SPECIAL ISSUE
Original article

doi: 10.1111/j.1365-2729.2007.00234.x

Do handheld devices facilitate face-to-face collaboration? Handheld devices with large shared display groupware to facilitate group interactions

C.-C. Liu* & **L.-C. Kao**†

*Graduate Institute of Network Learning Technology, National Central University, Taiwan
†Department of Computer Science and Engineering, Yuan-Ze University, Taiwan

Abstract One-to-one computing environments change and improve classroom dynamics as individual students can bring handheld devices fitted with wireless communication capabilities into the classrooms. However, the screens of handheld devices, being designed for individual-user mobile application, limit promotion of interaction among groups of learners. This study proposes a design of classrooms that incorporates personal workspace and public workspace. Students use handheld devices as private workspace and work with peers on public workspace with shared displays through their handheld devices. Experiments confirmed that students with only handheld devices did not demonstrate expected participation ratios and actively interact with group members. The proposed shared display groupware promoted shared understanding of the workspace and increased awareness of partner actions. Collaboration was enhanced by creating the opportunity for students to use handheld devices to perform ideal communication patterns and avoiding ineffective communication patterns.

Keywords groupware, handheld device, one-to-one learning, shared display, small group collaborative learning.

Introduction

The development of handheld devices and wireless network has made possible numerous new approaches to individual work and learning. The Global Researcher and Testbed Network of 1:1 Digital Learning (http://www.g1to1.org/) promoted the notion one-to-one (1:1) learning, which refers to the scenario where students bring handheld devices fitted with wireless communication capabilities into classrooms and apply these devices for various learning activities. One-to-one computing environments change and improve classroom dynamics owing to computation and communication capabilities that augment face-to-face interactions. Researchers and educators emphasize the importance of cooperation among learners (Johnson & Johnson 1991; Stahl *et al*. 2006). Therefore, numerous researchers (Cortez *et al*. 2004; Ogata & Yano 2004) have attempted to utilize handheld devices and wireless network to promote interaction or collaboration among learners. However, the screens of handheld devices, being designed for individual-user mobile application, limit promotion of interaction among groups of learners.

Accepted: 20 February 2007
Correspondence: Chen-Chung Liu, Graduate Institute of Network Learning Technology, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan Country 32001, Taiwan (R.O.C.) Email: ccliu@cl.ncu.edu.tw

Johnson and Johnson (1991) proposed five key guidelines to successful cooperative learning, namely positive interdependences, face-to-face promotion of interactions, individual accountabilities/personal responsibilities, interpersonal/small-group skills, and group processing. Promotion of interaction should be considered especially in relation to one-to-one computing environments because it is strongly affected by the design of mobile learning applications for use on handheld devices together with wireless networks. Inappropriate design of workspaces designed for collaborative learning may cause inefficient communication patterns and thus defeat efficient collaboration performance.

According to Roschelle and Teasley (1995), 'Collaboration is a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem'. Dillenbourg *et al*. (1996) indicated collaboration involves the processes of diagnosis (to monitor the state of the other collaborator) and feedback. Handhelds interconnected by a wireless network were successfully applied to improve coordination, communication, organization of materials, negotiation and interactivity in classrooms (Zurita & Nussbaum 2004a,b). Students can share simple information on the screen of a Tablet PC or personal digital assistant (PDA). However, when collaborative activities involve complicated information and more than two students, students must crowd together to compete for the display of the Tablet PCs or PDAs. Scott *et al*. (2003) indicated that a lack of shared displays may lead to loss of eye-contact and unawareness of visual focus. They found that students were frequently active at the same time and had trouble reaching a mutual understanding of the workspace when they were performing collaborative activities with individual displays and computers. Although groupware can be designed to support document sharing through networks, the side-by-side interaction mediated by computer networks still interferes with group collaboration because students view the documents of others on their own handheld devices. Students are unaware of the visual focus of their group partners. Therefore, the one-to-one computing environment still has some difficulty in supporting promotion of interactions among students.

Handheld devices such as PDAs and Tablet PCs are private spaces for individuals to perform learning activities. However, the lack of public spaces and a shared visual focus among group members impedes group communication and leads to fragmented communication patterns in which groups are broken into parts and information sharing occurs only between some members. Most classrooms currently are equipped with peripheral devices such as projectors and displays to support whole-class lecturing and activity. However, it is rare for classrooms to have peripheral devices augmenting handheld devices to support small-group activities. While mobile learning applications are incorporated into handheld devices to support learning, the methods through which peripheral devices in classrooms can augment handheld devices to support efficient and lively collaborative learning remain limited. Therefore, this study attempts to examine the face-to-face collaboration in one-to-one computing environments and explore whether the handheld devices, wireless network and shared displays in classrooms sufficiently facilitate face-to-face collaboration.

Display technology has greatly changed human use of information technologies during recent years. Liquid crystal displays (LCD) are becoming increasingly cheap and popular peripheral devices. An LCD flat panel affords numerous novel usages of computers because LCDs occupy less space than cathode-ray tube (CRT) monitors. For instance, KOALA (Divitini & Farshchian 2004) used LCDs in public areas for promoting informal cooperation. Classrooms can also be fitted with multiple LCDs on the walls to support multiple group learning activities. This study proposes a shared display groupware system. Shared display groupware (DiMicco *et al*. 2004; Divitini & Farshchian 2004; Morris *et al*. 2004; Paek *et al*. 2004) can facilitate collaboration by promoting shared understanding of the workspace and increasing awareness of partner actions, as participants can get close to one another's centre of visual focus with the shared display (Scott *et al*. 2003). All students can freely use the system to share information and their handheld screens with others, just as can be done using other classroom facilities such as blackboards and bulletin boards. Students can bring their handheld devices and utilize the shared display system to share their documents and display the screens of their handheld devices. Therefore, this study aims to explore the research question of whether the display equipment in classrooms fitted with shared display groupware can augment the handheld devices in promoting the communication patterns among participants.

One-to-one collaborative learning scenario with shared display

A shared display groupware was designed to help students collaboratively learn Statistics and Data Mining Techniques in Thinking-Pairing-Sharing (TPS) learning activity (Lyman 1981) using Tablet PCs. Each student uses a Tablet PC as a personal learning device to collect data, run statistical tools and write statistical statements. Instead of pairing students, students are divided into groups containing three to five members to learn statistical and data mining techniques. The teacher initially writes problems and asks students to think about how to solve statistical problems and record their answers. Following an assigned time period, students share their answers with their group partners. Group partners must jointly generate group answers, and all group members must agree on these answers.

