Design of Systems for Supporting Collaborative Learning Augmented with Physical Artefacts

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In this chapter, the design process of systems for supporting collaborative learning is described. We have developed the collaborative learning support systems called Epro, Epro2, and CarettaKids and evaluated through educational practices in elementary schools. Based on our experience with these systems, lessons related to the design issues of tangible or tabletop interface systems for supporting children's collaborative learning are discussed.

Keywords Collaborative learning, Tabletop interface, Environmental learning, Elementary school children, Sensing board, PDA

1 Introduction

We have been developing systems to support collaborative learning (Koschmann 1996) in elementary school education. The underlying philosophy of our research project is that learners should be regarded as active creators, rather than passive recipients, of information and knowledge (Fischer 1998). Therefore, the role of computational media should be to support learners' active participation in the learning process.

Many computational systems or media used in school education support learning by allowing children to access and to explore virtual information spaces, to search Internet resources for information related to their learning and to have synchronous or asynchronous discussions with other children in separate locations. The proposed systems in this chapter, on the other hand, integrate physical and virtual spaces to enhance active learning. Children can experience, in virtual space, visual feedback of their interactions with physical artefacts in a physical space.

The systems are designed to enhance learning about environmental problems through simulations and discussions. Each system allows children to construct a model town in a physical space and view the environmental impact of their actions simulated in the virtual space. With these systems, a group of children can verify knowledge they acquired from their schoolteachers or textbooks. Therefore, the

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systems are more effective at augmenting children's learning experiences, raising their learning motivation and supporting their participation than systems that allow them to interact only within a virtual space.

In this chapter, we discuss the design processes of the systems. As users of the systems are elementary school children and their teachers, the author's group first asked them to use a paper-based prototype system, to identify requirements of systems to be designed through interviews with children and teachers and analyses of their behaviours. The designed systems have evolved through the evaluations of educational practices in elementary schools. This chapter describes three systems called Epro, Epro2, and CarettaKids, respectively, and the issues raised in their evaluations. Based on our experiences with these systems, recommendations related to the design of tangible or tabletop interface systems for supporting children's collaborative learning are given.

2 Key Issues Collaborative Learning in Designing Systems for Supporting Children's Collaborative Learning

When we think of learning support technologies, we can take various approaches or systems based on different learning theories. The underlying conceptual and theoretical premise of our project is that people learn through interactions with others by participating in a learning community (Lave and Wenger 1991, Fischer and Sugimoto 2006, Resnick 1991). They are also related to theories of social constructivism (Steffe and Gale 1995). Based on these learning theories, we investigate how learning support systems should be designed, utilizing information and communication technologies to enable the systems to enhance learners' experiences. Our basic strategies for designing systems for supporting collaborative learning are as follows.

2.1 Designing User Interfaces That Allow Physical Manipulations

In many conventional systems for supporting learning, learners stay in a fixed position, such as sitting in front of a computer, using it with a keyboard and a mouse and viewing a display. However, when we think of our daily lives, we interact naturally with other people and manipulate real-world artefacts. Therefore, we believe that user interfaces of systems for supporting collaborative learning should allow learners to conduct physical manipulations. Moreover, as users of our systems are children who are not always good at using computers, we have to design computational media that allow children to conduct an intuitive manipulation to promote their participation in learning situations.

2.2 Designing Computational Media That Enhance Interactions Between Learners

In school education, children have traditionally learned by absorbing knowledge provided by their teachers and textbooks, that is, they have been passive recipients of knowledge. Recently, some schools have begun to try different learning/teaching approaches: children actively discuss topics with each other and construct knowledge by themselves (Scardamalia and Bereiter 1996). One effective way to support such knowledge construction through discussions and interactions between children, is to design computational media integrated with physical media that allows children to manipulate and share concepts in the physical world (Arias et al. 2000).

2.3 Introducing a Sense of Play for Learners' Engagement

A sense of game or play is useful for raising the level of learners' engagement and excitement (Kafai 1996). Learning through playing is one of the most effective approaches because it provides learners with an easy starting point for learning and immerses them in their activities. If learners' play activities are smoothly linked to authentic learning, they will learn by themselves while retaining high levels of motivation.

A solution that satisfies the issues raised above is a tabletop and tangible interface system that allows learners to manipulate physical artefacts and share them with each other. However, the design requirements for such a system enhancing children's collaborative learning were not clear when the author's group started their project. Therefore, a prototype system for investigating the requirement was first developed.

3 Prototype System for Identifying Design Requirements

3.1 Overview

The system to be designed was used for supporting children's collaborative learning about environmental problems. The functions first thought to be necessary were:

- The system should automatically and rapidly recognize types and locations of objects manipulated by learners.
- Based on the arrangement of the objects, the system should calculate environmental changes and visualize them through simulations.

