tabletops, categorizing it, and articulating corresponding design recommendations.

When we examine existing recommendations for designing collaborative technology for tabletops, it becomes readily apparent that different researchers emphasize very different elements of the problem. Looking at the problem from the perspective of distributed cognition helps us structure design recommendations with respect to three main dimensions: distribution across planes, distribution across space, and distribution across time (Figure 3). *Distribution across planes,* refers to the distribution of cognition across the people involved in the classroom. *Distribution across space* takes a device perspective and looks at how content is distributed across the different spaces (devices), inside and outside the classroom. Finally, *distribution across time* looks at the distribution of the process during the classroom session and also extends that to consider preparation for the class and reflection both during and afterwards.

Distributed cognition proposes the concept of representation states to understand the interaction between people and technology, and specifically the transformations undergone by such representation states during a process. Representation states, in addition to material things, include representations in the mind of students and teachers, and the verbal and non-verbal communication in the classroom. It is important that the technology is designed to help making thinking more visible and accessible to improve the awareness of the individual, group, teacher, and the class as a whole. Accordingly, technology should also be flexible to allow effective manipulation and sharing of such representations across planes, space, and time.

### Orchestration model

The orchestration model [6] filled a gap in HCI research by addressing the support of technology for small groups collaborating in the classroom. Dillenbourg and Jermann [6] defined orchestration as "*the real time management by a teacher of multiple learning activities within a multi-constrained environment*". The orchestration model included 15 factors to be considered in both the analysis and design of technology in the classroom: leadership, flexibility, control, integration, linearity, continuity, drama, relevance, physicality, awareness, design for all, curriculum relevance, assessment relevance, minimalism, and sustainability. Not all of these factors are directly related to technology such as assessment and curriculum relevance for example. To date, all accounts of multiple tabletops in the classroom have, to different extents, used the orchestration model [8, 17, 23, 27].

The categorization of distribution across planes, space, and time, allowed by distributed cognition, provides a frame to understand the context of the recommendations presented in this paper, whereas the orchestration model is used to inform discussion at a finer level of details.

## DESIGN RECOMMENDATIONS

We frame our design recommendations according to the theory of distributed cognition in three dimensions: distribution across planes, space, and time (Figure 3). For each, we describe the motivation, its formulation and a number of implementation examples.

### Distribution across planes (people perspective)

Scott et al's recommendations [35] focused on supporting interaction and transition across different planes. They stated that the technology must not hinder interpersonal interaction, should support seamless transitions between personal and group work, and support transitions between tabletop collaboration and external work.

The recommendations are still very relevant when considered in a classroom context with multiple tabletops. The different levels one needs to think about in this case, however, extend to include a more complex network of interactions. In a classroom context, the planes axis (Figure 3) includes the individual students, the groups of students, and the teacher. Accordingly, in addition to interactions among group members around a table, one needs to consider inter-group, group-teacher, and classroom-teacher interactions.

#### *1) Support visual/auditory interactions across planes*

*Motivation* In the *Tables in the wild* and the MTClassroom studies, the orchestration model identified teacher awareness as a key requirement for supporting classroom orchestration [7, 17, 25]. It is also desirable to support the awareness of student groups to the overall classroom state and progress of other groups. The level of significance of this can be a subject of further investigation and is likely to depend on the teaching model adopted by the teacher (e.g. competition vs collaboration between groups).

*Recommendations* Support unobstructed visual and auditory access across individual tables [19, 35], and ultimately, across all planes in the classroom. This is important for exploiting the benefits of the tabletop technology and for maintaining the awareness of those involved of what is happening across the classroom. Accordingly, this means not introducing anything that may cause visual or auditory breakdowns, for example, stands that hold overhead devices or vertical displays between two tables.

#### *2) Support transitions across planes*

*Motivation* Transitions from group work around the tabletop to classroom-level discussions prompts groups to move to higher levels of reasoning, facilitates more coherent understanding and the propagation of the best solutions by contrasting differences; it also allows for reflection to take place at the classroom level [5, 8, 27]. This was illustrated by AlAgha et al. [2]'s study, in which one of their teachers described the need for transitions as: "*the ability to link the [tabletop] to the vertical screen allowed me to maintain an emphasis on group problem solving but to vary the size of the group from three children on one table to the whole class and back again*".

