Collaborative Problem Solving with Objects: Physical Aspects of a Tangible Tabletop in Technology-Based Assessment

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Abstract. This chapter analyses how the physical objects and space of a tangible user interface supports groups of participants to collaboratively solve a problem. Our aim is to understand which characteristics of the physical space support the participants in thinking collaboratively. We describe a user study with a tangible tabletop for technology-based assessment. We identify a series of patterns extracted from a video analysis using the Collaborative Learning Mechanism framework. In our discussion, we elaborate the characteristics of the TUI that support interactions based on the observed patterns: the physical interaction objects, the shareability of the space, and the non-responsive spaces.

Keywords: tangible user interface, interaction design, external cognition, collaborative problem solving, computer-based assessment, user study.

1 Introduction

Technology-based assessment (TBA) can facilitate learning and instruction in ways that paper and pencil cannot. Besides assessing that a learner has a certain level of competency (i.e., assessment *on* learning), it allows optimizing the learning process for both the student and the teacher, i.e., assessment *for* learning. During the last years, topics such as measuring solving strategies (i.e., measurement of dynamics in a test) and *collaborative problem solving* are getting more attention. Such approaches could allow assessing higher levels of comprehension and synthesis, e.g., the students' critical-thinking skills [1]. While current, web-based e-assessment frameworks (e.g., TAO [14]) exploit multimedia capabilities of graphical user interfaces to support a large range of different questions types, their possibilities for supporting and measuring aspects of collaborative problem solving are extremely limited. Hence, we need new technologies that support and allow collaborative activities in a setup, supporting more natural activities and interactions.

A potential solution are tangible user interfaces (TUIs), which create new types of interaction combining physical and digital elements as part of a physical space. Exploratory, design-focused studies have suggested that TUIs provide some learning benefits, due to the additional haptic dimension, the better accessibility for example for children, and the shared space that supports group interactions [9, 22]. According to Klemmer et al. [8] our human bodies and our interactions with physical objects have an essential impact on our understanding of the world. Bodily actions, physical manipulations, and tangible representations are an active component of our cognition; they act as cues for our memory [21] and allow us to think in a tangible way [17].

While a number of projects have provided different insights on how tangible interfaces are suitable for collaborative learning [2, 5, 11, 19, 22], we lack of a more detailed understanding of how collaborative problem solving is done on a TUI. A better characterization of the different interactions on a tabletop TUI could allow us to understand which aspects of TUIs support and describe our thinking processes in a collaborative problem solving activity.

In this chapter we explored a tangible version of a matching test item that recalls knowledge (i.e., facts) about our planets. The test item provides a task to the test takers (i.e., assign names to the planets), which we consider as simple problem that can be solved in a group on the tabletop. Our aim is to investigate the characteristics of the physical space that support different kinds of actions in a collaborative problem solving activity. Our approach is to analyse an effective collaboration situation around a tangible tabletop and to extract those patterns of external, physical actions that are used as a support for cognition.

On our prototype, physical cards labelled with names of planets could be matched to their visual representations on the tabletop. The test item was solved by eight groups of three subjects in August 2011. Based on a video analysis we extracted a number of patterns related to actions in the physical space and classified them according to a set of mechanisms, provided through the Collaborative Learning Mechanisms (CLM) framework [4]. In our discussion we describe three properties of the physical space that were considered being particularly relevant for external actions of collaborative thinking: the physical interaction objects, the shareability of the space, and the non-responsive spaces.

2 Related Work

A number of researchers are working on the development of learning environments using tangible user interfaces, without emphasizing onto assessment. For example, the Chromatorium [16] is an environment where children may discover and experiment with mixing of colours. A similar type of setup allows students to learn about the behaviour of light [12]. Through manipulating a torch and blocks on a table surface, the students could explore concepts of reflection, absorption, transmission, and refraction.

Another type of learning system implements the concept of digital manipulatives [15], computationally enhanced building blocks, which allow the exploration of abstract concepts. This principle is followed by SystemBlocks and FlowBlocks, two physical, modular interactive systems, which children can use to model and simulate dynamic behaviour [22]. The approach of concept mapping for self-regulated learning is followed in [10]: A tangible tabletop allows users to reflect and evaluate their learning tasks through externalizing and representing their knowledge on concept maps. They can, for instance, place physical tokens, assign names, make connections, and use tokens as containers.

