An Artifact Ecology in a Nutshell: A Distributed Cognition Perspective for Collaboration and Coordination

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Abstract. An artifact ecology is an environment where multiple heterogeneous technologies co-exist and are interlinked as a unified system. To construct effective ecologies of artifacts for collaborative activities we need to acquire deep understanding of the complex interactions and interdependencies between users and tools. Researchers have identified Distributed Cognition (DC) as a powerful tool for understanding these interdependencies. In this study, DC, and particularly the DiCoT framework, were considered ideal for constructing this understanding for four student-groups during collaborative activities in an artifact ecology. Using DiCoT we analysed learners' behaviour and how the artifact ecology supported collaboration and cooperation. The cognitive system was described from three different perspectives - physical layout, information flow and artifacts - which (i) allowed an in-depth understanding of the interactions among learners and tools during collaborative activities and (ii) provided insights on how the affordances of the artifact ecology supported collaboration and coordination.

Keywords: distributed cognition, DiCoT framework, artifact ecology, technology-rich workspace, HCI education, collaboration, coordination

1 Introduction

As technology progresses, ubiquitous computing, once envisioned by Weiser [1], is now partially a reality. This evolving nature of technology has brought new possibilities to the design of technology-rich learning environments for collaborative activities. As tablets and smartphones are blended with personal computers in our everyday lives, we are no longer locked in front of a single screen, at work or during learning activities. These technologies communicate and share information with each other creating their own network, an ecology of artifacts [2] [3]. Further, Loke and Ling [4] explained that these heterogeneous technologies are interlinked as a unified system. In the case of collaborative environments, group members may work together tackling the same problem while also work individually on sub-tasks. Digital and physical artifacts within the artifacts ecology may be used for a variety of tasks while each individual may perform a task differently. Therefore, there are endless possibilities and design considerations for the construction of an artifact ecology for collaborative activities.

Salomon [5] claimed that the design and integration of new technologies in an environment cannot be studied independently of its surroundings. To design effective technology-rich environments we need to acquire a deep understanding of the complex relations and interactions between collaborators and information technologies. Distributed Cognition (DC) considers a collaborative activity taking place across individuals, tools and representations, as a unified cognitive system. In the areas of human-computer interaction (HCI) and computer supported cooperative work (CSCW) DC has been identified as a powerful tool for understanding the interdependencies between users, tools and tasks [6]. The added benefit of examining a complex collaborative system through DC is that it allows researchers to take a step backwards and see the "whole picture", focusing on interactions and actions central to the coordination of collaborative activities [7]. Such an understanding will allow researchers and practitioners to pin-point where changes should occur or should not occur in the cognitive system as a whole.

Specifically, in this work, DC was considered an ideal framework to disclose the fundamental processes for collaborative activities in a multi-participant, multi-tool environment. In this paper, we present an in-class investigation of four groups of postgraduate students during collaborative learning activities in an artifact ecology over a period of 12 weeks. More precisely, the study adopted the Distributed Cognition of Teamwork (DiCoT) framework of Blandford and Furniss [8] which emerged from the need to develop a methodology for DC analysis [8]. Using DiCoT we analysed learners' behaviour in order to understand the interactions and interdependencies in the environment, between learners, tools, and the physical architecture. The purpose of the study is to illustrate the utility of DC and DiCoT as a tool for modelling interactions and interdependencies during collaborative learning activities in an artifact ecology. In this context, we showcase learner - learner and leaner-artifacts interactions evident in the workspace and highlight the affordances of the ecology of artifacts that support collaboration and cooperation during collaborative learning activities. The paper concludes with implications for designing technology and technology set-ups for collaborative learning activities in an artifact ecology.

2 Theoretical Framework

2.1 Distributed Cognition

The evolution of cognitive sciences has brought to the forefront the idea that cognition cannot be bounded inside an individual's mind [9], but should conjointly consider an individual's surroundings. DC suggests that cognition must be seen as a more complex mechanism, one that encloses cognitive processes outside one's mind, such as manipulating external objects, transitioning and transforming information between actors and tools. When these cognitive processes are studied during collaborative human activity we can observe the distribution of cognition from different perspectives: distribution amongst members of the group, distribution across the physical or digital structure of the group workspace. Hollan, Hutchins and Kirsch [10] emphasized the importance of understanding the distribution of cognitive processes when designing effective human computer interactions.