Moreover, in addition to group-class transitions, interactions between groups allows for learning from other teams in addition to learning from group members and classroom discourse [10]. Supporting the inter-groups transactions may also be highly desirable in scenarios like the jigsaw classroom teaching model.

*Recommendations* Support smooth transitions from group to classroom level activities to allow the teacher to lead debriefings, give instructions, or scaffold reflection. The system should also allow for creating opportunities for inter-group and intra-group interactions.

*Implementation examples*

- Allow the teacher to freeze all interactions on all the tables to help realize a transition from table-level to classroom-level discussions (and back again by unfreezing) [8, 10, 17, 25].
- Allow for the projection of one group's final or partial product to a classroom public display [25], or to other tabletops, to support a transition to classroom-level reflection around the work of a selected group [10, 17].
- Allow the teacher to move contents between groups' tables to support and promote interactions between groups [2].
- Allow the teacher to include transitions between group work and classroom-level in the planning stage [23]. These can include, for example, the provision of new learning material or activating additional application features according to the class script.

#### *3) Accountability: Who did what and when*

*Motivation* Accountability refers to the identification of who did what at both individual and group levels. Accountability within a group is identified as a desirable yet often ignored feature (probably due to technical challenges) for collaborative learning applications [22] and is considered as one of five variables that mediate effective group work [15]. It is important to have an indication of the nature of an individual's contribution to group work if the teacher intends to monitor progress or performance on an individual basis [22]. Accountability at an individual level can also promote a sense of responsibility in students for their actions within the group and can help in the regulation of levels of participation and collaboration of group members [16]. The data captured by the MTClassroom has shown the potential of acquiring accurate participation data to monitor group's progress. These results highlight the importance of conducting future exploration on capturing student's data in the classroom, including verbal and non-verbal communication.

*Recommendations* Support user identification within groups and make level-of-participation data available (e.g. using visualization) to both the students and the teacher.

*Implementation examples*

- At the classroom level, provide the teacher with key indicators of group interactions in real-time. In the MTClassroom, with accountability made possible through the use of pervasive external devices, such indicators helped the teacher decide which group to attend next [25].
- At the group level, provide simple visualization of participation levels to students (e.g. using a pie chart). Such visualizations, even when limited to the level of interactions with the table's surface (and not including verbal and non-verbal interactions), have proven to be effective in encouraging students to regulate their participation levels [16].
- At both classroom and group levels, logging differentiated students' actions can provide evidence for teachers or designers to reflect on how effectively the classes are delivered among sessions [23] or to analyze frequent patterns in students' data [26].
- Provide the teacher with the means to refer to each table by a visual identifier (e.g. a color) [25]. This allows the teacher and students to coordinate the collaborative activities and follow the script for the session in-time.

### Distribution across space (devices perspective)

Distributed cognition points to the importance of use of space in the reduction of cognitive load on humans [13, 31]. Kirsh highlighted the importance of the use of space to externalize thinking and in supporting cognition "Space is a resource that must be managed, much like time, memory, and energy. When we use space well we can often bring the time and memory demands of our tasks down to workable levels." (Kirsh [21], pp.32).

In the modern classroom, tabletops (groups' shared spaces) can be integrated into a technology-rich environment that is designed to support a variety of collaborative activities. Other devices are likely to be included in modern classrooms such as an interactive whiteboard (a public space), the teacher's computer (private space), and other personal devices such as tablets, smart phones, and even cameras (private spaces). Furthermore, the classroom may be connected to external devices over a remote network [12] or to sensing systems that collect students' data [23]. Each of these spaces can serve a different purpose in the classroom and needs to be utilized accordingly.

#### *4) Support sharing of resources across spaces*

*Motivation* Sharing resources both across a table space and between the table space and the external world is recommended for single-tabletop settings [35]. In a classroom context, this should be extended to include sharing of resources across all the other spaces in the classroom. This has a number of pedagogical benefits as identified by Higgins et al. [12], including: (i) increasing the capacity and range of information that can be incorporated for or from learners; (ii) allowing the teacher to interact with groups and get feedback remotely; and (iii) sharing resources between groups allows collaborative or competitive interaction.