The first function relates to the design of the hardware, and several existing methods for object recognition – such as sensors or image processing – were applicable. The second function relates to the software and user interface design. The author's group decided to investigate the hardware design first, because hardware would take longer to develop and because – in contrast to software – changing hardware is difficult and costly once implementation has begun.

3.2 A Prototype System: Paperboard and Software

To understand the requirements of users (teachers and children), "Wizard of Oz" experiments were conducted. The following prototype system was brought to classrooms:

- Paperboards: Several paperboards were created and used not only to find suitable size and number of grid cells, but also to identify how children behave while using them. Figure 1 shows an example of a paperboard.
- Simulation and visualization software: From discussions with teachers, and from a textbook used in lessons, the knowledge with which to construct a simulation model of the software was extracted. The teachers requested that the simulation model should not be complicated, enabling the children to guess the relationship between cause and effect. Therefore, three types of pieces (a house, a factory, and a tree, each of which represents people, industry, and nature, respectively) to be directly manipulated on the paperboards by the children were created, and five parameters describing environmental changes in a town were selected.

Elementary school children (fifth graders aged 10–11) participated in the experiments. The prototype system could not automatically identify the pieces on the paperboard. When children put a piece on the paperboard, one of the experimenters would manually input the type and location of the piece into a personal computer.

Fig. 1 An example of a paperboard for clarifying design requirements and children's behaviours

Then the computer started the simulation and created a visualization of the results. Through these experiments, post-experimental interviews with the children, analyses of their behaviours, and discussions with teachers, the following issues were clarified:

- While using the system, children pushed and pulled the paperboard so that they could easily place a piece on it. They sometimes leaned over the paperboard to place a piece on it.
- As the system must be designed to be used in one class period, the time to construct a town on the board needed to be less than 50 min. However, for all the children in one group to have sufficient opportunities for manipulating pieces and to make the results of computer simulation educationally meaningful, more than 200–300 pieces should be placed on the board.
- The system must be large enough for four to eight children to sit around it.
- As the system would be used in an elementary school classroom, not in a university laboratory, special equipment requiring remodelling of the room cannot be used. The system design must secure children's safety and also allow for their unpredictable movements and behaviours.
- It is desirable that children be able to independently set up and dismantle the system.
- Although the simulation model was simple, it effectively stimulated children's thinking. For example, they discussed the factories on the board that should be removed or where trees should be placed to reduce the level of CO_2 density. They also considered the level of noise in residential areas (where many houses were placed).

Based on these findings and from discussions with the teachers, the design requirements for the system were formulated as follows:

- For object recognition, a method using image-processing technology (e.g., Underkoffler and Ishii 1999) or a touch-sensitive display (e.g., Arias et al. 2000) is not suitable for this project and a sensor-based method is preferable.
- The system should be more than 60 cm × 60 cm, and large enough for four to eight children to sit around it.
- The system should simultaneously accept the input from about 500 objects and rapidly recognize their types and locations.
- The system should be as light and simple as possible, allowing children to use it independently.

A design decision at that time (Spring 1999) was not to use image-processing technology or a touch-sensitive display for object recognition. To use image-processing technology, a camera must be installed over or below a desk. Installation requires very tall, large or heavy special equipment that may be difficult to use without remodelling the classroom. The camera must be calibrated before using the system, which is not an easy task for children to perform. Another problem with image-processing technology is related to occlusions that happen when children hide pieces with their hands, heads or bodies. Moreover, processing time for object recognition is also significant. Children become frustrated if feedback is not immediately given after manipulation of pieces. At that time, stable recognition of hundreds of different pieces within a sufficiently short period (e.g., a tenth of a second) seemed very difficult. Touch-sensitive displays are single input devices and are not suitable for applications required to recognize multiple pieces quickly.

In experiments with the prototype system, a suitable size for a piece was also investigated, because children would have difficulty manipulating pieces that were too big or too small. The size was chosen by asking children to grasp pieces of differing sizes in the palm of their hand, place them on the paper-based board, and move them by picking them up with their fingers.

4 How Designs of the Systems Evolved

4.1 Design of Sensing Board

Through these investigations, we decided to use a sensor-based technology called RFID (Radio Frequency Identification) technology, and developed a board-type multiple input device (we call it a “sensing board”). RFID (Omron V720 series in this study) is a non-contact object identification and data transfer technology. The RFID system consists of two components: an antenna (with a transceiver and decoder) and a tag as shown in Fig. 2.