Researchers in HCI and CSCW communities have identified DC as a valid tool to understand the interactions and dependencies amongst participants, technologies and activities [6]. Hutchins and Klausen [11] studied the distribution of cognitive processes among members of a cockpit flight crew. They reviewed the interactions between internal and external representations and the architecture of information propagation in the cognitive system. Through their analysis they could identify patterns in the collaboration and coordination of the cockpit crew. Such understanding is important not only for redesigning existing system designs and practices but also for creating the basis for new technologies. For instance, Nobarany, Haraty and Fisher [12] employed DC to design a collaborative system to facilitate analytics. Researchers identified cognitive processes that could be used to support users' collaboration from the beginning, in order to design the system accordingly.

Based on previous studies, DC can provide a detailed identification of issues with existing work practices and mediating artifacts [13]. In addition, DC allows researchers to highlight what is salient in the design of existing collaborative working systems and practices and indicate aspects that require redesigning. In this work, we focus on understanding classroom interactions during collaborative problem-based learning activities within an artifact ecology. Therefore, DC was considered an appropriate framework for building this understanding and highlighting affordances of the artifact ecology supporting collaboration and cooperation.

2.2 Distributed Cognition for Teamwork (DiCoT)

Nevertheless, there is no established methodology towards applying DC to a learning environment. Therefore, in order to build a concrete understanding of our data from a DC perspective, we adopted the Distributed Cognition for Teamwork (DiCoT) methodological framework introduced by Blandford and Furniss [8] for collaborative work. DiCoT framework emerged from the need to develop a methodology for DC analysis. It draws on ideas from Contextual Design [14], but re-orients them towards the DC framework. Compared to DC framework analyzed previously, Contextual Design can be viewed as a structured approach to collect and interpret data from fieldwork to build a product [14]. The "context" aspect highlights the need for in-situ and field investigations. DiCoT models were derived from the Contextual Design approach but are re-oriented towards principles that are central to the DC framework. Our decision to use DiCoT was based on the fact that DiCoT combines the theoretical framework of DC and the structure that Contextual Design provides, in order to provide an effective modelling tool to investigate and understand human behavior in a socio-technical environment.

DiCoT methodology encloses 22 principles, 18 of which are loosely classified in three models; physical layout, information flow, and artifacts [15]. More particularly, the physical model relates to the physical organization of collaborative activities and covers all aspects which are associated with a physical layout component [8]. This model focuses on factors that influence the way a system performs at a physical level, such as situation awareness, naturalness, bodily movements. Based on the aim and scope of the researchers, their focus can be differentiated, switching between key participants and primary locations/settings of the system.

On the second level, the information flow model, focuses on the flow of information neglecting the design of the mediating artifact by which information is transmitted [8]. There is a diversity of viewpoints, depending on the depth a researcher may want to examine or the issue that needs to tackle, e.g. focusing on the system as a "black box", focusing on the actors, or the way information flows and is transformed within the system.

Finally, the third aspect of the DiCoT framework - the artifact model - focuses on the detailed design of individual artifacts that are important within the cognitive system [8]. In particular, the artifact model focused on the artifacts deemed important to the activities and highlights the role of individual artifacts and pinpoints their affordances that support or hinder cognition. Table 1 presents the DiCoT principles classified in three models adopted from [8].

Table 1. DiCoT principles per model

	No	**Principle name and description**
Physical Layout	1	Space and Cognition: Space as a medium of supporting cognition during an activity.
	2	Perceptual: Spatial representations supporting cognition.
	3	Naturalness: Each representation match the features of that which it represents.
	4	Subtle Bodily Supports: How bodily actions are used to support activity.
	5	Situation Awareness: How are people kept informed of the activity.
	6	Horizon of Observation: What can be seen or heard by a person.
	7	Arrangement of Equipment: Physical arrangement affecting access to information.
Information Flow	8	Information Movement: Mechanisms used to move information.
	9	Information Transformation: How information is transformed in the system.
	10	Information Hub: Central point of information flow and decisions.
	11	Buffering: Hold up information until it can be processed.
	12	Communication Bandwidth: Richness of information during communication.
	13	Informal and Formal Communication: Importance of informal communication channels.
	14	Behavioral Trigger Factors: Individuals act in response to certain behavior.

