Integration of Interpersonal Space and Shared Workspace: ClearBoard Design and Experiments

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We describe the evolution of the novel shared drawing medium ClearBoard which was designed to seamlessly integrate an interpersonal space and a shared workspace. ClearBoard permits coworkers in two locations to draw with color markers or with electronic pens and software tools while maintaining direct eye contact and the ability to employ natural gestures. The ClearBoard design is based on the key metaphor of "talking through and drawing on a transparent glass window." We describe the evolution from ClearBoard-1 (which enables shared video drawing) to ClearBoard-2 (which incorporates TeamPaint, a multiuser paint editor). Initial observations and findings gained through the experimental use of the prototype, including the feature of "gaze awareness," are discussed. Further experiments are conducted with ClearBoard-0 (a simple mockup), ClearBoard-1, and an actual desktop as a control. In the settings we examined, the ClearBoard environment led to more eye contact and potential awareness of collaborator's gaze direction over the traditional desktop environment.

Categories and Subject Descriptors: H.4.3 [**Information Systems Application**]: Communications Applications—*computer conferencing and teleconferencing*; H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—*video*; H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces—*evaluation/methodology*; *synchronous interaction*

General Terms: Design, Human Factors

Additional Key Words and Phrases: Eye contact, gaze awareness, gaze direction, groupware, seamless design, shared drawing, video conference

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A previous version of this article was presented at the 1992 ACM Conference on Computer-Supported Cooperative Work (CSCW '92) [Ishii et al. 1992b]. Descriptions of ClearBoard-1 given in an ACM CHI '92 paper [Ishii and Kobayashi 1992] are incorporated into this article.

Jonathan Grudin participated in the experimental and observational phase of the ClearBoard research during his stay at NTT Human Interface Laboratories in November 1991 as a visiting professor and contributed to the preparation of this article.

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1. ITERATIVE DESIGN OF SEAMLESS COLLABORATION MEDIA

Ideally, tools enable us to work smoothly and without interruption. Complex computer-based tools, however, often require too much of our attention, distracting us temporarily from the work we are doing. "*Seamlessness*," in the sense of eliminating unnecessary obstructing perceptual seams, has been a key concept of our evolving media design. Collaborative work, in particular, is marked by spatial, temporal, and functional constraints that force us to shift among a variety of spaces or modes of operation. Seamless design undertakes to decrease the cognitive loads of users as they move dynamically across different aspects of their work.

Our research progressed through iterative design steps from TeamWorkStation-1 and TeamWorkStation-2 to ClearBoard-1 and ClearBoard-2 [Ishii et al. 1992a]. Ishii designed TeamWorkStation-1 (TWS-1) to enable smooth transitions over