In such a collaborative learning activity, the group partners resemble a coherent, intelligent organism working with single mind, and are responsible for all aspects of artefacts (Williams & Kessler 2000). However, various guidelines must be fulfilled when engaging students in TPS collaborative learning activity. First, the activity must enforce individual contributions to avoid only the more prepared students benefiting from the activity. Additionally, participants must continuously concentrate on contributing to the group answers. Therefore, the TPS activity requires a workplace where participants can simultaneously view individual and group work.

One-to-one computational environments can fulfil the guidelines for enforcing individual contributions during the thinking stage. Participants can work on statistical problems using their own handheld devices. In this study, students work with their Tablet PCs. The handwriting interface of Tablet PCs enables students to freely write down complicated statistical diagrams, statistical procedures and statements. Additionally, the wireless network enables students to identify and use proper statistical tools on the Internet to generate individual answers.

Students in collaborative learning groups must closely interact with group partners. Milson (1973) introduced communication patterns, such as ideal, tête-à-tête and fragmented communication patterns, to represent group communication. These patterns provide useful indicators for estimating group performance

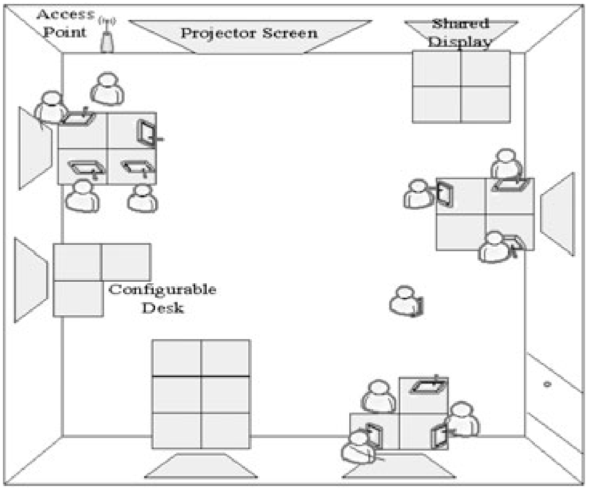

Fig 1 One-to-one collaborative learning scenario using a shared display.

(Chen *et al*. 2003). However, the fact that students work and discuss using only their own screens as a reference creates unawareness of the visual focus of their partners. The lack of shared workplace also impedes the exchange of information in statistical diagrams, statistical procedures and statements. The communication among TPS group partners can be divided into tête-à-tête and fragmented communication patterns as students cannot conveniently share and discuss information with non-adjacent partners. The difficulty in communicating with group partners and defective communication patterns interferes with the participation of group members in collaborative activity. Students have difficulty in generating group answers following an ideal communication pattern based on individual answers.

Using a shared display groupware with the classroom equipment enables students to actively participate in collaborative activities and closely interact and exchange ideas. This study developed a one-to-one collaboration classroom (Fig 1) in which group workspaces were equipped with multiple shared LCDs and configurable desks to support collaborative learning. Students can move freely to a workspace and login the shared display groupware at the workspace. Each configurable desk in a workspace can be used by only one student, and can be rearranged according to group size. Additionally, instead of using the flat panel monitor commonly used with computers, this study adopts 16:9 aspect ratio and 32-inch diagonal widescreen LCDs which are capable of displaying 1280×768 lines of

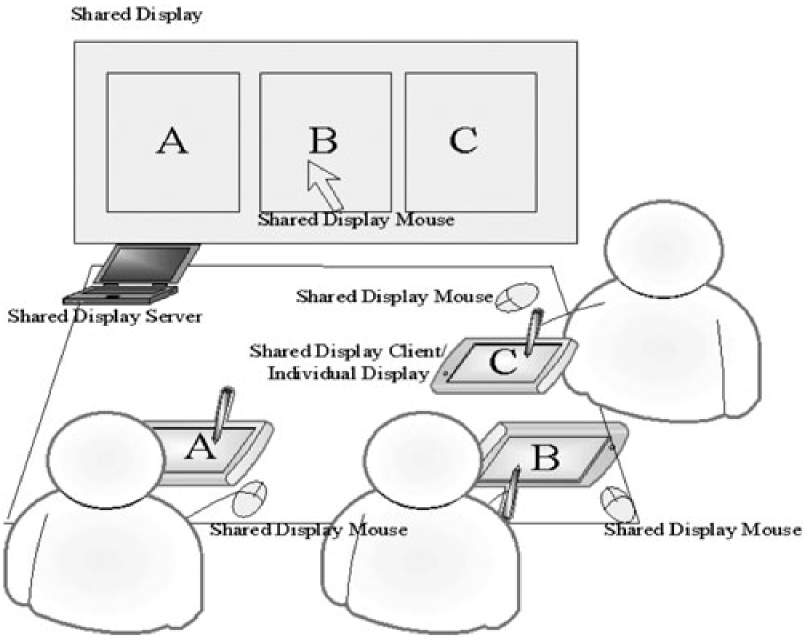

Fig 2 Workspaces with shared displays.

resolution. The LCDs are more suitable for group learning than computer monitors because they have wider view angles and screens.

One-to-one collaboration classrooms with shared display groupware satisfy the requirements of TPS. Students not only work within their handheld devices but also share complicated statistical diagrams, statistical procedures and statements using shared display groupware. During the sharing stage, students do not have to continuously guess and ask their partners for information about what they are looking at on the screens of handheld devices. Instead, students can easily show others what they are looking at by using their hands to indicate information on the shared displays. Additionally, they can be aware of the actions of their partners as the handheld devices do not interfere with their eye contact. Consequently, group members can use the shared displays to actively participate in the sharing activity for achieving effective collaboration.