Artifacts	15	Mediating Artifacts: Elements used to fulfill an activity within the system.
	16	Creating Scaffolding: How people use the environment to support their actions?
	17	Representation-Goal Parity: How close is the representation of current and goal state?
	18	Coordination of Resources: Plans, goals, history etc and their coordination to support cognition.

DiCoT methodology was evaluated and validated within a large ambulance call control center [15]. The analysis of a complex system through DiCoT may also support reasoning for both existing and future system designs [15]. Furthermore, DiCoT has been also applied in various research studies under the project CHI+MED for evaluating and improving healthcare technology in collaborative working environments such as the intensive care unit [16] [17]. Such an environment is considered of high complexity due to the strict and multiple interdependencies between nurses, doctors and healthcare technology. Stepping outside the healthcare system, DiCoT has also been useful in understanding and expanding the collaboration and coordination paradigm amongst eXtreme Programming teams [18]. Such teams are highly collaborative and self-structured, breaking down the problem into singular tasks. Through these numerous tasks, they manage to keep and distribute the status of each task, coordinating their team successfully.

2.3 Artifact Ecology

An artifact ecology is a space rich in technological tools with which individuals interact. These technologies communicate and share information with each other creating their own network [2] [3]. Further, Loke and Ling [4] explained that these devices interact "with one another, with users, and with Internet" (p. 78). Researchers have utilized the metaphor of "ecology" to indicate the co-habitation of multiple heterogeneous devices that are interlinked, acting as one system. In the case of collaborative environments, group members may work together tackling the same problem and working on sub-tasks individually. Digital and physical artifacts within the artifact ecology may be used for a variety of tasks while each individual may perform a task differently. Therefore, there are endless possibilities and design considerations for the construction of an artifact ecology for collaborative activities.

Researchers from various fields of engineering, design and education, have designed and investigated artifact ecologies from their own perspectives. For example, artifact ecologies have been designed to improve problem solving activities [19], support classroom learning [20], boost creativity in design conversations [21], or orchestrate teamwork in complex systems [22]. All these different artifact ecologies have been designed each time taking into consideration the people, the activities and the aim of the setting.

When it comes to collaborative learning activities in a real world setting, as team-members work together with a particular goal in mind, several tasks run at the same time and each team member may acquire a different way of performing a task. As Huang et al. [22] highlighted, projections, screens, and interactive displays have clear interdependencies within an ecology, although not designed as a unified system. Laying technologies next to each other to work together will result into a wider cognitive system. To design effective collaborative learning environments we need to acquire a deep understanding of the complex relations and interactions between collaborators and information technologies. Looi, Wong and Song [23] stressed the importance of what affordances or constrains different technologies such as mobile devices can bring to a technology-rich environment. More recently, surface computing technologies have been embedded in classroom settings creating an artifact ecology to support collaboration [24]. What is important, however, is to understand what each one of these technologies brings to the collaboration and coordination of group-work.

Based on previous studies in technology-rich environments, DC can provide a detailed identification of issues with existing work practices and mediating artifacts [6][7][13]. In addition, DC is prompted on highlighting what is salient in existing collaborative working system designs and practices and indicate aspects that require redesigning. The added benefit of examining a complex system through the lens of DC is that it allows researchers to take a step backwards and see the “big picture”, focusing on interactions and actions central to the coordination of work activities [7]. Such an understanding will allow researchers and practitioners to pin-point where changes should occur or should not occur in the cognitive system as a whole. As explained earlier, DiCoT framework explicitly emerged from the need to develop a methodology for DC analysis [8].