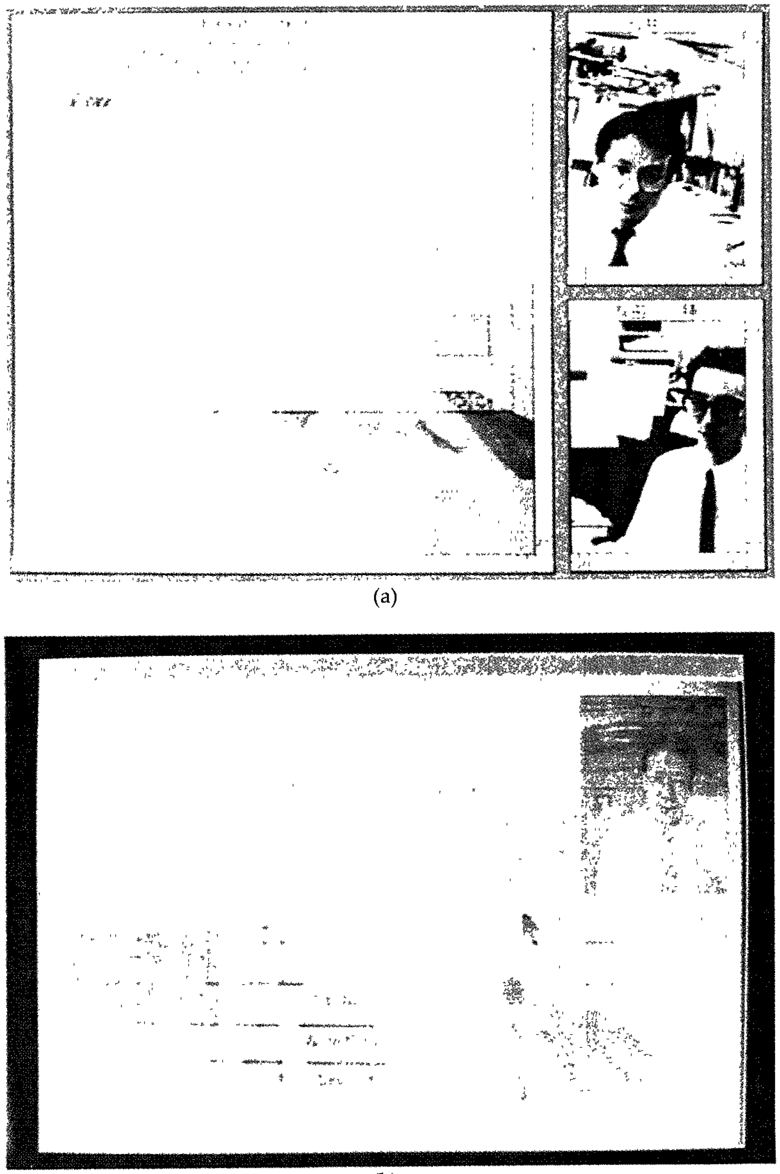
(1) the seam between individual and shared workspaces, and
(2) the seam between computer and desktop tools [Ishii 1990; Ishii and Miyake 1991].

TWS-1 provides a shared workspace in which participants can freely use a variety of everyday media, such as computer tools, handwriting, printed materials, and hand gestures (see Figure 1a). The two windows on the right provide live video images of the participants' faces. The left window provides a *shared workspace* that is made by *translucent overlay* of the individual workspace images (live video images of desktop surfaces and/or computer screen images).

TeamWorkStation-2 (TWS-2) is developed to provide the shared workspace over narrowband ISDN (Integrated Services Digital Network) using the CCITT H.261 standard [Ishii et al. 1993]. ClearFace, a new multiuser interface for TWS-2, superimposes translucent live-video facial images over a workspace image to enable the more effective use of the normally limited screen space (see Figure 1b). Users have little difficulty in selectively viewing either the facial image or the workspace image [Ishii and Arita 1991].

These multiuser interfaces for TWS-1 and TWS-2, however, suffer from an undesirable seam between the facial images and the shared workspace. We realized that the problem was not just the superficial physical discontinuity of spatially separated windows. Absent are the cues that would enable a smooth shift of focus between the shared workspace and the partner's image. Camera positioning prevents one person from knowing the direction of the other's gaze; it could be directed toward the face image, toward objects in the shared-workspace window, or elsewhere. A shift in focus is not apparent until accompanied by a visible gesture, a mouse movement, or an audible remark. Awareness of gaze direction and mutual eye contact is impossible.

To overcome this limitation of TeamWorkStation, and to realize a seamless environment for real-time collaboration, we started the ClearBoard project. Based on the new metaphor of a transparent glass board, we have developed



(a)

(b)

Fig. 1. Shared-screen examples of TeamWorkStation.

two working prototypes, ClearBoard-1 and 2, and conducted experiments with them [Ishii and Kobayashi 1992; Ishii et al. 1992b].

This article first discusses the notions of *shared workspace* and *interpersonal space* and reviews existing support technologies for activities in these spaces (and their limitations) to fully explain the goal of the ClearBoard project. In the next section, we introduce the metaphor on which ClearBoard is based: *looking through* and *drawing on* a glass board. We then introduce the architecture of ClearBoard-1, a prototype that supports remote collaboration through *shared video drawing*. Next we describe ClearBoard-2, which utilizes computer-based shared drawing to overcome the limitations of ClearBoard-1. We briefly outline an alternative architecture that represents an interesting technological possibility. Finally, we briefly describe the experimental use of these prototypes. Both informal use and formal experiments are covered; the latter are designed to explore the feature of "gaze awareness."