The performance of data transmission between tag and antenna is stable, and a tag is small enough to be invisible once embedded in a piece. However, the data transmission speed between a reader and a tag is not very fast (10 ms–20 ms). This may cause serious communication delays; for example, it will take one to two

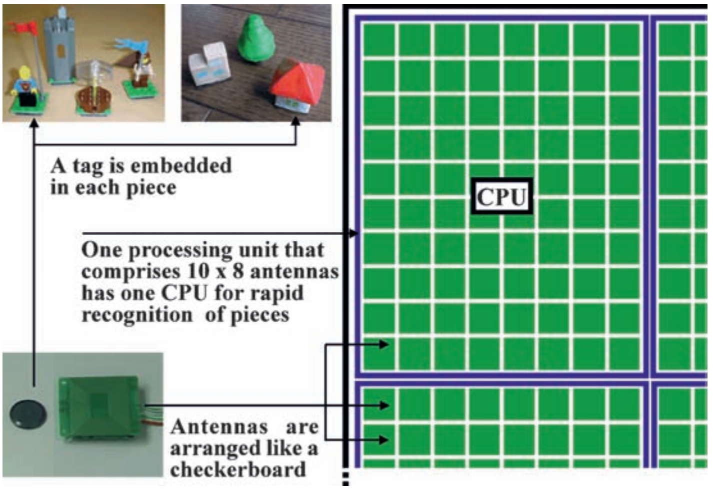

Fig. 2 A sensing board and pieces that utilize RFID technology

seconds to identify a hundred pieces. We devised a method that reduces the processing time for data transmission. In the current implementation, one central processing unit (CPU) (Hitachi H8 16 MHz microcomputer unit) is attached to a unit comprising 10 × 8 squares as shown in Fig. 2. When the sensing board receives a command for detecting the arrangement of pieces on it from the attached personal computer, it first simultaneously sends a read command to all CPUs through the interface CPU. Then, the CPU of each unit sequentially activates and controls 80 antennas in its unit, enabling each to activate a tag and read its data. Finally, the sensing board sends the tag data from the CPUs through the interface CPU. The architecture of the sensing board enables parallel processing of communication between tags and readers, and makes the communication time theoretically independent of the number of units, or the size of the board. The time taken to acquire the arrangement of pieces on the current version of the sensing board is less than 0.05 s. The merits of this architecture are as follows:

- Multiple users can simultaneously place or move multiple pieces on the sensing board.
- By changing the number of units, the sensing board can be freely extended or reduced without increasing response time.

Slits are aligned on the surface of the sensing board, allowing users to recognize a checkerboard-like grid. A tag embedded in a piece is placed inside a grid cell, and a reader is embedded in the board under each cell. The current version of the sensing board (Sugimoto et al. 2001), has 20 × 24 cells with sides of three centimetres (the size of the board: 60 cm × 90 cm). The board can be separated into two parts whose weights are about 4 kg and 3 kg, respectively. The sensing board is not light enough to be portable, but one or two children can easily set it up once they learn how. The setup involves assembling the parts and connecting a personal computer and the sensing board through their RS-232C interfaces. Then the sensing board is ready to start object recognition on its surface.

4.2 Epro: Integrating Physical and Virtual Spaces to Enhance Children's Interactions

The author's group developed their first generation system called Epro (Kusunoki et al. 1999, 2002; Sugimoto et al. 2002) based on the design requirements and lessons gained through the prototype system. The sensing board was used to identify objects manipulated by children. In designing Epro's software, the simulation model and the visualization of simulation results in the prototype system were modified: To enhance the effects on children's learning, a simulation model was developed based on lessons given by the teachers and textbook material. Through further discussions with the teachers, the following input and output parameters were chosen:

- Input parameters: house, tree, factory (input by placing pieces on the sensing board).
- Output parameters: noise, distribution of CO_2 and NO_X/SO_X, finance, population, water pollution, garbage.