In this study, DC and the DiCoT methodological and analytical framework, were considered ideal for constructing this understanding for four student-groups during collaborative learning activities in an artifact ecology.

3 Methods

3.1 Participants

Participants in this study were 21 students (13 female) attending a postgraduate HCI course. Students were assigned to groups of four to five members. For the allocation of students in groups, we kept in mind the aim of creating multidisciplinary groups. Thus the procedure of forming groups was in part based on each student’s background, including studies in computer science and games, graphic arts and interactive multimedia, and education and communication media. Therefore, each group was composed of members from different disciplines.

The age span of the participants was between 22-45 years old (M=30). All students were familiar with digital technologies such as smartphones and tablets as well as with social networking spaces.

3.2 Context

The course was organized in three-hour weekly face-to-face sessions and followed a problem based learning (PBL) approach. Every session included phases of problem analysis, research, reporting and reflection as indicated by Koschmann and Stahl [25] while research could also occur online in-between the face-to-face sessions. PBL enables students to draw the path of their own learning while working within a group towards the solution of an open-ended problem. The tutor provided a short lecture at the beginning of each session in order to provide a triggering point for students' self-directed learning, as it was deemed important by Hmelo-Silver [26]. Students would then get into their groups for the collaborative activities, which focused on providing hands-on experience allowing active collaboration and engagement with the problem at hand.

3.3 Design Problem

The selection of the problem scenario is a crucial aspect of PBL. For the current in-class investigation the problem was derived from the student design competition of CHI 2007, entitled "Changing the Perspectives of Public Transport" and indicated the need to design an object, product or system that would promote the use of public transportation in Cyprus. The selected problem provided an open and real-world call for action, challenging students to provide a solution that could help drivers and improve the local transport infrastructure.

3.4 Artifact Ecology

We sought to create an artifact ecology, by enriching the classroom environment with various technologies aimed to support student collaborative activity, particularly brainstorming, researching, reporting or reflecting, both in-class and in distance (in-between the face-to-face meetings) [27]. Furthermore, this physical space, together with the PBL approach aimed to promote openness and flexibility. Students were encouraged to use the technologies as they perceived appropriate for each activity and task. Each group worked in a physical, technological set-up exhibiting three main attributes that we considered important for collaborative learning activity:

1. A downward pointing projection was provided as a central focus point to support students' fertile discussions and activities (see Figure 1). This setup would cultivate the blend of physical and digitally projected artifacts, mixing paper and technology, on the same workspace [28][29].
2. The multitasking nature of the group was invigorated with mobile devices such as tablets, iPods and laptops for concurrent research and record-keeping (see Figure 2). The students were also allowed to enrich the artifact ecology with their own devices.

3. Last, a widely used social networking platform (Facebook) was used to strengthen information sharing, coordination and collaboration, both between group members and devices.

3.5 Data Collection and Analysis

During the three month duration of the study, we observed and kept field notes of weekly sessions regarding group's procedures and the role of technology in their practices. We also collected self-reported data through conducting a focus group with each group at the completion of the course. The focus groups aimed to collect information about students' learning experiences within the artifact ecology, cognitive aspects of their actions and the affordances of the technologies provided. As a triangulation data source, we video-recorded all the collaborative sessions.

Fig. 1. Downward pointing projection

Fig. 2. Mobile devices in the artifact ecology

Initially, field notes were reviewed to create a preliminary system description guided by concrete principles provided by the DiCoT framework. The preliminary analysis indicated properties of the physical layout, main participants/tools and channels of communication and artifacts emerging as important. Second, we transcribed and reviewed the focus group data, classifying them in three major thematic units according to the DiCoT models - physical layout, information flow and artifacts as in Table 1.

From the thematic analysis we retrieved information regarding particular aspects of the physical workspace practices, communication channel protocols and purposes of artifacts' use for each team. Last, we reviewed the video data and selected video episodes that corresponded to principles for each one of the models. Video data assisted us on validating findings from field notes and focus groups (i.e., triangulation of findings). Selected video episodes were transcribed to enrich the existing descriptions of the three DiCoT models constructed from the analysis of the field notes and focus group data. In addition, the review of the video data provided snapshots of the physical layout in real-use, communication channel examples, and artifacts physical movement and information flow. A schematic representation of the analysis process is demonstrated in Figure 3 below.