The shared display groupware

Shared display groupware, for example, electronic whiteboard and public large displays have been proposed to facilitate various types of group work, such as meetings, presentations (Errod *et al*. 1999), learning (Scott *et al*. 2003), information sharing within communities (Divitini & Farshchian 2004; Koch 2005) and collaboration. Researchers (Greenberg *et al*. 1999; Paek *et al*. 2004) have proposed scenarios involving the use of mobile devices with shared displays to support mobile note taking and meeting. However, studies of how shared display groupware can be utilized in classrooms to improve student participation using handheld devices remain limited. Therefore, this study implemented collaborative workspaces in classrooms with shared displays (Fig 2) to support one-to-one collaborative learning and examine the effect of shared displays on student participation.

This study implemented a shared display groupware. Students can share documents collected and formed during the thinking stage of TPS, or can demonstrate the use of statistical tools by displaying their handheld screens on the shared displays. Students can then clearly view the shared documents and handheld screens of others via the shared displays. Upon logging onto the system, students can manipulate the presentation of the shared documents using the input devices of the shared display groupware. The layer design of the shared display groupware facilitating the above activities functions as follows:

1 Constraint layer: The layer links individual student names to the shared documents. After students log onto the shared display groupware with an arbitrary name, the layer links the documents uploaded by the

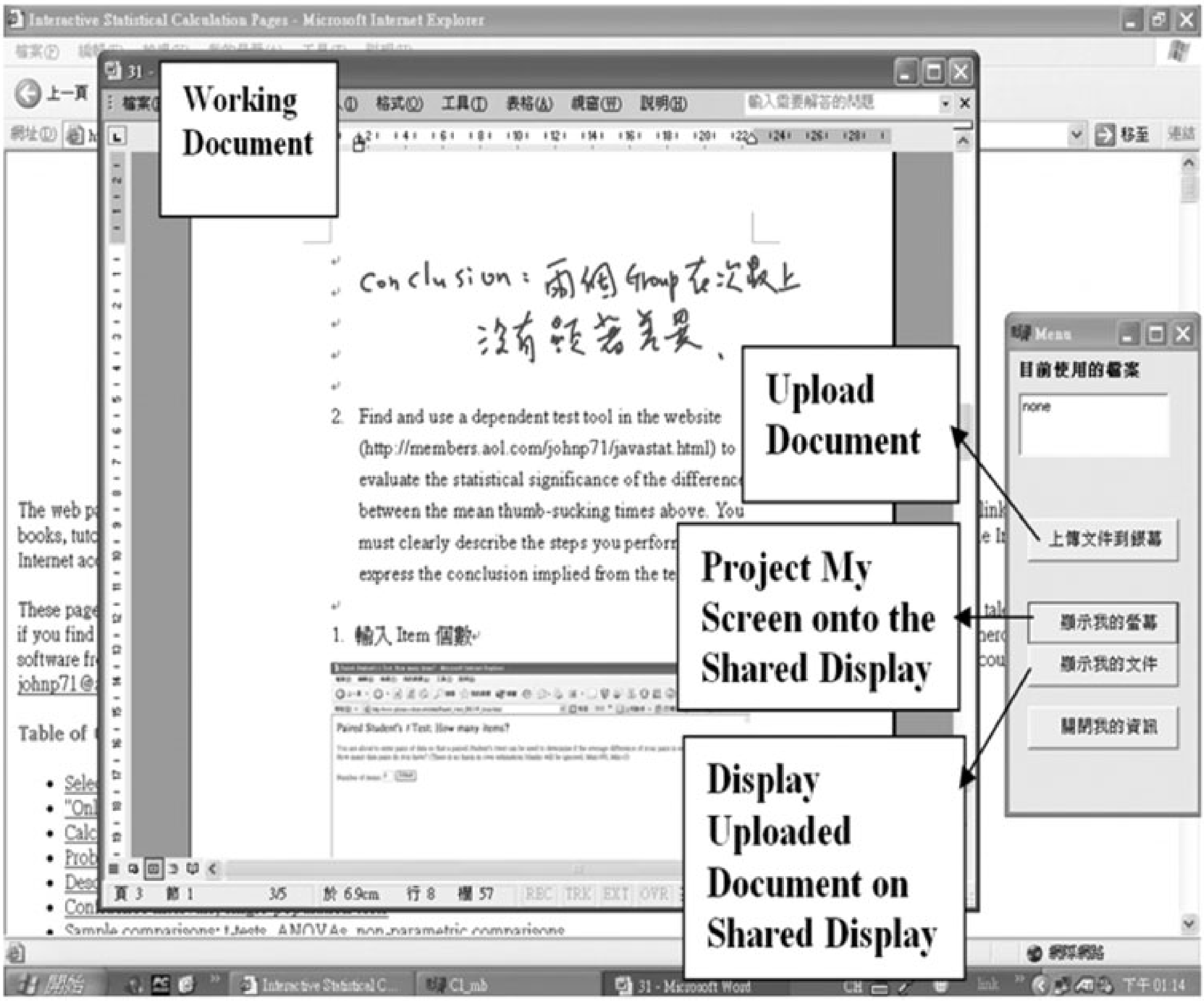

Fig 3 Workspace layer for displaying documents and screens on the shared display.

students with their user name. Additionally, TPS activity constraints are enforced in the layer. For instance, the layer enforces a constraint in which the shared display groupware cannot display documents until all students have uploaded their individual answers.

2 Workspace layer: The workspace layer (Fig 3) enables students to connect the shared display groupware and individual handheld devices through the network. Students can access and view the documents of all of their partners via the shared display. Consequently, the layer contains functions for uploading the documents in individual handheld devices and displaying the documents on the shared display. Students then can share their documents on the shared display. Additionally, the workspace layers also support simultaneous screen video projection from individual handheld screens to the shared display via the wireless network. Such screen projection helps students demonstrate complicated statistical procedures and tools using their handheld devices.