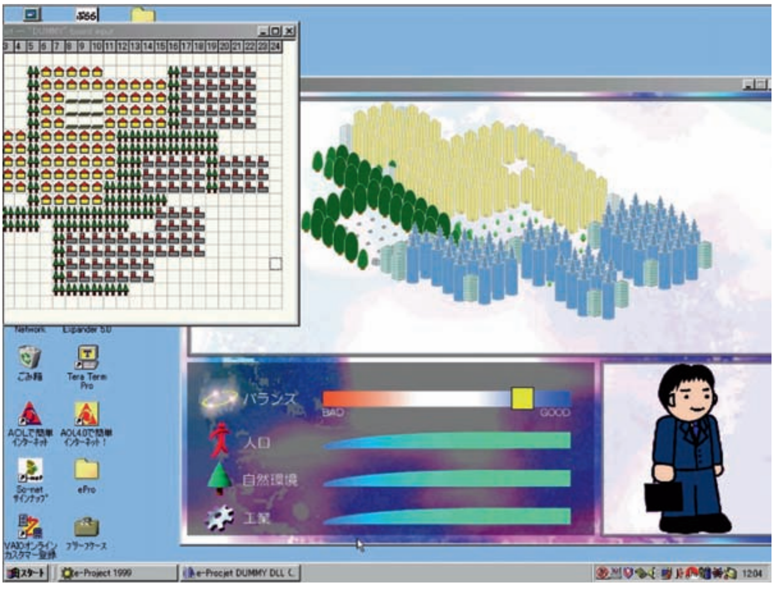

Fig. 3 An example of visualized simulation results

Figure 3 shows an example of visualized simulation results. When individual children conduct their manipulation on the sensing board, the simulation software calculates the current status of the town based on the arrangement of pieces and updates the visualized results on a computer display. Horizontal bars that appear on the lower middle of the figure represent the status of the town, such as its population, natural environment, and industry based on how many houses, factories, and trees are in the town: children are requested to change the number of the pieces and their locations on the sensing board and to have as high a score as possible by keeping the values of the bars balanced. By using characters (at the lower left corner), Epro makes children intuitively understand what happens as their town is being designed.

Figure 4 shows how children used Epro in their classroom. Three-year evaluations with fifth and sixth graders in elementary schools indicated that (1) Epro allowed children to easily test and understand knowledge acquired through textbooks or teachers, (2) children who were not good at using a computer (by mouse or keyboard) could participate in collaborative learning, and (3) by sharing artefacts (a physical board and pieces), children could actively externalize their own opinions and discuss them with others.

4.3 Epro2: Supporting Collaborative Learning by Integrating Face-To-Face and Networked Environments

Epro proved to effectively support children's collaborative learning in elementary schools. However, through analyses of children's behaviours and comments from schoolteachers, the following issues emerged:

Fig. 4 Children use Epro in their classroom

1. Does a sense of play really support children's learning?

A sense of play was useful for supporting children's participation in a learning situation, and raising the level of their engagement and excitement. However, evaluations of Epro indicated that some children were interested in the system as a game, but were not as motivated to learn with it. For example, when children reviewed bad simulation results given by Epro, they did not think deeply about the reasons for such results by using their knowledge, nor did they intensively discuss how they should change the situation. They often tried to improve the results by moving pieces randomly.

2. How should children's learning be contextualized?

Learners are engaged in their learning when they realize that their practice is situated in the real world, and is meaningful and authentic (Jonassen et al. 1997, Roussou 2004). On the other hand, when children learn about environmental issues in a classroom only through textbooks or Epro, they may not feel that their learning activities are related to problems in the real world.

These findings drove the research project to the next step. The author's group first examined how a system with a sense of play could support authentic learning by children. Then the second generation system called Epro2 (Sugimoto et al. 2003) was developed by retaining the sense of play of Epro and extending its functions for raising the level of authenticity in learning about environmental issues. The author's group also collaborated with schoolteachers to develop a new curriculum. What follows describes our approach.

- Epro2: a system for supporting group learning in face-to-face and networked settings.

In dealing with environmental issues, we need to not only use scientific knowledge, but also to reach a certain agreement through negotiations with different stakeholders. In Epro, discussions and negotiations between children in a face-to-face setting were supported. Epro2, on the other hand, was designed to support discussions and negotiations in face-to-face and networked settings. In Epro2, multiple sensing boards are located in different places and connected through a computer network. Like Epro, a group of children sits around a sensing board and constructs a town by manipulating physical pieces in a face-to-face setting. Epro2, however, makes these physically distant towns virtually contiguous and executes environmental and financial simulations based on the arrangement of pieces on the boards. Therefore, these towns are mutually affected by the other town's activities. Epro2 visualizes the environmental and financial status of a town on each board and the influences received from another town. By reviewing the visualized results, a group of children can negotiate with children in a different place through a chat system.

The author's group extended the system from a standalone system (Epro) to a networked system (Epro2) because, on several occasions, problems occurring in the real world have to be solved through negotiations between people separated by distance or who do not know each other. Moreover, through the evaluations, we found that learning with Epro in a face-to-face setting was not always appropriate, because some children who were leaders among their classmates seized the leadership role and the other children often followed without discussion or consideration of the arguments. Therefore, to avoid as much as possible the influences of interpersonal relationships in daily lives on children's activities with Epro2, and to activate discussions and negotiations between them (Sproull and Kiesler 1991), communications between groups were carried out using a chat system with anonymity; the name of a child in one group could not be identified by children of the other group.

- Design of a curriculum to enhance authentic learning with the system.

To contextualize children's learning, fieldwork in the neighbourhood of the children's elementary school was introduced into the curriculum. Investigating and experiencing for themselves what happens in the real world gave children opportunities for discovering, in collaboration with other children, their own problems (Boud and Feletti 1997). After the fieldwork, children used Epro2 to solve the problems. To enhance the continuity between children's learning in the fieldwork and with Epro2, its simulation software was designed to accept geographical or meteorological features of their fieldwork sites as simulation conditions.