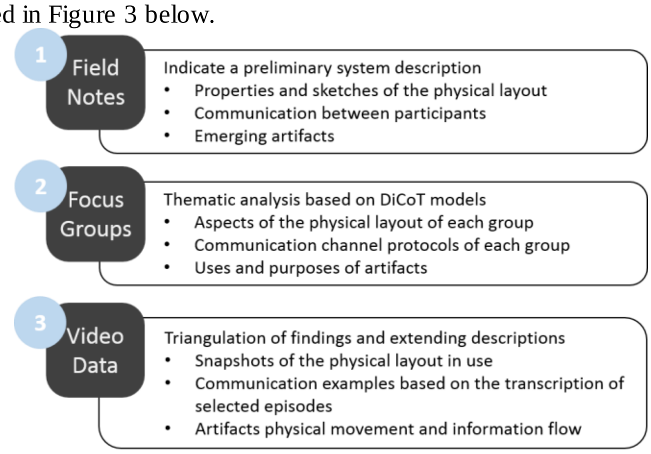

Fig. 3. Data analysis procedure

4 Findings

The analysis focused on understanding the interactions and interdependencies during collaborative learning activities in an artifact ecology. In this context, we showcase learner-learner and learner-artifact interactions evident in the workspace and highlight the affordances of the ecology of artifacts that support collaboration and cooperation during collaborative learning activities. In the following section, we describe the three DiCoT models, namely physical layout, information flow and artifact that were constructed during the analysis. Each model is described in depth, referring to DiCoT principles and providing additional materials such as information flow examples.

4.1 Physical Layout

The physical layout model covers aspects of collaborative learning activities that have a physical layout component. In this case, the group's physical workspace was mainly the downward pointing projection area which was fairly centered in the middle of a table surface leaving a 20cm wide space around it as individual work area. During PBL activities it was extensively used for research purposes and projecting group artifacts such as working documents or the groups' progress on Facebook (Principle 7). Group members were sitting around the workspace ensuring equal opportunities of access to artifacts and communication channels (Principle 1).

Other digital tools and physical artifacts were spread around the projection, space used as an individual learning space. Laying out their material and working in the individual workspace, learners could still be aware of the group activities (Principle 5). Furthermore, group members were within each other's zone of normal hearing which resulted in listening to the conversations and issues raised by their group-mates (Principle 6). The focal point and proximity between learners and tools enhanced group awareness, and consequently influenced group's monitoring of events and tacit learning.

Often, students attempted to interact with the projection naturally using gestures (Principle 3); they falsely perceived the projection as an interactive screen indicating a perceptual shift in human-computer interactions. Furthermore, group members used bodily movements to support their discussion of artifacts projected on the shared workspace, e.g. pointing to screen areas (Principle 4). Pointing directly at the artifact under discussion attracted the group's attention, turning their eye gaze towards the screen, potentially supporting their cognitive processes. For instance, a group observed a video playing and a group member (GM) explained aspects of the video while pointing to the screen.

GM 1:	This is what he is seeing. [Points to a particular area on the screen that encloses the view of the Google Glasses user.]
GM 2:	Yes on the mirror of the glasses.
GM 1:	He tells the Google Glasses to record. Tells it to look for a specific animal on the Internet.
GM 3:	[Points to the screen area where the search results will show up for the user]
GM 1:	It says to capture a photograph.
GM 4:	So you talk and Google Glasses are doing what you instruct them to do?
GM 1:	Yes, yes.

4.2 Information Flow

The information flow model pays attention to the perspective that deals with the way information propagates around the cognitive system. In this case, group members were located around the projected surface and freely moved around the downward pointing projection retaining equal opportunities towards the collaborative activities. Yet, the projection was handled by one individual at a time. This restricted the communication channels between individuals and shared projection, since every information had to be channeled towards the group member handling the physical mouse and keyboard operating the projection. The communication between the group members happened informally, face to face during collaborative activities (Principles 12, 13). The group member handling the projection took notes based on his/her own evaluations or instructions from other group members indicating what should be noted down or shown on the shared screen. This was problematic at times, as the more active students continuously expressed their thoughts and requests for the projection handler, while the less talkative participants would passively observe. Further, group members used digital tools to access online resources, shared documents and their Facebook group page. These tools enabled the communication between group members, in between the face-to-face sessions.