3 Presentation layer: The presentation layer provides functions for displaying the workspace properly to support group collaboration. By default, the presentation layer displays all the individual documents of students with equal size on the shared display. However, the display may be too crowded to allow students to clearly view all the displayed documents. Therefore, the layer provides an option of displaying documents using a fish-eye layout in which only the focused document is enlarged while others are shrunk

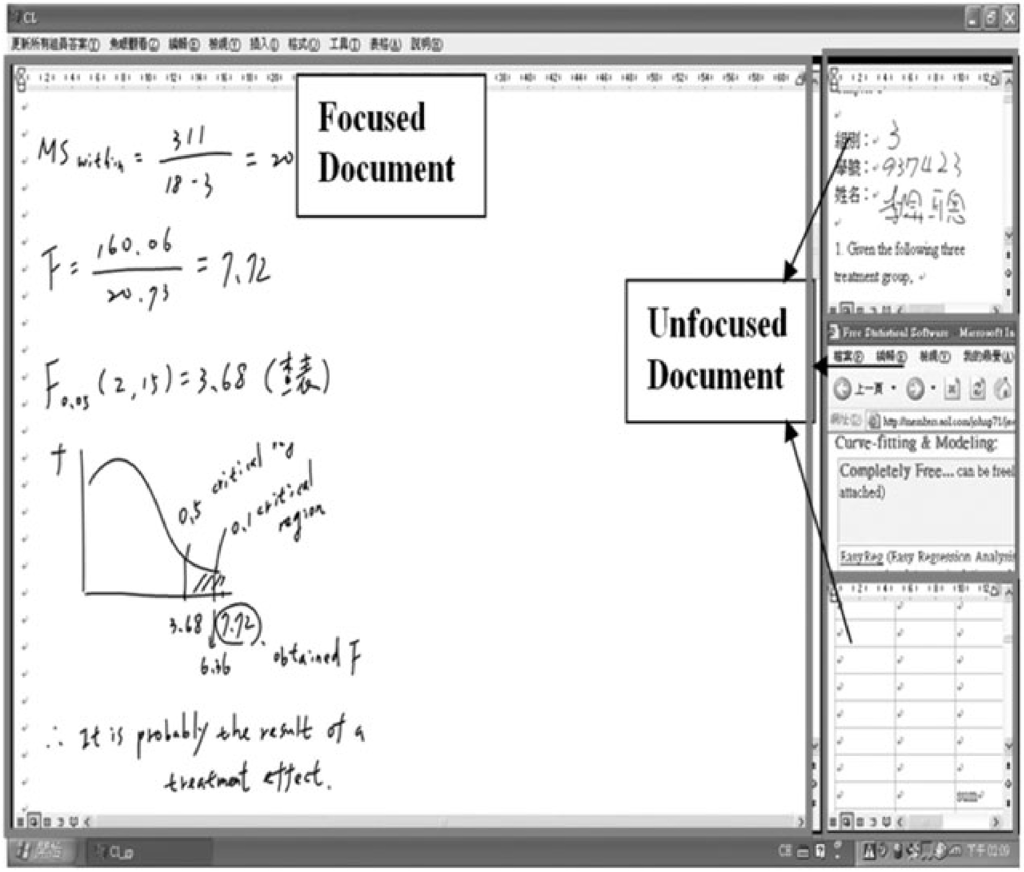

Fig 4 Fish-eye display on the shared display.

on the shared display. Figure 4 illustrates how students work on the shared display using the fish-eye layout.

4 Input device layer: Students require an interface to interact with the shared display server. For example, students must select a focus document when using the fish-eye layout. Students also need an edit interface on the shared display for editing group common answers. The input device layer provides all students using the shared display with an input device for performing editing and presentation layer activities. The shared display server is fitted with multiple wireless mice. Each student using the shared display can use a wireless mouse to edit the group common answer by copying and pasting text or images from individual documents (shown on the shared display). Students can also use the mice as pointers to present their visual focus and change the fish-eye focus of the shared display.

Group members were expected to participate closely in the sharing activity for achieving effective collaboration. Group members use shared display groupware and handheld devices in a collaborative workplace. Students use their handheld devices to work on a question while their screens or documents are projected on the shared display. Simultaneously, students share documents and discuss the questions via a shared display. Students can easily indicate their visual focus by using their hands or wireless mice to indicate particular parts of the shared display. Students thus are aware of the actions of their partners on the documents on both the shared display and individual handheld devices.

A comparative evaluation

This study administrated an experiment to explore the effectiveness of shared display groupware on communication patterns. However, there were seven different communication patterns. It becomes difficult to distinguish the patterns in which students will communicate with a certain technological setting. Therefore, this study examines how the shared displays affect student participation in the collaborative learning activity. The study involved 13 graduate students enrolled in a Statistics and Data Mining Techniques course at National Central University, Taiwan. The 13 students were divided into three groups, each containing 3–5 members, to share their answers to the questions given by the teacher.

Shared display tools were the main experimental factors. The experiment involved four sections of collaborative activities which were supported by three different settings, namely, the Tablet-PC-Only setting, the Network-File-Sharing (Tablet PC with network file sharing) setting, and the Shared-Display (Tablet PC with shared display) setting. The Tablet-PC-Only setting allowed students to use Tablet PCs alone in the TPS collaborative activity, during both the thinking and sharing stages. Meanwhile, the Network-File-Sharing setting enabled students to view the answers of others on their own Tablet PCs in the TPS activity through the wireless network and application programs. Furthermore, the Shared-Display setting enabled students to use Tablet PCs or PDAs together with the shared display groupware to share their answers and generate group answers during the sharing stage (Fig 5). The Shared-Display setting was used to support two sections of TPS collaborative activities. Student discussion behaviours in the four sections were videotaped for further analysis.

The experiment lasted 8 weeks. During the first 4 weeks, students engaged in collaborative learning activities in the three experiment settings. Students thus familiarized themselves with the experimental environments. During the following weeks, students performed a collaborative activity using the Tablet-PC-Only setting in 1 week, Network-File-Sharing for 1 week, and Shared-Display setting for 2 weeks. During each week, one of the students introduced the main concepts of individual chapters of the textbook. The teacher then announced questions related to the concepts that were introduced. Students began to answer these questions and learn collaboratively in the TPS activity.

This study explored student reactions to the three experimental settings. Students were expected to demonstrate effective communication which occurs among all group members, and no partner is excluded from group discussion. In addition to the large shared displays, six video cameras were mounted on the ceiling of the classroom and connected to a computer monitoring system. Each camera was set to point to a group workspace to videotape group discussion behaviours. Students were told their discussion behaviour would be videotaped for further analysis. Students did not feel the cameras intrusively interrupt their discussion activities as the cameras were hidden on the ceiling of the classroom. This study analysed a total of 225 min of discussion activity videos.