2. SHARED WORKSPACE AND INTERPERSONAL SPACE

One major focus of groupware development has been the creation of virtual "*shared workspaces*" in distributed-computer environments. Some groupware definitions take this workspace-oriented view, such as:

> "Groupware... the computer-based systems that support groups of people engaged in a common task (or goal) and that provide an interface to a shared environment" [Ellis et al. 1991].

Whiteboards and overhead projections of transparencies are examples of shared workspaces in face-to-face meetings. Participants can see, point to, or draw on a whiteboard simultaneously. An overhead projector makes handwritten or computer-generated documents visible to all participants in a room while permitting the speaker to point or draw. Shared-workspace activities include sharing information, pointing to specific items, marking, annotating, and editing.

In a distributed, real-time collaboration these activities can be supported by computer-based groupware, including

(1) shared screen systems such as Timbuktu [Farallon 1991],
(2) shared window systems such as VConf and Dialogo [Lauwers et al. 1990], and
(3) multiuser editors such as Cognoter [Foster and Stefik 1986], GROVE [Ellis et al. 1991], ShrEdit [Olson et al. 1993], Commune [Bly and Minneman 1990], CaveDraw [Lu and Mantei 1991], Aspects [Group Technologies 1990], GroupSketch and GroupDraw [Greenberg et al. 1992], We-Met [Wolf and Rhyne 1992], WSCRAWL integrated in SEPIA [Streitz et al. 1992], Tivoli [Pedersen et al. 1993], and TeamPaint (described later). Use of hand gestures in a shared workspace can be supported by shared-video drawing media such as VideoDraw [Tang and Minneman 1991a] and TeamWorkStation [Ishii 1990].

In face-to-face meetings, we speak, make eye contact, and observe each other's facial expressions and gestures. These verbal and nonverbal channels are important in building confidence and establishing trust [Argyle 1975; Buxton 1992; Mantei et al. 1991]. The focus of telecommunication technologies such as the videophone and video conferencing has been the creation of "*interpersonal spaces*" that maintain a sense of "telepresence" or "being there" [Hollan and Stornetta 1992] through the visibility of gestures and facial expressions of distributed group members. Media Space [Bly et al. 1993], CRUISER [Fish et al. 1993], and VideoWindow [Fish et al. 1990] are examples of such technologies. Figure 2 illustrates these concepts and identifies the technical support available for real-time remote collaboration.[1]

3. LIMITATIONS OF EXISTING SUPPORT TECHNOLOGIES

Both shared workspace and interpersonal space are present in ordinary face-to-face meetings and may be essential for remote real-time collaboration. Several media space technologies support both spaces.[2]

Figure 3 illustrates three typical display arrangements of media spaces. In (a), a display providing a live video image of the partner's face adjoins a display showing the shared work. The ARKola simulation [Gaver et al. 1991] in the IIIF environment [Buxton and Moran 1990] and some nodes of CAVECAT [Mantei et al. 1991] adopt this arrangement. SEPIA-IPSI media space [Streitz et al. 1992] locates small custom-built desktop video devices (small monitors and camera) on top of the computer screen. In (b), the displays are repositioned to resemble the situation of interacting across a table. VideoDraw [Tang and Minneman 1991a] and Commune [Bly and Minneman 1990; Minneman and Bly 1991] experiments adopt this arrangement. In (c), the live video images and the shared workspaces are incorporated into different windows of a single screen. TeamWorkStation (see Figure 1), PMTC [Tanigawa et al. 1991], MERMAID [Watabe et al. 1990], and some CAVECAT nodes employ this desktop video technology.