Primary flows of information between the group member (GM), group member handling the projection (GMp), tutor and the tools within the artifact ecology are shown in Figure 3.

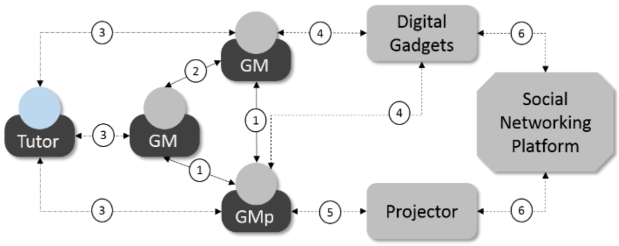

Fig. 4. Flow of information and communication channels

The primary mechanism used for information movement around the cognitive system is face-to-face interactions. Group members gathered around the downward pointing projection, brainstormed, identified learning issues, researched and acted as a united information decision hub (Principle 10). The high proximity between group members ensured that during collaborative learning activities information propagated in diversified forms. Physical artifacts, such as field notes or prototypes, or digital tools, such as smartphones and tablets, moved across group members facilitating information movement and discussion (Principle 8). A typical conversation between a group member and the handler of the projection included suggestions or instructions for action. This communication channel could also include the projection handler requesting clarifications concerning previous instructions from group members as shown in the example below (see Table 2 - "Channel 1").

GM 1:	"Move to another concept, other factors are in the way of using buses and we can say what regular people can do to help with this!" [Reading from notes]
GM 2:	Oh! Write this down. [Turning head to the projection handler with instructions]
GM 3:	And it can concern all the types of bus users, for example older people.

GM 1:	Yes, and we can… Em…
GM 4:	Basically, is raising awareness.
GM 1:	Yes, yes. We can take it as a public problem. [Nodding her head]
GM 4:	How to write it down though? [Handler requests clarifications]
GM 1:	With whatever comes first in your mind. Key-words, short description. Just the way you explained this to us earlier.

Another mechanism for the propagation of information was Facebook where groups posted their ideas, resources or snapshots from physical artifacts and discussed about the product design process. The social networking platform was used particularly to support communication between face-to-face sessions. Sharing on the social networking platform ensured that the content was available to the rest of the group anytime, anywhere, turning the Facebook into an information buffer (Principle 11).

In the case of information transformation mechanisms, learners turned the physical artifacts into digital artifacts (Principle 9). While working towards the solution of the design problem, group members took notes and created sketches as initial steps of their solution. Using digital gadgets, such as tablets or their own smartphones, they took snapshots and shared them, transforming them into digital artifacts.

The initial description developed based on field notes and focus groups indicated that all groups kept tasks and learning goals in checklists for every session. The video analysis verified and extended the description revealing that one particular group – in addition to the checklist – enabled triggering points to scaffold their collaborative activities (Principle 14). In particular, in every session, groups discussed and reflected on their findings and crossed checked the issues that were completed, indicating "COMPLETE" next to each issue. An unfinished issue would cause the group another cycle of research, reporting and reflection.

Table 2. Summary for information flow channels of the cognitive system

Channels	Summary
1 Group Member to Projection Handler	A group member expresses a suggestion that requires a reaction from the group member handling the projection, e.g. "open the report", "note that down". The projection handler receives the information and takes action by: • Taking notes about the idea • Requesting further information or • Researching the idea further through online sources

2 Group Member to Group Member	The group members discuss regularly the problem, the solution and the procedure to construct the solution. These conversations take place during face-to-face collaborative activities or through Facebook in-between sessions.
3 Group Member to Tutor	The dialogue between a group member and tutor might be initiated in two ways: • A group member requests guidance towards a particular aspect of the problem. The tutor provides additional triggers or hints, allowing the group to direct their own learning and discover the answers to their questions. • The tutor provides new material for the group to review and embed in their solution. The group members review material individually and collaboratively reflect on the new information.