All of the analyses of discussion behaviours were performed by one of the researchers and an independent coder. The main tasks of two coders included (1) identifying communication instances and (2) determining the

(a)

(b)

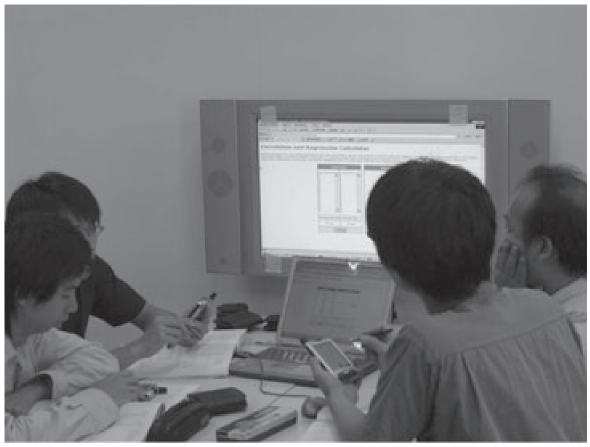

Fig 5 The Shared-Display setting. (a) Students interact with one another on shared-displays using Tablet PCs. (b) Students interact with one another on shared-displays using PDAs.

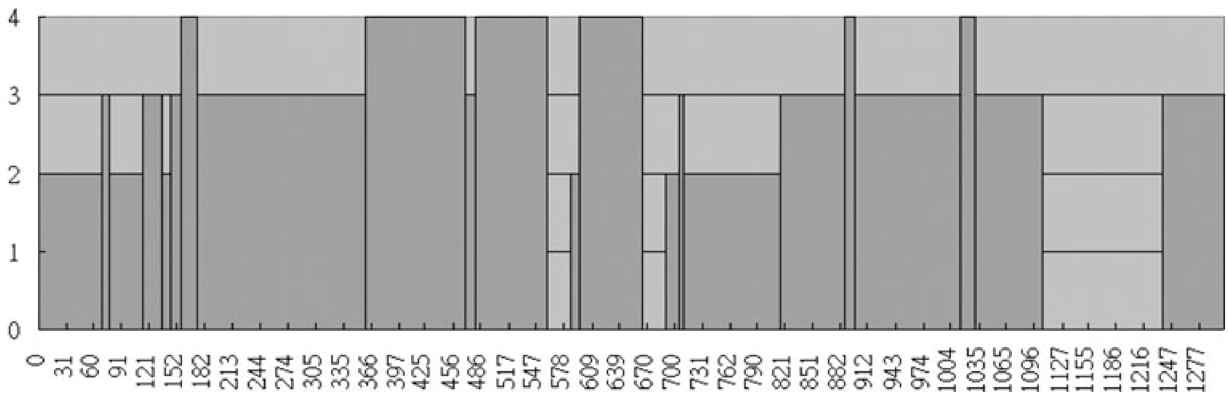

Fig 6 Communication sequence diagram of the Tablet-PC-Only setting.

number of students involved in the communication instances, and (3) identifying the non-verbal interpersonal interactions based on the videos recorded. This study identifies the communication instances in which issues were originated by and concluded by a group of students. The issues may be a simple question such as 'What's your answer? Mine is 4.43' or a sophisticated discussion process such as 'You computed it by yourself? But why is your answer so different from mine. I computed it with Microsoft® Excel.' An issue originated by a student may obtain several responses from multiple group members. Therefore, it is possible that students demonstrated long sequences (a minute or more) of multiperson communication.

While analysing discussion activity videos, the two coders identified communication instances and the students' visual focus. For instance, in the Tablet-PC-Only and Shared-Display setting, a student was identified to be excluded from a communication instance, if the student kept looking at his or her computer and without talking to any of the other students while they were talking. The network file sharing system logged the pages that students viewed on their own Tablet PCs. Therefore, a student was not included in a communication instance, if the student was not looking at the page which others were discussing it. The inter-coder correlation for the analysis was 0.85, indicating that the analysis was reliable.

Analysing student participation

Student communication behaviours were videotaped and analysed throughout the collaborative activities. If all group members actively participate in a communication instance, then the student participation is seen as ideal. On the other hand, students might exhibit a fragmented communication pattern, if only a portion of group members participate in certain communication behaviours.

Student communication behaviours in the videos were analysed and codified into communication sequence diagrams (Figs 6–8) to clarify the number of group members who participated in communications. Each bar in the diagrams represents a communication instance involving a number of students (y-axis) and lasting a certain number of seconds (x-axis). For instance, the first bar in Fig 6 exhibits a communication period lasting 70 s involving only two students.

Analysing the communication sequence diagrams of the three experiment settings reveals how shared display tools affect the student participation in the collaborative learning activity with Tablet PCs. The participation ratio of a group discussion activity is computed by the formula below to represent how group members performed communication behaviours:

$$\sum_{\text{Communication Instance } i} \frac{\text{Period}(i) \times \text{Participated}(i)}{\text{Period}(i) \times \text{group size}}$$

where Period(i) is the time period lasted and Participated(i) the number of students participated in communication instance i.

If the participation ratio of a group discussion is close to 1, then the group performed effective communication behaviours by which all group members were attracted to and actively participated in the group discussion activity. Figure 8 exhibits a superior participation compared

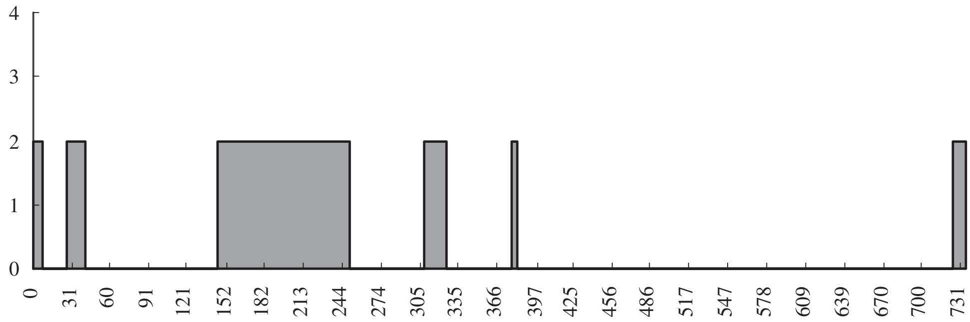

Fig 7 Communication sequence diagram of the Network-File-Sharing setting.