*Recommendations* Support the ability to easily share resources across the different spaces available in the classroom as well as the outside world.

*Implementation examples*

- Use graphical representations as metaphors to other devices, ideally to be located to mimic the physical layout in the class. Resources are transferred to the required device when they are moved to the corresponding graphical representation [29].
- Use tangible objects as physical bookmarks into the virtual world. This means that transfer of resources is done through a physical action that is made visible to the whole class thus increasing awareness, enriching the act of sharing data, and making workflow management easier [5]. While actual information transfer is carried out over a network, a uniquely identifiable tangible object (e.g. using visual markers, or proximity sensors) is used to physically control information transfer [37].
- Use orientation adaptation when content is transferred from the horizontal spaces (tabletops) to vertical spaces [2, 25]. This mostly means reorienting tabletop contents in the best way possible to be comprehensible for users. In the MTClassroom, the sensing systems provide information to the learning application to orient elements towards the students [25].
- Use internet based services [39], a database [23] or students' devices (such as USB memory drives) to allow sharing of resources with the outside world [1].

#### *5) Consider ownership and access rights*

*Motivation* Supporting the ability to change the access rights of a document on a tabletop facilitates sharing resources yet allows users to protect their data from undesired intentional or accidental alteration. Furthermore, making data access rights status visible is important to prevent confusion [30]. Ownership and access rights have not been previously investigated in a classroom context. Resource accessibility can be very important in such context, as sharing of resources can take place among groups, with the teacher or with the entire classroom.

*Recommendations* Allow for dynamic assignment and modification of access rights when moving resources across the different spaces in the classroom. The access rights of these resources must also be made clearly visible to minimize confusion as to ownership and editing rights.

*Implementation examples*

- Assign default access rights to the different spaces [35], [29]. For example, a resource may be set to read-only automatically once it is moved to a public space.
- Allow for easily overriding the default settings when moving resources across different spaces. Crossing based techniques such as *Attribute Gates* [38] integrate the setting of different resource attributes (including access rights) with resource movement operations (e.g. towards a graphical representation of another space).

#### *6) Provide a private teacher space*

*Motivation.* The teacher's awareness and control over the classroom are among the factors that have the largest impact on the outcome of a learning session [8, 10, 17, 25]. The barrier-free affordance of the tabletop is not always enough to maintain the level of awareness needed to keep the teacher in maintaining control over the classroom [8, 10, 17, 25]. According to AlAgha et al. [2], teachers frequently looked at a representation of all the tables that is displayed on their private space, and compared these with the observed talk and interaction, which helped the teachers in deciding on the best possible interventions.

*Recommendations* Provide a private space for teachers to present information that enhances their awareness, and commands that help increase teacher's classroom control.

Implementation examples

- Use a dedicated interactive tabletop, meant to be used only by the teacher, to control or monitor students' tabletops or the content that the teacher wants to show on the public display [2]. The downside in this case is that this forces the teacher to physically move to a fixed position to have access to the private controls.
- Use a personal device that allows the teacher to move around the classroom while, at the same time, have access to the classroom controls (SynergyNet) and visualizations of participation, progress, and key indicators of the process (MTDashboard).

#### *7) Provide a classroom-level (public) space*

*Motivation* A shared public space in the classroom serves more than one purpose. In addition to being a focal point during classroom-level discussions and a source of joint attention [25, 27], it can serve as a space for sharing resources across the classroom. Moreover, by displaying different visualizations on the public display (such as progress and current status of the different groups), the overall awareness of the current classroom status increases for the groups as well as the teacher [2].

*Recommendations* Provide a classroom-level public space that is visually accessible to all the class. The goal of the public space is to improve awareness, support teachers' explanations and foster reflection and class discussion. It can also be used as a location for resource sharing.