Figure 5 shows the configuration of Epro2. Epro2 is composed of a server computer and multiple sets of sensing boards, a simulation client, an LCD projector, and a chat client. A group of children constructs a town on each sensing board in a face-to-face setting. A personal computer for the chat client is placed next to each sensing board and is used by the group of children to discuss and negotiate with the other groups at different sites.

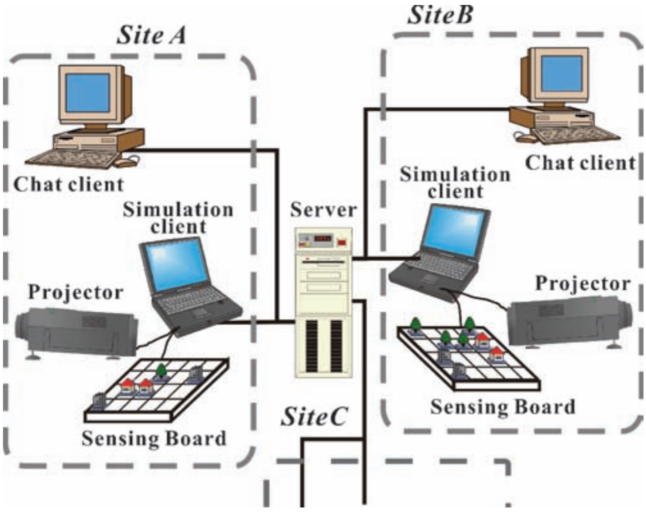

Fig. 5 System configuration of Epro2

The server computer receives piece arrangement information on the sensing board from each client and broadcasts it to all the clients. Each client computer executes environmental and financial simulations based on the data sent by the server, and provides children with graphical simulation results. The arrangement data of the pieces are updated periodically (in the current implementation, every 0.1 s). In Epro2, there are four different types of pieces: a house, a tree, a factory, and one "whatever" piece. The roles and functions of the "whatever" piece (e.g., a school) are given by schoolteachers based on the curriculum or on the children's learning tasks. In the evaluations reported here, this "whatever" piece was taken to be a shopping mall.

Epro2 displays the simulation results as shown in Fig. 6 and provides them to the children. In the case of Fig. 6, two sensing boards placed in physically different locations are virtually placed next to each other: A river flows from one sensing board (the upstream board) to another (the downstream board). This means that the environment of the downstream town is damaged by water polluted by the upstream town. Figures 6a and b show the arrangement of pieces on the upstream and downstream boards, respectively, and Fig. 6c shows the simulation results for the town on the upstream board. In the right part of Fig. 6c, distribution maps of six parameters (CO_2, NO_X/SO_X, noise, water pollution, amount of disposed garbage, and population) are displayed. Each grid cell of a map corresponds to that of a sensing board, and a different colour is assigned to a cell based on its value (for example, the level of noise or pollution). By viewing these maps, children are aware of the circumstances of the town as they are being constructed on the sensing board.

The upper left part of Fig. 6c shows the wind direction (from southwest to northeast). This causes heavier air pollution (CO_2, NO_X/SO_X) in the north eastern area of the town. The toggle buttons in the middle left of the figure are used to

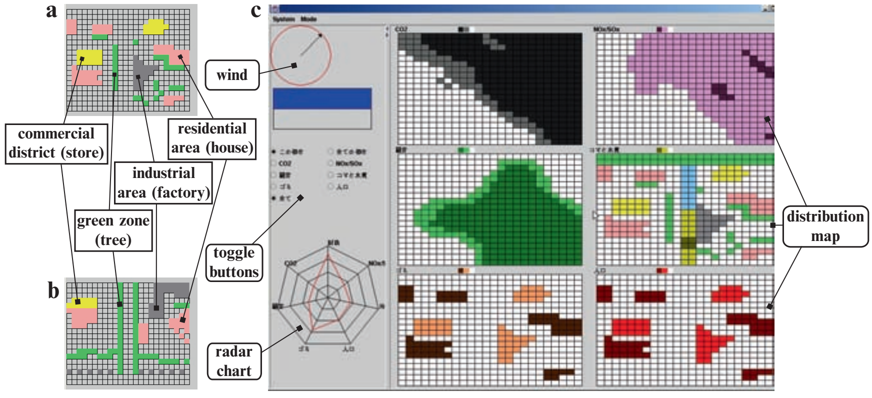

Fig. 6 (**a**) Piece arrangement on the upstream board, (**b**) piece arrangement on the downstream, and (**c**) an example of visualization of the upstream town

Fig. 7 Epro2 in use (upstream and downstream boards). The group of children pictured in the right figure has constructed a downstream town on a sensing board and used a chat system

switch towns (local or remote) or parameters to be visualized as distribution maps. A radar chart in the lower left of Fig. 6c shows the evaluations of the town being visualized: when a red polygon becomes bigger, the conditions of the town are desirable in terms of parameters related to its living environment and finances. (In this example, the radar chart shows that the town has a good financial position, but is faring poorly in terms of the other parameters).