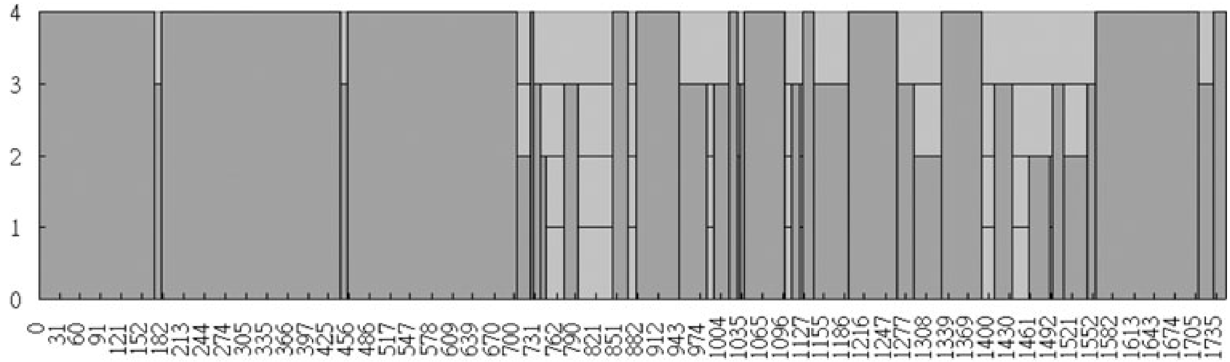

Fig 8 Communication sequence diagram of the Shared-Display setting.

to Fig 6, as Fig 8 indicates a participation ratio of 0.91 while that in Fig 6 is only 0.76. Table 1 lists the participation ratios among different experiment settings.

Students in a Tablet-PC-Only environment tended to participate loosely in collaborative activities. Group 1 exhibited a low participation rate which showed that only half of the students participated in the majority of communication instances (a ratio of 0.57). Students naturally communicated with their partners who sat closest to them. Group 3 demonstrated effective communication even when the students were in the Tablet-PC-Only environment.

Students in networked file-sharing environments tended to focus only on their own Tablet PCs. All three groups displayed low participation ratios (0.59, 0.51 and 0.75). In addition, students in the Network-File-Sharing setting tended to select an individual answer as the group answer without discussion. Students rarely indicated to others what they were looking at by using non-verbal interactions such as eye contact or hand-pointing behaviours in such an environment. Students made statements and referred to one another's answers only on their own Tablet PCs. Consequently, group partners rarely discussed a

Table 1. Participation ratios among different experiment setting.

	Group 1	Group 2	Group 3	Average
TPS activity with Tablet-PC-Only	0.57	0.76	0.93	0.76
TPS activity with Network-File-Sharing	0.59	0.51	0.75	0.61
Section 1 of TPS activity with Shared-Display	0.61	0.91	0.88	0.8
Section 2 of TPS activity with Shared-Display	0.65	0.83	0.98	0.82

Table 2. Frequencies of hand pointing behaviours.

	Group 1	Group 2	Group 3	Average
Tablet-PC-Only	19	6	8	11
Network-File-Sharing	2	7	0	3
Shared-Display 1	12	42	10	21.3
Shared-Display 2	25	40	13	26

common topic and most interactions involved only two members.

Students exhibited higher participation ratio (0.61–0.98) in the environment with shared displays. Moreover, students easily viewed and compared the answers of all of their partners on a large shared display. Students conveniently expressed statistical statements and referred to individual answers on the shared display. Moreover, the students noticed the statements and non-verbal gestures of each partner. In this condition, students were attracted by a common topic and discussed the common group answer together. The students generated the common answers of the group without switching their visual focus between different displays. Therefore, in the environment involving shared displays, students demonstrated more equal participation rates than those in environments with only Tablet PCs and networks.

Non–verbal interpersonal interactions

Non-verbal interpersonal interactions are important in collaborative activities. How a computer environment enhances or impedes these interactions ultimately impacts its effectiveness as a collaborative environment (Scott *et al*. 2003). Student non-verbal interpersonal interactions were also analysed using videos to reveal how students react to different collaborative learning environments. Hand-pointing behaviour, eye contact between group peers, and the behaviour of looking at peers' computer screens were measured. Records of hand-pointing behaviours demonstrate students used their hands to indicate the locations they are referring to in individual answers. The eye contact indicates the atmosphere of student communication. The behaviour of looking at peers' computer screens reflects the ambiguity of peers' explanation and the request for further explanation from peers' screens. Tables 2 and 3 list the frequencies of hand pointing and eye contact behaviours. Table 4 displays the frequencies of looking at peers' computer screens demonstrated by students.

Zurita and Nussbaum (2004b) analysed the student interactions in the environment with a shared PC, side-by-side PCs and handheld devices. They indicated that when students interact with handheld devices, they use their fingers to show the information they have on their handheld devices to the other children. They pointed out that with the handheld devices, the problems of visual contact and body language disappear. Scott *et al*. (2003) analysed children interaction with PCs in shared-display, side-by-side displays, and separate displays. This study compared student interactions in the environment with only Tablet PCs, Tablet PCs interconnected with wireless network, and Tablet PCs connected to large shared displays.

Students rarely exhibited pointing behaviour in the Tablet-PC-Only and the Network-File-Sharing settings. However, students displayed more frequent pointing behaviour in the environments with shared displays. Students frequently used their hands to refer to individual answers on the shared displays (Fig 5a).

Analysing student interaction videos found that students demonstrated high frequencies of eye contact in the Tablet-PC-Only environment. However, the eye contact behaviour in the Tablet-PC-Only setting represents the ambiguity of peers' explanation and the

Table 3. Frequencies of eye contact.

	Group 1	Group 2	Group 3	Average
Tablet-PC-Only	28	46	28	34
Network-File-Sharing	16	18	7	13.7
Shared-Display 1	21	62	21	34.7
Shared-Display 2	23	25	16	21.3

Table 4. Frequencies of looking at peers' computer screens.

	Group 1	Group 2	Group 3	Average
Tablet-PC-Only	51	27	49	42.3
Network-File-Sharing	4	16	0	6.7
Shared-Display 1	10	4	2	5.3
Shared-Display 2	9	6	0	5

Table 5. Mean and median of students' perceptions regarding Tablet-PC-Only, Network-File-Sharing and Shared-Display settings.