These designs, although they represent an advance, share a major limitation: an arbitrary seam between shared workspace and interpersonal space. Experiments on TeamWorkStation proved that the problem is not just the superficial physical discontinuity of spatially separated windows. Users experience an undesirable gap between the two functional spaces, shared workspace and interpersonal space.

In a face-to-face design meeting, while using a whiteboard or drawing surface we frequently switch our focus between the two spaces. Even when drawing, we briefly glance at our partner's face to attract attention or gauge comprehension. Similarly, our partner's turning head, eye movement, and gestures also attract our attention and trigger a focus shift. This dynamic and interactive focus switching between shared workspace and interpersonal space is made possible in ordinary meetings by the presence of a variety of *nonverbal cues*.

Current media space technologies do not provide strong cues. Spaces created by these technologies are discontinuous and arbitrary [Gaver 1992]. Users cannot switch their focus between the two spaces naturally and

[1] This framework was developed through a discussion with Buxton, who pointed out the importance of a smooth transition between what he calls "shared task space" and "person space" [Buxton 1992].

[2] "Media space," originally the name of a specific system [Bly et al. 1993], is used here in the sense of Mantei et al. [1991] as a general term to represent computer-controlled video environments.

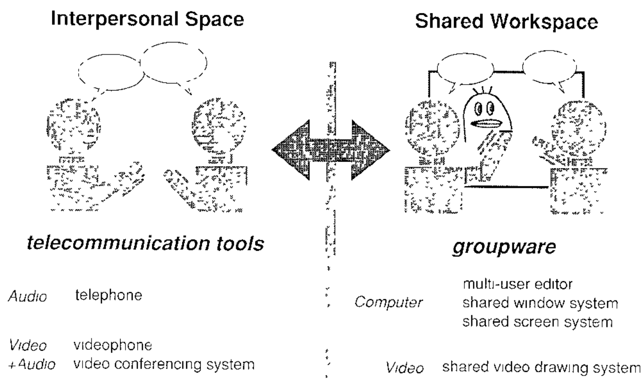


Fig. 2. Interpersonal space, shared workspace, and support technologies in real-time remote collaboration.

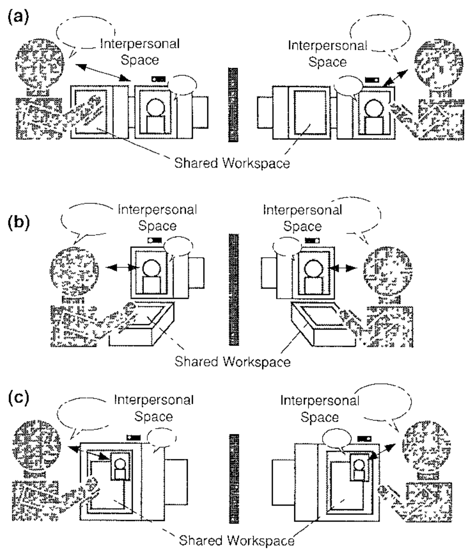


Fig. 3. Typical screen arrangements in media space.

smoothly. ClearBoard is designed for pairs of users and overcomes these limitations by seamlessly connecting interpersonal space and shared workspace. ClearBoard allows users to shift easily between interpersonal space and shared workspace using familiar everyday cues such as the partner's gestures, head movements, eye contact, and gaze direction.

4. GLASS BOARD METAPHOR OF CLEARBOARD

Our first step was to consider the metaphors needed to create a medium that allows people to use everyday skills without special training. We first investigated two familiar metaphors: (a) talking over a table and (b) talking in front of a whiteboard.

Work carried out across a table, or with a system based on this metaphor of sitting on opposite sides of a table and talking over it, is suitable for face-to-face communication because the participants can easily see each other's face. Unfortunately, the drawing orientation is upside-down for one party. Work carried out with a whiteboard or a system based on a whiteboard metaphor (or by participants on the same side of a desk or table) has the advantage that the participants share a common board orientation.