Only a few systems go beyond the learning aspects, and implement possibilities for assessment. The Learning Cube [20] acts as a tangible learning platform where multiple choice tests can be done. One side shows a question while up to five answers are shown on each of the other sides. The user turns the cube to the side with the right answer and then shakes it to select it. Another example provides new possibilities for assessing spatial and constructional ability. The Cognitive Cubes [18] are a set of cubes that are used for reconstructing a target 3D shape. The change of each shape is recorded and scored for assessment.

The learning benefit of TUIs has been reflected in a number of design-focused and empirical studies. The use of large artefacts and physical props encourages collaboration as it slows down interaction, makes them more visible to others, and gives everyone “a vote” [19]. A comparative study [5] revealed that TUIs, in contrast to GUIs, are more inviting to use and provide a better support for active collaboration. A tangible programming space showed that physical cards support thinking and negotiating about design decisions of the programed game [2]. The multiple senses engaged in interactions with tangible objects correspond to the natural way that children learn [22]. Further, the shared space of TUIs enables social interactions, such as shifting the focus of a conversation or organizing themselves into subgroups [2], and encourages interference which often leads to argumentation and collective knowledge building [11].

Although a number of publications can be found that describe different kinds of strengths of TUIs for learning applications, there is still a lack of knowledge for using TUIs to assess different kinds of skills and competencies in technology-based assessment. We are missing a detailed understanding of how to design the physical objects and space in a TUI in order to support and measure the individual skills in a collaborative problem solving activity. In this chapter we contribute to this problem through providing the results of a user study, investigating which physical characteristics support groups of users in solving a task on a tangible tabletop. Our work provides a set of characteristics that need to be investigated in further empirical studies in order to understand how they impact social and cognitive aspects of the solving activity.

3 Case Study Design and Setup

For the case study, we set up a tangible tabletop system, based on the optical tracking framework “reactivision”. The worktop was sized 95x120cm, with an interactive area of 75x100cm. On the table, we projected an image of the solar system, showing the sun and each of the nine planets. We further created 9 cards, each with one name of the planets. A camera and projector had been placed underneath the table to track the positions of the physical objects and project feedback onto the semi-translucent tabletop surface. The implemented task was to match the correct name of a planet to the correct image of a planet.

When a user places a card onto a planet, she/he gets an immediate feedback in form of a red (false answer) or green (correct answer) circle that is shown around the planet. During the solving of the task, the system counts the number of attempts (i.e., wrong pairing of a card and a planet's image was counted as one attempt), and the time needed to solve the task. As soon as all the planets are correctly assigned, the system shows a scoring window which displays the results.

Fig 1. Mapping the cards with the images of the planets

The study was conducted with 24 participants divided into eight groups of three. The participants were randomly selected from the research department, with no deep background in astronomy. A briefing questionnaire revealed that the available knowledge was acquired at schools and through personal interests.

At the beginning of each test, the participants were explained the concept of a TUI and how it detects physical objects. We described the goal of their task and which kind of feedback they can expect from the system. They could place themselves around the table as they preferred.

The study was video recorded and at the end we distributed a questionnaire. The video recording was made from one angle, showing the movements on the table and the bodily interactions made close to the table. The questionnaire consisted of three questions asking the background knowledge on astronomy and the System Usability Scale (SUS) with ten questions. Further, we took notes on the performance of the group and how the users placed themselves around the table.

While the results from the quantitative evaluation have been described elsewhere [13], we focus here on a qualitative analysis of the different ways of interacting with the physical objects and space as support for solving a task.

4 Video Analysis and Findings

The first step of the video analysis was to extract a set of key scenes showing the most significant moments of interaction involving the physical space and objects. Those key scenes are described with a few snapshots and a transcript of what happened.

The key scenes have then been analysed using the CLM framework [4]. This framework supports the analysis of mechanisms for collaborative learning by suggesting four categories of behaviour. Groups are discussing collaboratively through "Making and accepting suggestions", i.e., introducing and accepting knowledge and ideas, and “Negotiating”, i.e., sharing statements and suggestions for joint consideration. Further, the collaboration is coordinated through mechanisms of “Joint attention and awareness”, allowing to monitor ongoing activity, and “Narrations”, where participants say aloud what they are doing.