Item	Tablet-PC-Only M (median)	Network-File-Sharing M (median)	Shared-Display M (median)
1. I can clearly view the answers of my partners.	1.79_a (2)	4 (4)	4.43^a (5)
2. I can conveniently compare the answers of my partners.	1.79_a (2)	3.5_b (3)	4.29_{ab} (4.5)
3. I can clearly view the progress of generating common group answers.	1.86_a (2)	3.71_b (4)	4.79_{ab} (5)
4. I can conveniently generate common group answers.	1.86_a (2)	3.79 (4)	4.21_a (4)
5. I know what my partner is referring to in individual answers.	2.36_a (2)	3.5_b (4)	4.28_{ab} (4)
6. My partners know where I refer to in individual answers.	2.5_a (3)	3.5 (3.5)	4.07_a (4)
7. More partners listen to my statements and discuss common group answer with me.	2.71_a (3)	3.36_b (3)	3.93_{ab} (4)
8. I am aware of the visual focus of my partner.	2.14_a (2)	2.64_b (3)	4.14_{ab} (4)
9. I can express complicated information.	2.43_a (2.5)	3.43_b (3.5)	4_{ab} (4)
10. I carefully listen to my partners and look at the areas they are referring to.	2.71_a (3)	3.71_b (4)	4.21_{ab} (4)
11. I frequently discuss a common topic with all my partners.	3.36_a (3.5)	4 (4)	4.36_a (4.5)
12. My partners and I hold detailed discussions to generate group common answer.	2.93_a (3)	3.71 (4)	4_a (4)

The first number represents the mean of students' feedback to the item while the number in the parentheses indicates the median of students' feedback.
Means with same subscripts differ by the Wilcoxon matched-pair test at the 0.05 significance level.

request for further explanation from peers. The phenomenon can be observed by the high frequency of looking at peers' screens (Table 4) as they had to take note of the visual focus of their partners and refer to information in the Tablet PCs of others. On the contrary, in the Network-File-Sharing environment, most students focused completely on their own Tablet PCs and did not notice the non-verbal signals of their partners. Students in the Network-File-Sharing environment exhibited low frequencies of eye contact and looking at peers' screens. It should be noted that, in Shared-Display environment, students demonstrated much frequently eye contact behaviour (on average 34.7 and 21.7) than in Network-File-Sharing environment (on average 13.7). In addition, students rarely demonstrated the behaviour of looking at peers' computer screens (on average 5 and 5.3). Instead, they were attracted to the shared displays and continued watching the shared displays and listening to the expressions of their partners. Therefore, shared displays enable students to interact with one another and refer to related information naturally.

Student questionnaire feedback

A questionnaire containing 5-point Likert scale items (Table 5) was administered to measure the perceptions of the students of the Tablet-PC-Only, Network-File-Sharing and Shared-Display settings. The Wilcoxon signed-rank test was used to test for differences. The analysis revealed that the Shared-Display scores significantly exceed the Tablet-PC-Only and Network-File-Sharing scores. The questionnaire result indicates that shared displays are effective in supporting more equal student participation rates in collaborative learning activities. It is interesting that feedback from the students did not reveal significant difference between Shared-Display and Network-File-Sharing environment regarding the awareness of peers' answers ($Z = -1.38$, $P = 0.166$). Despite this, student feedback (for instance items 7, 8, 9, and 10) confirmed that the Shared-Display environment significantly facilitated more effective communications than the Network-File-Sharing environment did.

Discussion and conclusion

Previous study of mobile computer supported collaborative learning (MCSCL) (Cortez *et al*. 2004) has successfully used the computation capability of PDAs to facilitate group activity dynamics. The network communication of MCSCL environment facilitated the interaction among students in a structured collaborative activity. MCSCL enforces an activity structure which children groups followed to attain common answers (Zurita & Nussbaum 2007) or achieve a group task collaboratively (Zurita & Nussbaum 2004b). Cortez *et al*. (2005) also demonstrated a promising use of MCSCL to mediate teacher trainees to work collaboratively in discussing answers and exchanging classroom experiences. MCSCL design that forces students to exchange idea and reach a consensus answer fulfils the guideline of facilitating promotive interactions during collaborative activities.

This study proposed a different setting of using handheld devices in higher education. The learning activity that occurred in classrooms did not enforce strong discussion structure. The TPS activity enforced personal accountability by requiring students to contribute their individual answers before group discussion. Except for personal accountability, the TPS activity did not enforce other activity constraints during the group discussion. Instead, students freely discussed their answers to open-ended questions and viewed the documents of all of their partners from their handheld devices. Moreover, students in this study had to complete more complex group works than the works presented in MCSCL for teacher trainees. They were given some row data and required to choose a statistical analysis methodology and draw conclusion from the analysis with the statistical methodology. Therefore, in addition to the resources available around their workspace such as textbooks and notebooks, students demonstrated the demand of accessing resources on their handheld devices such as Microsoft® Excel and the Internet as a support for complete group tasks during discussion. For instance, they frequently searched for statistical tools on the Internet and discussed how these tools complete their individual tasks (Fig 5b). Therefore, there is a strong demand to support students to discuss and share their experiences in accessing the Internet as they collaboratively worked on open-ended questions. The workspace with handheld devices and shared display systems satisfied student needs as students can access the Internet through their handheld devices and in the meanwhile demonstrated the whole process on the shared display for their partners.

This study examined the communication behaviours of students when they used handheld devices. Students with handheld devices did not demonstrate expected participation ratios and actively interact with group members. In addition, they frequently guessed the visual focus of their partners and did not notice the nonverbal signals of their partners. Although handheld devices and wireless network provide personal workspace for individuals to prepare group work, student communication behaviours suggested that the use of handheld devices for group learning did not facilitate group interactions and lead to fragmented and ineffective communication. This study has proposed a design of classrooms that incorporates personal workspace and public workspace. Students use handheld devices as private workspace and work with peers on public workspace with shared displays through their handheld devices. This study has implemented such design of personal workspace and public workspace in classrooms to support one-to-one collaborative learning activities.