*Implementation examples*

- Allow for the flexibility of showing the contents of more than one table on the display to allow for making comparisons [2].
- Allow for the display of visualizations of participation, progress, and key indicators of the process when possible to increase the overall level of awareness [8]. Effective and simple visualizations can, in many cases, solve the limited resolution of the display that prevents showing the contents of more than one table [25].
- Allow for orientation adaptations (as discussed) when projecting tabletop contents on the display.
- Allow for zooming in parts of the display to focus discussions on specific parts, or improve readability [2]. MTClassroom allowed students to highlight parts of their solution to drive their reasoning to the class [25].

### Distribution across time

The time dimension brings designers' attention to the whole process of a teaching session rather than only focusing at instances of interactions or transitions in the process. Extending the time axis to include the time before and after the session highlights the need to consider the tabletop session as an integrated part of the learning process rather than an isolated technology-based task. The orchestration model uses the term 'continuity' to refer to designing successive learning activities circulating via a workflow based on a shared data structure [6].

#### *8) Dividing the process into stages*

*Motivation* Kharrufa et al. [16, 20], Martinez-Maldonado et al. [23] and Shear et al. [36], in their designs of tabletop learning applications, made a number of recommendations that focused on the process-dynamics (as compared to plane/space dynamics). They recommended dividing the learning task into stages to allow for the provision of scaffolding/instructions and times for reflection at stage boundaries, teaching students that large problems can be solved by dividing them into smaller ones, and providing different representations of the same problem. The studies conducted in the MTClassroom [23] showed how tasks design can be structured and controlled by the teacher in the classroom; the system logs, and then, visualizes how the time was utilized for each stage.

However, further work is still needed to understand the effect of visualizing and controlling the current stage in real-time [17]. Task structuring provides an observable indicator of the progress of each group thus making it easier for the teacher to be aware of the overall classroom state, and help maintain classroom linearity (maintaining similar level of progress for all the groups) or differentiation (e.g. lower achieving groups need not go through all the stages). Increased teachers' awareness and the provision of flexibility and control to maintaining (or even break away from) linearity in the class are among the orchestration model factors suggested by Dillenbourg and Jermann [6]. Task-structuring can also provide opportunities for cross-plane integration in that it allows for movement from individual/group planes to classroom plane at stage boundaries (and back again). Transition to the classroom plane, in such cases, is usually for the purpose of providing instructions before starting a small-group activity, or reflective feedback after the completion of a stage.

*Recommendations* Divide the task into smaller sub-tasks (stages) when possible with instructions and reflection prompts at stage boundaries. Make the current stage clearly accessible to the teacher both on the table and in the teachers' private space. Additionally, provide the teachers with tools to move the class or specific groups to a desired stage overriding any conditions. This allows a certain level of flexibility and control that is required to follow the lesson plan and maintain the same progress for all the groups when needed.

*Implementation examples*

- Make the current stage as well as some type of progress visualization for each group clearly visible on the tabletop space so that it is clearly accessible to the teacher [16].
- Provide a teacher's dashboard that can show either real-time minimalist indicators of task progress to allow the teacher to provide feedback effectively (MTClassroom) or more detailed information to allow the teacher to reflect on the process followed by specific groups [24].
- Provide visualizations that represent the progress of the individual groups and the overall class on the public space so that students can assess their level of progress compared to others, as well as helping the teacher assess the overall progress of the class [8].
- Provide the teachers with overall class controls to advance the classroom activity from one activity to the next one but, at the same time, provide the flexibility to allow the slower groups to keep working at their own pace towards the completion of the task [25].

#### *9) Design for the process as well as the outcome.*

*Motivation* The process of an enquiry based learning task is an important part of learning, arguably as important as the outcome of the task [36]. While previous recommendations to promote the teacher's awareness focused on the current state of each group, keeping an accessible record of the interactions both in real-time and after the session, increases the teacher's awareness of the process leading to the current state as well. Moreover, making a trace of the history of the interactions visible on the table increases students accountability of their actions and reduces the chances of them messing around as such behaviors might be visible in the process history [17].

*Recommendations* The layout at the table should reflect, not only the current state, but a trace of history of the process that led to the current state. Log all the interactions on the table to keep a record of the process for post-activity analysis/reflection.