4.3 Artifacts

The artifact model focuses on the thorough analysis of individual artifacts that are deemed important within the cognitive system. In this case, the downward projection, mobile devices and Facebook emerged as key mediating artifacts (Principle 15) to analyze further and interpret how they supported the collaboration and coordination during the collaborative activities. The downward pointing projection acted as a focal point for group activities, keeping the group concentrated on the task at hand, distributing awareness. Mobile devices such as tablets and smartphones, played a significant role mediating the transformation of physical artifacts into digital. For example, iPod was particularly used by Group 1 as a recorder to keep track of the ideas that were being discussed around the table, as in the example below.

GM 1:	Where is the iPod? Oh yes in the box. [Reaching for the iPod in the box.]
GM 2:	I think we should record whatever we discuss around the table because we will not remember everything.
GM 1:	Yes. Because now you all have said too many things and I could not take notes for all these. Wait a minute. [Searching an application in the iPod]
GM 3:	Doesn't matter. These were just thoughts that came out randomly, no formal ideas. Just preparatory phase. [Waving her hands]

GM 1:	Where is the…recorder? [Searching recorder application in the iPod]
GM 2:	Come on, I will do it. [Getting the iPod from Student 1]

Furthermore, Facebook constituted the primary communication and coordination medium for in-class and online interactions. As a coordination tool, Facebook captured the storyline of the group work, keeping a record of shared resources and issues discussed (Principle 18) [27]. In terms of scaffolding, the social networking platform offered the ability to categorize posts in themes or associate a post to an individual (Principle 16). The to-do list created in the previous session was either shared on Facebook or as a list in a shared document. Next to each item on the to-do list there was an indication of the learner or pair responsible for completing the task, thus, reducing the cognitive load of the group members to recall the roles assigned to each of them.

5 Discussion and Implications

Our study sought to illustrate the utility of DC and DiCoT as a tool for modelling interactions and interdependencies during collaborative learning activities in an artifact ecology. The findings showcase how the principles of DiCoT organized in three models – physical layout, information flow and artifacts – support the understanding of the learner-learner and learner-artifact interactions evident in the collaborative learning environment. Furthermore, the study highlights the affordances of the ecology of artifacts that support collaboration and cooperation during collaborative learning activities. The following sections elaborate on these findings and discuss implications of the study in relation to the literature.

5.1 DiCoT as a Modeling Tool

As claimed in the literature, DC is a well suited conceptual framework when dealing with technology-rich collaborative environments. The DiCoT framework explicitly emerged from the need to develop a methodology for DC analysis, using three models of behavior – physical layout, information flow and artifacts [8]. Extending the literature, one question this study sought to address was whether DiCoT is particularly well suited for modelling interactions and interdependencies during collaborative learning activities in an artifact ecology.

Considering the physical layout model of DiCoT, results illustrate that information is externally represented in the physical surroundings. The analysis demonstrated how the technological set-up (i.e., the artifact ecology) impacts the access to artifacts and the propagation of information through the cognitive system. The artifact and information flow models highlighted the distinguished roles that technological artifacts such as the downward projection, mobile devices and social networking platform (in this case, Facebook) play in coordinating activities and facilitating reflection of the product design process. Findings of this study support previous literature that DC can provide a lens for understanding collaborative learning activities in technology-rich spaces. Furthermore, the study adds to the validity of DiCoT as a well-suited modelling tool and a methodological and analytical tool for understanding complex interactions amongst learners, tasks, and tools in collocated technology-rich, learning environments.