Students can bring their handheld devices into the classroom and utilize the shared display groupware to perform collaborative learning activities. Experiments confirmed that the proposed shared display groupware attracted group members to perform effective communication. The groupware also promotes a shared understanding of the workspace and increases awareness of the actions of partners, as participants use the shared display to view what others are interested in. Shared displays improved non-verbal interaction and awareness of visual focus. Such displays thus helped students to illustrate their meaning using their hands to refer to the information on the shared displays and also using eye contact with partners. Collaboration can be enhanced by creating the opportunity for students to use handheld devices to promote student participation and avoid ineffective communication patterns. The shared displays enable group members to participate closely in shared activities achieving effective collaboration.

Overall, students demonstrated a more equal participation ratio (on average 0.8 and 0.82) in the Shared-Display setting than in the Tablet-PC-Only (on average 0.76) and Network-File-Sharing (on average 0.61). However, the improvement of participation ratio for Group 1 is not as large as Group 2. One possible explanation for the difference in the observed improvement between the two groups is the configuration of the two groups. Certain configurations of students' background knowledge leads to a particular communication pattern (Liu & Tsai 2006). Group 2 and Group 3 contained at least one senior member who often took on the leader role to coordinate the group discussion. Group 3 contained two senior members. Consequently, they demonstrated high participation in both of the Tablet-PC-Only and Shared-Display settings. The members of Group 1 were all first year graduate students and this possibly could explain why there was not a large improvement in participation ratio in the shared display setting compared with the other two groups. However, it should be noted that students of Group 1 and Group 3 exhibited more frequently pointing and eye contact behaviours in the Shared-Display setting than they did in the Network-File-Sharing setting.

Gibson (1977) proposed the theory of affordances which has been widely applied to design human–computer interaction environments. Kirschner and Kreijns (2003) noted affordances as 'opportunities for action'. The environment with different technological settings will provide different educational affordance in collaborative learning context. Norman (1999) related affordance and constraints and pointed out 'Physical constraints make some actions impossible: there is no way to ignore them. Logical and cultural constraints are weaker in the sense that they can be violated or ignored, but they act as valuable aids to navigating the unknowns and complexities of everyday life. As a result, they are powerful tools for the designer'.

The three environments impose different types of constraints while they create different affordances. This study examined how the large shared displays bring benefits to small group learning and compares three conditions of using handheld devices for collaboration. Handheld devices facilitate coordination and provide mobility for a new scenario of collaborative learning. Large shared displays create a workspace for student groups to cooperate and work on complex tasks. Environments in the Network-File-Sharing settings could be designed to allow students to display their screens on all the other screens. However, in some settings, such design becomes infeasible because of the limited computational power of the handheld devices. Handheld devices such as PDAs have limited computational capability compared with desktop PCs. The physical computational constraint makes it difficult to display one student's screen on all the other screens, because the handheld device of the student has to process two computational threads, one for capturing the screen of the student's device and the other for continuously sending the screen images to others' devices within a very rigid time constraint. Therefore, this study did not develop completely equivalent functions for students in the three settings with handheld devices. Instead, this study compared student interactions in the Shared-Display environment with the other settings in which students used handheld devices with only file-sharing functions which did not require complicated computation from handheld devices.

In addition to the scenario of using Tablet PCs, this study analysed the effect of the shared displays on facilitating collaboration and interaction among students who were using PDAs. Displaying one student's PDA screen on the screens of all the other students' PDAs becomes infeasible because of the limited computational power of PDAs. This study created an activity in which a student group performed the TPS activity with PDAs and a shared display (Fig 5b). Students only used their PDAs as remote terminals to access the shared display system with Virtual Network Computing (VNC) software (Richardson *et al.* 1998). By using PDAs and VNC, students navigated among the World Wide Web and performed statistical analysis on the website they identified as if they were using the PCs that were mounted to the shared display. All the web browsing behaviour and the statistical analysis task were shown on the shared display. In such a setting, students demonstrated more equal participation ratio (0.87), frequent hand pointing behaviour (57) and eye contact behaviour (32).

Displaying one student's screen on all the other screens represents a workspace transfer from a private space (a handheld device) to another private space (private-to-private) rather than from a private space to public space (private-to-public). The shared-display environment supports the workspace transfer from a private space to public space (private-to-public). People frequently bring their own laptop computers to communal space for discussion. An informal survey in one of the researchers' lecture indicated that among 32 students, 21 of them bring their own laptop computers to the lecture for collaborative discussion activities. The students, divided into five groups, mounted their laptop computers to the large shared display when they are discussing their group work. The desire for projectors or large displays represents a logical and cultural constraint (Norman 1999, p. 41) indicated that 'the current choice is an intelligent fit to human cognition, but there are alternative methods that work equally well.' The provision of shared displays facilitates private-to-public workspace transfer which is helpful to create a shared focus that people frequently demonstrate in discussion activities involving complex group tasks.

Previous studies (Gutwin *et al.* 1996; Jang *et al.* 2000; Kirschner & Kreijns 2003) have emphasized the importance of group awareness in online collaborative learning activities. In this study, students considered Network-File-Sharing and Shared-Display environments significantly promote group awareness for the collaborative work, compared with Tablet-PC-Only settings (item 1 in Table 5). Therefore, both of the private-to-private and private-to-public workspace transfer could support the information awareness of collaborative works. The finding suggested the necessity to provide group awareness of the collaborative work for face-to-face collaborative learning activities involving complex tasks. Students agreed that the private-to-public workspace transfer facilitated peer interaction compared with private-to-private workspace transfer (items 7, 8, 9, 10). Therefore, although private-to-private workspace transfer is beneficial to maintain group awareness among peers, there is a necessity to support private-to-public information transfer to create a shared focus for students groups while students are working on complex collaborative tasks.

Because of the rapid market growth, LCD prices are decreasing dramatically. Recently, the prices of some LCDs have been almost comparable to PDAs in Taiwan, or even cheaper than some new models of PDAs in Taiwan. LCD prices decrease faster than computers or handheld devices as LCDs do not have to pursue expected computation performance year after year. In addition, researchers such as Brignull *et al.* (2004) have demonstrated the effect of deploying a single large display system in public areas where students come together to mix, socialize and collaborate throughout the day. Similarly, the deployment of a shared-display system in communal space such as meeting rooms or libraries can also enrich student interaction in after-class and informal discussion settings. In such application, schools do not necessarily invest too much budget in expensive hardware when the large LCD displays are still not widely affordable.

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