*Implementation examples*

- Design the user interface to show accumulated progress. In other words, new stages/actions visually build on top of existing ones rather than replacing them [11].
- If a trash bin/delete feature is supported in the application, it should make evident what has been trashed with the ability to get access to the deleted content. This prevents students from randomly creating and deleting elements during the process assuming that such acts will go unnoticed [17].
- Log all of the interactions to a central repository and provide playback and data analysis/visualization tools that allow the teachers (and the students) to examine and reflect on the process when needed [16, 20, 22, 25]. This also enables playback of certain groups' processes on the public space to allow for classroom level reflection on best practices.

#### *10) Extend the impact of the task beyond the tabletop session duration*

*Motivation* Even when interventions are conducted in the wild and are curriculum based, if the inputs and outcomes of tasks involved are not well integrated within the normal learning process, they will be perceived by the students as isolated sessions [17, 23]. Accordingly, students may not realize how a session contributes to their learning and assessment, and consequently may not be motivated to fully engage with the task.

*Recommendations* Integrate the tabletop activity with the regular learning activities by linking its input and output to the previous and future curriculum-based activities. Ensure that the impact of the tabletop-learning extends beyond the duration of the session and that the outcome of the session feeds into future learning activities.

*Implementation examples*

- Allow the use of resources prepared/collected in advance by students and the teacher in the application when needed [39].
- The outcome and the history of the process need to be made available to the students and teachers as tangible evidence of the session that students can refer back to, or build upon, when needed [17, 23].
- From a teachers' perspective, provide information to allow post-activity assessment of the enactment of the

class sessions to be compared with the initial plan in order to identify problems and re-design activities [23].

## DISCUSSION AND CONCLUSION

Deploying tabletop collaborative learning systems in the classroom imposes many practical challenges. The difficulty of conducting iterative design in the wild means that designers need to build a system that works well in as few iterations as possible. A number of exemplar systems and recommendations exist that can inform the design of effective learning applications targeting a single group working around a table. However, this is not the case when designing for multiple tabletops in a classroom. In this paper, we presented a number of design recommendations based on previous research and experiences in conducting multi-tabletop studies in realistic settings.

We used distributed cognition as a framework to guide the analysis of previous studies/guidelines as well as guide the reflection on previous experiences in designing and deploying such systems. Accordingly, the problem space was investigated from three different dimensions: planes, space, and time. The *planes dimension* takes a learner's perspective and considers the issues related to distribution of cognition across the different planes inside the classroom. These included the individuals, the groups, the teacher and the class. Consequently, in a classroom environment, it is recommended to support barrier-free visual and auditory interactions across planes; support mechanisms to allow for transitions across planes, and to support the ability to distinguish individual learners input.

The *space dimension* takes a device perspective and looks at the issues related to distribution of cognition across the different spaces inside and outside the classroom. These spaces include the tabletop space (with consideration to its personal and group territories), the classroom public space (e.g. the classroom interactive board), the teacher's private space (e.g. a laptop or a handheld device), and any other personal devices that the students and the teachers use inside and outside the classroom such as smart phones and tablets. Accordingly, it is recommended to support sharing of resources across the different spaces; consider the ownership and access rights of resources when moved between spaces; and to provide a teacher private space and a classroom-level public space.

The *time dimension* looks at the process during and beyond the session. From the time perspective, it is recommended that the process is divided into a number of sub-stages. This can facilitate the analysis and reflection on the learning processes and outcomes. Additionally, it is recommended to extend the effect of the task beyond the classroom by allowing the integration of previous resources into the class session as well as exporting the outcome for use in later sessions or in other learning environments.

Each recommendation was followed by a number of implementation examples. Most of the recommendations are based on previous studies of multiple tabletops. Others, due to the limited number of such studies, are extensions of single tabletop settings along one of the three dimensions of the proposed model (e.g. ownership and access rights, and maintaining linearity by controlling the progress through stages). These recommendations represent opportunities for further investigation.

This work aims at providing a unified approach that can help researchers consider the variety of issues to consider when designing for a classroom context. It also helps designers understand the relations of the scattered recommendations found in previous research by looking at these from planes, space, and time perspectives. While the recommendations presented mainly target settings of multiple tabletops, many of these can still apply to other technologies that afford small-group collaboration in the classroom. This is especially valid when looking at the general recommendations rather than the technology specific implementation examples.


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