As a collaborative problem solving activity can also be considered as a type of learning activity, we can assume that the CLM framework will provide us an adequate scope for focusing onto the following research questions:

- What types of behaviour can be found in the collaborative problem solving task?
- How did participants make use of the physical space to express this behaviour?

4.1 Collaborative Discussion: Making and Accepting Suggestions

To solve the task in a group, the participants made suggestions about potential names of different planets by speaking aloud, pointing, and making movements with the physical objects. A typical pattern was to express a suggestion through pointing to a planet and verbally suggesting the corresponding name. The acceptance of such a suggestion was then expressed in the form of an action: a second participant grasped the corresponding card and placed it on the planet’s image.

Fig. 2. *P1 looks at a planet, and points to it:* “This is the earth”. *(1) P3 grasps the card of the earth and places it on the according planet. (2)*

Another approach for making suggestions was to perform a slow movement with wide gestures, resulting in the placement of a card onto a planet. For example, in Figure 3, one participant grasped a card and slowly moved it towards a planet to express a suggestion. During this action he makes sure that he has the attention of a second participant. The fact that the other user did not object, is interpreted as agreement to his suggestion.

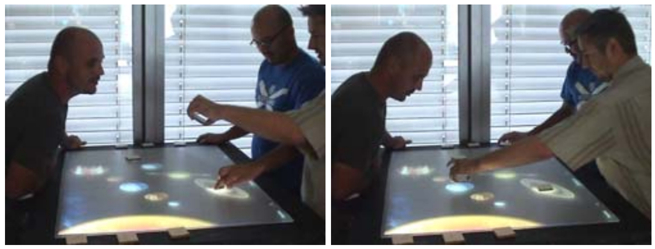

Fig. 3. *P6 grasps the earth card and holds it high to raise the attention of P4. (1) He slowly lowers his arm to place the card onto earth. P4 follows his movement with his eyes and head and does not object (2).*

In another example, a participant combined talk with a physical manipulation to express a suggestion (Figure 4). He holds the card at a small distance over a planet and raises the attention onto that planet. This physical manipulation allows him to more specifically illustrate a suggestion he is making to the other participants.

Fig. 4. *P13 holds the Jupiter card over a planet (1):* "Can I put Jupiter?" *P14:* "That seems reasonable to me" *P13 places the card on the planet by letting it fall down from a small distance. (2)*

4.2 Collaborative Discussion: Negotiating

When participants were unsure about assignments, they started to negotiate. In our analysis we identified patterns of sharing knowledge, asking questions, and disagreement, using the physical objects and space in different ways.

While a typical approach was to share knowledge about planets by speaking, making gestures, and pointing, we could also observe situations where the statement was underlined with physical actions. For example, Figure 5 shows a situation where a group decided to first place all the nine cards on an edge of the table in order to sort them according to their distance to the sun.

Fig. 5. *P24 knows a mnemonic for remembering the order of the planets. P24 and P23 then grasp the cards one after the other and place them in this order on the bottom edge of the table.*

In negotiation phases, we further observed different ways of asking questions. For example, a participant combined talk, with pointing and gestures:

> *P10, pointing to a planet:* "Jupiter is not the… ", *making an iconic gesture*, "…biggest planet?"

In a similar way, disagreement has been expressed through talk and pointing. For example:

> *P12 points with her finger onto the yellow planet: "So… here?"*
> *P10 moves the card towards the planet and holds it slightly over it:* "Here? We tried… no?"

4.3 Coordinating Collaboration: Joint Attention and Awareness

The working situation around a tabletop in a physical space provided an excellent environment for monitoring current activities and reflecting upon them. The participants are working on one shared space and each manipulation can be followed by everyone. We could identify a few working mechanisms that even reinforced the general awareness of what is going on.

In a number of situations, participants worked in turns, and there was always just one participant making an assignment at a time (Figure 6). This allowed the other two users to follow his action and to note the corresponding feedback of the system (e.g., red or green circle). Such a situation could usually be observed when participants had already placed the planets they knew, and started to work on the remaining ones using a try and error strategy.

Fig. 6. *P5. places a card on a planet (1). He sees the response turning red and removes the card very quickly (2). P4 follows this action while holding another card in his hand. As soon as P5 is done, P4 places his card (3).*

In another situation (Figure 7), we observed how participants grasped a few cards, to hold them in their hands while discussing the suggestions. Holding the objects in the hands allowed them to jointly focus on these three names and concentrate the discussions around them.