In the evaluations of Epro2, fifth and sixth graders who had used Epro participated in classes that integrated fieldwork and the use of Epro2. They formed groups of seven to eight and a pair of groups simultaneously constructed a town on the upstream and downstream sensing boards, as shown in Fig. 7. The post-experimental interviews of the children and the video analyses on their usage of Epro2 indicated that children who manipulated pieces as they would play a game, intensively discussed within their group and negotiated with the other group: Based on their own knowledge and simulation results, children had to explain the reasons for their manipulation not only to the others in the same group, but also to children in a remote place to convince them to change the design of their town. Therefore, Epro2 could more successfully support children's learning than Epro by retaining a sense of play in contextualized settings.

5 Carettakids: Face-To-Face Collaborative Learning by Integrating Personal and Shared Spaces

Through the evaluations of Epro and Epro2, we have found several problems in supporting collaborative learning. The following two are especially critical:

- When multiple children manipulated pieces on the sensing board at the same time, they were not always able to understand how their individual manipulations on the board changed the simulation results. This was because their manipulations were simultaneously visualized along with the simulation results and children could not easily find the relationship between each manipulation and the corresponding simulation result.
- Some children with a reserved nature or who were not confident of their own idea often hesitated in manipulating pieces on the sensing board. They did not want to represent the idea on the board visibly to all children.

The problems mentioned above are related to those in Single Display Groupware systems (Stewart et al. 1999) that accept simultaneous inputs by multiple users. To solve the problems described above, the author's group developed a third generation system called CarettaKids (Sugimoto et al. 2004) that integrates personal and shared workspaces for supporting face-to-face collaborative learning. In CarettaKids, a sensing board is used for the shared workspace and a personal digital assistant (PDA) is used for each child's personal workspace, as shown in Fig. 8. The followings are important features of Carreta:

- Based on the arrangement of pieces, CarettaKids executes computer simulations and visualizes the simulation results using an overlay on the physical pieces. Using augmented reality technologies, CarettaKids not only increases the level of visibility of the children's actions, but also creates an immersive environment that enhances their learning experiences and raises the level of awareness (Dourish and Bellotti 1992) among children.
- CarettaKids allows children to conduct tasks on their own PDA: children can arrange (virtual) pieces on their own display and execute personal simulations without being disturbed or seen by other children.
- The shared workspace and personal workspaces are linked: children can easily display the results of their tasks conducted in the shared workspace on their own PDA, and project their personal tasks from their own PDA into the shared workspace. This allows children to work seamlessly in both personal and shared workspaces. To support children's seamless use of the shared and personal workspaces, an intuitive method for supporting children's smooth transition between the workspaces was developed.

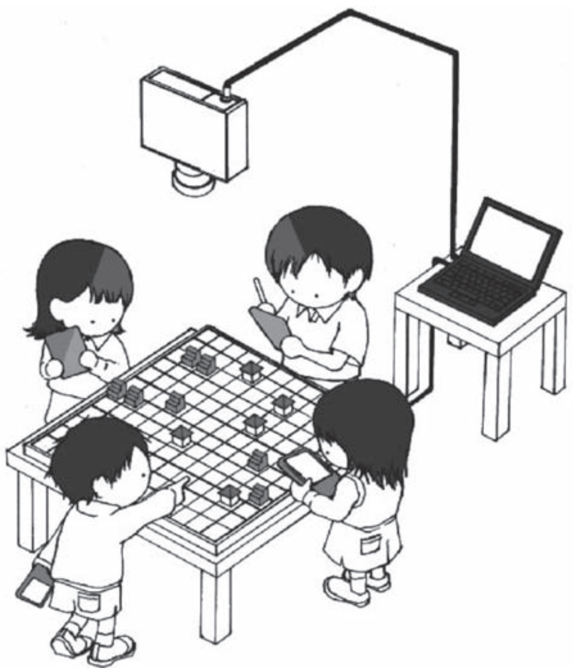

Fig. 8 Overview of CarettaKids

Figure 9 shows the shared workspace of CarettaKids. A group of children, with PDAs in their hands, surrounds the shared workspace. They manipulate physical pieces such as houses, stores, or factories, to redesign a town. When CarettaKids identifies changes to the piece arrangement in the shared workspace, it starts computer simulations, and updates the simulation parameters and the visualization overlaid onto the workspace. Some simulation parameters shown in the upper right corner of Fig. 9 are related to the status of the whole town, such as the town's revenue and expenditure, population, etc.