5.2 Affordances of Artifact Ecology and Design Implications

Furthermore, the study sought to reveal the affordances of the ecology of artifacts that support collaboration and coordination during collaborative learning activities. A major affordance of the physical rearrangement of the ecology of artifacts is the close proximity between team members and artifacts, increasing awareness and supporting distributed cognition within the group. In a study by Sharp and Robinson [18], large areas namely "The Wall", assisted in the coordination of an eXtreme Programming team's activities. Team members could identify the progress of the collaborative activities from a distance, wherever in the room. In the present study the proximity between groups and tools assisted on increasing awareness by observing and listening to the issues raised by other group members. In one case, the large vertical surface distributed the status of the group work, while in the other case, the downward pointing projection created the necessary proximity to distribute awareness. We can conclude that tools perform differently across tasks and users, creating numerous possibilities for designing artifact ecologies and widening the horizons of research for in-situ studies in a variety of contexts.

Furthermore, considering the flow of information within the artifact ecology we can suggest a number of design directions for the design of learning environments. Due to the set up in communications channels, there is currently a lengthy procedure if a group member expresses an idea to be recorded or explored through the projection, resulting in delays in the collaborative activities. What's more, one or more group members might dominate the control of the projection through direct control of the mouse/keyboard or via multiple requests to the projection handler (see Section 4.2). Last, participants perceived natural to interact with direct and touch input with the projection on the table, suggesting a shift on what is nowadays perceived as natural interaction and transitioning towards tactile and gestural interaction styles. Based on the above, one potential design implication would be to switch the vertical projection with a surface computing system. That is, tabletops could help overcome the lengthy procedure of controlling the shared screen, reduce dominant actions, and increase the level of naturalness in the artifact ecology. There is already substantial work on using tabletops to support collaborative learning [30] [31]. There is also evidence that tabletops can help address the above-mentioned issues, moving attention away from a single input device such as a mouse or keyboard [32], promoting equal participation and shared control [33]. Therefore, the present work points attention to surface computing as a technology that can expand the artifact ecology to provide further support for collaboration and learning. Based on our findings concerning the use of the shared projection, we can provide a couple of directions for design elements in tabletop application for integration in this or similar contexts:

- Enable collaboration on shared artifacts that can be loaded into a group project
- Support pooling of information from previous meetings
- Enable discussion and recording of alternative solutions
- Allow tracking of decisions
- Enable continuity in learners' interactions across time and space (face-to-face and online).

Furthermore, findings from this study seem to suggest that the use of secondary displays and interactive screens is necessary for sharing awareness and providing behavioral trigger factors. In particular, participants used mobile devices, to demonstrate supporting material, physical or digital, as well as take personal notes (see Sections 4.1 and 4.3). This observation is consistent with Huang, Mynatt and Trimble's [22] showing that multiple displays can advance the distribution of cognition in a complex work space. However, based on the specific use of the mobile devices in the present study, we can provide few directions for implications for the design of mobile applications for integration in this or similar contexts:

- Support note taking and checklists applications with the ability to share or keep private
- Allow tagging for organization and searching of completed and pending tasks and
- Present notifications linked to the group project and its progress

5.3 Limitations and Future Directions

One limitation of this work is the lack of a detailed analysis of the dynamic and constantly changing artifacts that were encountered in the environment. For instance, the secondary displays in the environment changed constantly based on users' actions rather than being static representations during collaborative activities. In future work, this limitation can be overpowered by extending our analysis to include a temporal dimension, taking into account how users, tasks and tools change over time.

6 Conclusion

In the introduction we discussed how the different technologies available now at our fingertips can provoke new challenges on designing artifact ecologies. We also indicated the potential benefits of employing DC to understand the strengths and weaknesses of an artifact ecology designed to support collaborative learning activities. Through an in-class exploration, this work illustrated the utility of DC and DiCoT as a tool for modelling interactions and interdependencies during collaborative learning activities in an artifact ecology. We demonstrated that DC is a well suited framework for understanding collaborative learning activities in technology-rich spaces and that it can be applied practically through DiCoT. DiCoT enabled the consistent mapping of the complex interactions and interdependencies within the artifact ecology and allowed us to showcase learner-learner and learner-artifacts interactions evident in the workspace. We further highlighted the affordances of the ecology of artifacts that supported collaboration and cooperation during collaborative learning activities and presented potential areas of improvement linked to design directions for tools to be used in similar contexts.

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