Fig. 7. *P16, P17, and P18 each hold a card in their hand.* P16: “This little one, isn’t it Uranus?” P18: “Ah, you may be right, yes. Go on !” *P16 places it, the circle turns red:* “No…”

4.4 Coordinating Collaboration: Narrations

Although narrations in the classical sense of the word have not been observed, we identified an alternative way of telling stories, i.e., by the use of gestures and physical objects. Such practices have been observed during phases of individual working. In Figure 8, we see an example of narrations based on gestures. A participant individually places the Pluto card on a planet and gets feedback that it is correct. To tell the other ones that he just successfully placed the card, he raises his arm and expresses a winning gesture.

Fig. 8. *P4 looks at the image and then on the cards close to him (1). He spots Pluto, grasps the card and quickly places it on the planet (2). He sees the circle turning green, is happy and shows it by raising his arm (3)*

A second mechanism related to narrations in the physical space could be observed in a few groups. When placing cards on the table, those participants made such a strong movement that the placement created a noise which could not go unnoticed by the other participants. We can interpret that this audible aspect of physical manipulations is a way of telling the group about own actions and making it easier to follow interventions.

5 Discussion

To better understand what characteristics of the physical objects and space support the observed mechanisms, we analysed the respective interactions in more detail. We characterized each of the interactions based on the questions:

- Where does the interaction take place?
- What is physically manipulated during the interaction?
- Who is actively or passively intervening in the interaction?

Table 1 summarizes these major characteristics of the physical interactions.

Table 1. Mechanisms of collaboration supported though different characteristics of the physical interaction.

Physical mechanism	**Physical interaction**		
	Where	*What*	*Who*
Making suggestions through talk and pointing	Responsive area	Hands	Group
Agreeing by placing the card according to a suggestion	Responsive area	Hands and cards	Group
Making suggestions through slow and visible movements	Responsive area	Hands and cards	Group
Sharing knowledge through actions	Non-responsive spaces	Hands and cards	Group

Asking questions through talk, and pointing	Responsive area	Hands	Group
Asking questions through talk, and action	Non-responsive spaces	Hands and cards	Group
Working in turns	Responsive area	Hands and cards	Group
Holding cards in the hand	Non-responsive spaces	Hands and cards	Group
Narrations with gestures and body posture	Responsive area	Hands, body posture	Group
Placing cards with some noise	Non-responsive spaces	Hands and cards	Group

From this analysis, we can extract a few insights concerning the physical characteristics of collaborative thinking spaces, which we discuss in the following.

5.1 Physical Interaction Objects

In most of the mechanisms the physical cards showing the names of the planets are being used. Being small, they were hold in the hand, and moved to different locations on or next to the table.

Participants often used the cards to interact with the system and effectively assign names to planets. In addition, we could identify a number of situations where the cards have been used for 'offline' interactions. It was a common practice to hold a card close to a planet in order to demonstrate a potential assignment. Further, participants are holding several objects in their hands, to concentrate the discussion on the naming of this subset of planets. Other situations showed that the physicality of interaction objects allowed expressing an additional meaning during a manipulation. When participants placed the cards with some noise on the table, they were able to increase the awareness of the other participants. Besides assigning the name to the planet, they added additional information to their physical manipulation, which allowed for a better coordination of collaboration.

The physicality of the interaction objects allowed for a high range of flexibility in their potential manipulations. The participants had the possibility to vary the type and location of the manipulation in order to express different kinds of meanings. This freedom of action was a useful resource for mechanisms related to planning, discussion, and coordination. Such actions, that do not contribute towards the overall goal of the task, but facilitate mental computation of information, are called epistemic actions [7]. Kirsh and Maglio consider them as a valuable resource in improving human cognition and performance.

5.2 Shareability of the Space

The selected mechanisms all involve several participants, which communicate to each other either through talk and gestures, or through physical actions. Such a communication thus involves the faces, bodies, and hands of participants, the responsive area where the planets are displayed, and the cards. This can be illustrated, for example, through the situation described in Figure 1, where one participant points onto a planet and a second places the cards according to this suggestion. Such a mechanism involves the line of sights of the two participants, the pointing gesture, the card, the physical movement, and the image of the solar system.