Figure 10 depicts a personal workspace in CarettaKids that supports children's individual tasks. The arrangement of the pieces in this figure is the same as that in the shared workspace shown in Fig. 9. By themselves, children can freely redesign the town and test their ideas in their personal workspace – for example, by adding new pieces, or by removing or moving existing pieces. When children individually change the arrangement in their personal workspace, the visualization and values of simulation parameters in the workspace are immediately updated by computer simulations. Results of the simulations given to the children relate to both the whole town and their residential area shown in their personal workspace (for example, the level of convenience based on the distance from, and the number of working places such as factories). By viewing these simulation parameters, children can evaluate

Fig. 9 A shared workspace in CarettaKids. In the upper right of the figure, several simulation parameters are displayed

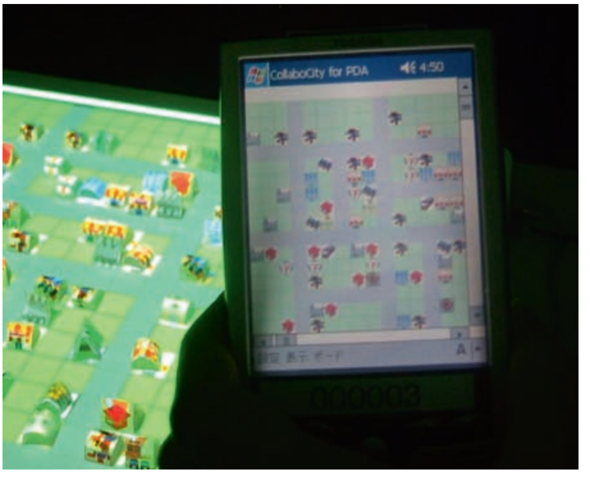

Fig. 10 A personal space in CarettaKids. A user can freely add, move, or remove pieces for personal simulation

their own ideas for designing the town. To support children in learning collaboratively in the shared workspace, and individually in their personal workspaces, CarettaKids has several functions:

- Manipulating the shared workspace through a personal workspace.

Children's PDAs can be used to manipulate pieces in the shared workspace. For example, when children discuss where a highway should be constructed, they can draw it on the shared workspace using their own PDAs. This function is useful for

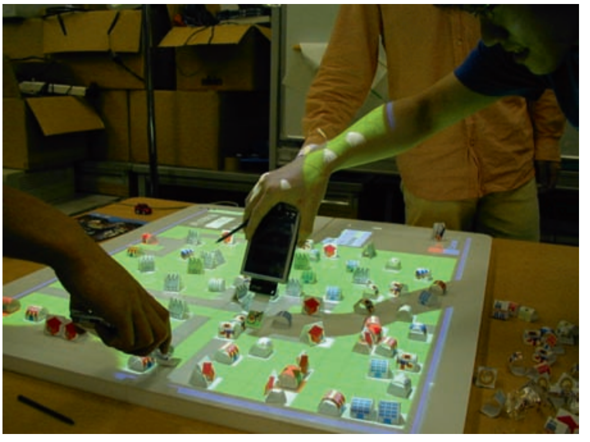

Fig. 11 By bringing a PDA near an area of interest in the shared workspace, the corresponding area appears on the personal workspace

placing virtual objects that are more difficult to place than physical pieces (for example, a bus service route, or physical items that are easier to draw than place physically, such as a railway).

- Transition from the shared workspace to personal workspaces.

When children collaboratively conducting design tasks in the shared workspace want to test their own ideas personally, they have to display the working area in the shared workspace on their personal workspaces. Children have to scroll through a small screen of their PDAs, and have difficulty in finding the corresponding area of the shared workspace. CarettaKids, therefore, provides children with an intuitive transition method from the shared workspace to their personal workspace. When children bring their PDAs close to an area of interest on the shared workspace (Fig. 11), the corresponding area immediately appears on their PDA screens. By using this method, children are liberated from the irritating task (scrolling through a small display to find an area of interest), and smoothly and intuitively transition to their personal workspaces.

- Copying a personal workspace to the shared workspace.

When children want to propose an idea for designing their town that has been examined individually in their own personal workspace, they can copy their personal workspace to the shared workspace. When children copy their idea over, the differences between their personal workspace and the shared workspace (such as piece arrangement, remarkably changed simulation parameters) are highlighted on the shared workspace. This function helps individual children easily propose their idea to other children, and helps them understand what will happen if their idea is adopted.

- Backtracking to reflect collaborative learning.

CarettaKids allows children to change design ideas previously decided in the shared workspace, or to look back over their design processes after they have completed their collaborative task. While backtracking, CarettaKids lets children know where pieces were placed by causing their corresponding locations to blink. Using this function, children can restart their collaborative tasks from any point in their design process.