These different elements thus need to be visible for each participant; the interaction area and physical objects further need to be reachable by them. This brings us to the conclusion that an important characteristic of this physical space is sharable on several layers. Each participant can easily follow and access what is happening a) on the responsive area, b) in the space between participants, and c) on the storing place of the objects. Those areas are merged in the space above the tabletop and create a shared space for a variety of actions combining talk, gestures, body postures, and physical objects.

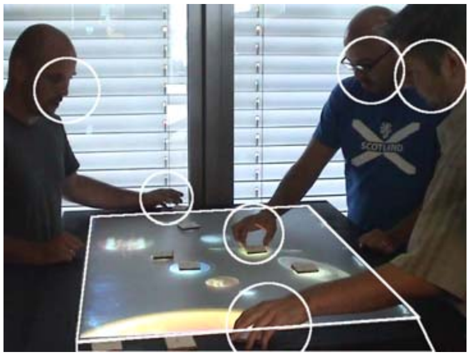

Fig. 9. The tabletop provides a shared space where gazes, body postures, gestures, physical actions, interaction area and storage places meet.

This characteristic of the physical space relates to what Hornecker [6] calls a "bodily shared space", i.e., a space where users and objects are co-present and where the user experiences his body to be in the same place as the interaction objects.

5.3 Non-responsive Spaces

When analysing the actual places where the participants are interacting with each other, we notice that a number of mechanisms do not occur on the interaction surface itself. The participants rather specifically looked for places which are not responsive in order to discuss suggestions without interacting with the application.

For example in Figure 5, the participants place the cards on the edge of the table to discuss the sequence of the planets according to their distance to the sun. Another example is described in Figure 4 where a participant explicitly makes use of the space above the surface, in order to demonstrate a suggestion without entering it into the system.

These non-responsive spaces are thus a convenient way for participants to discuss aspects of suggestions. Since no movements are tracked on these areas, participants cannot enter a wrong solution, and feel comfortable with exchanging their ideas. They are thus an essential characteristic for supporting epistemic actions. Participants use them to make suggestions, demonstrate next steps, or set a common focus; activities which do not directly contribute towards the overall goal of the task, but support the participants in thinking about the problem.

A similar observation was made by Fernaeus and Tholander [3], reflecting about an “extra layer of interaction” that is enabled through actions that are “not recorded into the system”. The physical space therefore allows a whole range of activities, such as planning and testing of ideas, or selecting and locating the programming cards.

6 Conclusions

Through analysing groups of three persons using a tangible tabletop, we have identified mechanisms of collaborative problem solving and related characteristics of the physical space and objects. We found three aspects that supported users in thinking collaboratively: the physical interaction objects, the shareability of the space, and the non-responsive spaces.

Our observations synergize with findings from related work on TUIs and the physical space. They provide another example of how the physicality of TUIs was used for a collaborative learning activity and thus contribute towards a better understanding of the design space of tangible user interfaces.

The assessment item used in this evaluation was assessing knowledge. We implemented a matching task, which is one of the classical tasks used by GUI-based assessment platforms, such as TAO [14]. This task provides only a simple example of a collaborative problem solving context, as the amount of potential solutions is very limited. Further, the system provides only limited digital feedback, and our study was done with a small number of people. Nevertheless, the analysed context was a problem solving situation in a physical interactive environment and allowed us to identify a range of very significant aspects of the physical space and objects that have been used in this situation.

These insights will allow us to set up a range of further experiments. For example, in the near future, we will study the impact of different characteristics of tangible interactions on the level of procedural knowledge. Focusing on procedural knowledge will allow us to assess problem solving skills, for example, in the context of simulations. In empirical studies, we will analyse the differences in the solving strategies and related performances of groups, when varying a) physical characteristics of the TUI and b) the nature of the task. This will allow us first to define a framework for designing TUIs to support collaborative problem solving tasks and second, such an understanding of solving strategies in the physical space allows us to identify new ways of measuring the different aspects of a collaborative problem solving activity and to improve techniques of technology-based assessment. A first step would be to classify the types of activities in the non-responsive spaces and to develop a taxonomy of events that we want to measure. New technologies need to be integrated into the table to measure those events. Educational data mining approaches will detect patterns in the logged events streams gathered from the non-responsive as well as responsive spaces. Those patterns can be mapped to solving strategies and cognitive behaviours during problem solving.

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