CarettaKids was implemented using the sensing board, a simulation and database server, an LCD projector, and PDAs as shown in Fig. 8. Data communication between the PDAs and the server is through a wireless LAN. To support smooth transitions from the shared workspace to children's personal workspaces, an RFID tag is attached to each child's PDA. When a PDA is brought near the surface of the sensing board, the PDA's location on the sensing board is identified. Then, the visualization of the PDA is updated and the corresponding area of the shared workspace appears on its screen.

Recent PDA models have considerable computational capability, but remain insufficient to rapidly complete computer simulations. Therefore, we implemented CarettaKids to execute the simulations for each PDA on the server: when a PDA receives a request for a simulation from a child, the request is sent to the server. The server generates a thread for the simulation, and returns the simulation results to the PDA. However, from the viewpoint of children, the simulation seems to be executed on their PDA, and they need not pay attention to the server while conducting tasks on their PDAs.

The evaluations of CarettaKids with school children indicate that (1) children can participate in their learning by using personal and shared workspaces interchangeably, and (2) children can easily show their ideas devised on their own personal workspaces to other children by displaying them on the shared workspace. Then, the children collaboratively improved the ideas through discussions on the shared workspace. However, (3) children often concentrated on tasks in their personal workspaces, and did not always pay attention to the shared workspace. Fewer interactions and discussions between children happened in CarettaKids than in systems without personal workspaces (Deguchi et al. 2006). More intensive analyses will be conducted to investigate how CarettaKids supports children's externalization and reflection by integrating their shared and personal workspaces.

6 Discussion

So far, the author's group has been designed, developed and evaluated the systems discussed in the chapter. The followings are lessons learned through the experiences:

- Knowing the constraints of the setting in which the proposed systems will be used.

Adapting a system originally used in a laboratory setting to a school classroom is sometimes difficult, because remodelling for special equipment is usually not allowed, and children's safety must be considered. As shown in the design process of the sensing board, even if utilizing several existing technologies was possible, abandoning them and devising a different technology or method of implementation was necessary. Therefore, being familiar with the constraining features of settings in which the system will be used before commencing the design is important.

- Observation of children's behaviour.

Children's requirements could not be adequately known from just interviews because they often did not or could not clearly articulate their needs or preferences. Therefore, children's behaviours were observed by using a prototype system (paperboard and simple software) at the start of the project. Analyses of children's behaviour and utterances while using Epro and Epro2 clarified their potential problems and clues for developing the next version of the systems (Epro2 and CarettaKids, respectively). The information learned through evaluations in classrooms provided the author's group with very useful information and insight for designing the proposed systems.

- Participation of stakeholders in the design process (Schuler and Namioka 1993).

The design of the hardware and software in Epro, Epro2, and CarettaKids was conducted in collaboration with developers, schoolteachers, and their children. For example, in the development of the sensing board, children were asked to grasp different shapes and sizes of pieces to confirm their preference and ease of manipulation. To contextualize children's learning and raise the level of its authenticity, their teachers designed the curriculum through discussions with the project members and decided on the kind of scientific knowledge to embed in the simulation software of Epro, Epro2 and CarettaKids. Although tabletop or tangible interface systems were effective for attracting children's interest and attention, designing systems in collaboration with different stakeholders was critical to increasing the level of motivation and engagement in children's learning.

- Tabletop interface systems for collaboration: group or individual.

Various tabletop systems for supporting collaboration were developed (e.g., Field et al. 2002). One problem with this type of system is related to how it can support users in working/learning collaboratively and individually, because a workspace in tabletop systems is shared with and visible to multiple users, and a trade-off inherently exists between a group and an individual in supporting collaborative tasks (Gutwin and Greenberg 1998). Several systems were proposed to simultaneously support group and individual activities (e.g., Zanella and Greenberg 2001, Shoemaker and Inkpen 2001). CarettaKids is an example of such a system. We believe that additional investigation for supporting groups and individuals in collaboration processes must be conducted by fully utilizing mobile and ubiquitous computing technologies.

7 Conclusion

This chapter discussed the design processes of systems for supporting children's collaborative learning. The systems are used for learning about urban planning and environmental issues in school education. Although numerous tabletop and tangible interface systems have been proposed in HCI research areas, the author's group started investigations for identifying design requirements of the systems using a paper-based prototype system. Three systems called Epro, Epro2, and CarettaKids were developed based on the requirements gained through the investigations and issues raised through their evaluations.

In this research project, the design of the systems was conducted in collaboration with different stakeholders, such as developers, teachers, and children. The author believes that the lessons gained through the project, such as "Knowing the constraints of the setting in which the proposed systems will be used" or "collaboration support for group and individual", are consistent with designing not only learning support systems but also other types of interactive systems.

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