With real tables and whiteboards, participants share the same physical space and may touch their partner. However, it is hard to implement a mechanism that can usefully recreate this shared space. The only way we found of realizing this metaphor is to employ virtual-reality technology with force feedback mechanisms. However, we do not think it is a good idea to force users to wear awkward head-mounted displays, special gloves, and a suit just to share some drawings. This solution places users in a computer-generated virtual world that definitely increases cognitive loads.

Kobayashi came up with the new metaphor of "looking *through* and drawing *on* a big glass board" and gave it the name "ClearBoard" [Ishii and Kobayashi 1992]. Figure 4 shows "ClearBoard-0" which is the simple mockup of this ClearBoard concept for colocated pairs of users. ClearBoard-0 consists of a glass board positioned between the partners on which they draw or post objects. This prototype represents the best possible case for visual clarity. In addition to reinforcing the actual physical separation of the partners, ClearBoard requires less eye and head movement to switch focus between the drawing surface and the partner's face than is needed in either the whiteboard or desktop environment. A real glass board has the problem that written text appears reversed to one's partner; we were able to solve this problem by "*mirror-reversing*" video images in ClearBoard-1 and 2 as described below.

The existing systems most similar to ClearBoard are VideoWhiteboard [Tang and Minneman 1991b] and LookingGlass [Clark and Scrivener 1992]. VideoWhiteboard utilizes the users' shadows to convey their gestures during shared-drawing activity. VideoWhiteboard looks like a *frosted* glass board, in contrast to the *transparent* glass board that ClearBoard reproduces. VideoWhiteboard merges elements of interpersonal space and shared workspace; however, the shadow images do not convey facial expressions, eye movement, or eye contact, all of which are present with ClearBoard.

LookingGlass displays the full-screen window of a ROCOCO sketchpad (shared-drawing software) over a full-screen video image of a remote partner. Using a half-silvered mirror, LookingGlass supports eye contact. However, the use of indirect drawing devices (mouse, digitizer) separates hand movements on a desktop from cursor movement on the computer screens, and users cannot see the actual hand gesture behind the cursor movement. The users cannot place their hands close to marks on the computer screen surface for pointing because the half-silvered mirror is angled backward at 45 degrees in front of the vertical screen surface. In contrast, ClearBoard allows users to draw on and gesture directly over the screen surface.

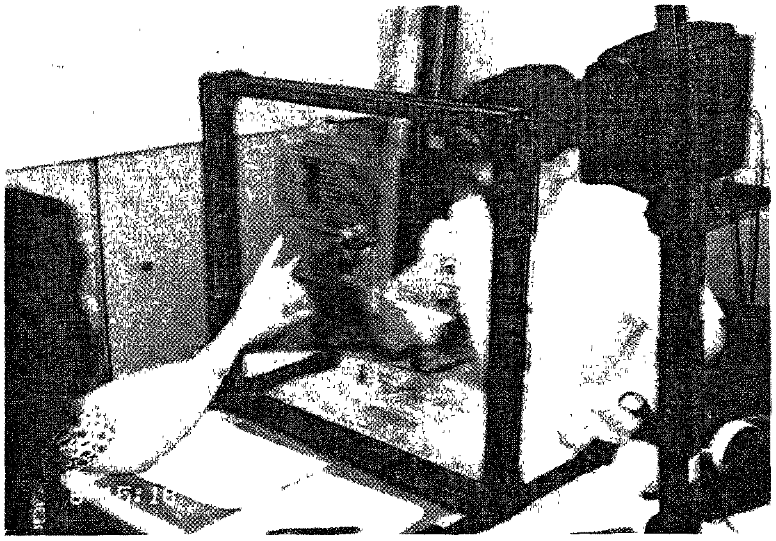


Fig. 4 A simple mockup of ClearBoard metaphor: ClearBoard-0.

5. THE DESIGN OF CLEARBOARD-1

In order to implement the remote version of ClearBoard, we identified three design requirements:

(1) direct drawing on the display screen surface must be supported;
(2) the video image of a user must be taken *through* the screen surface to achieve eye contact; and
(3) a common drawing orientation must be provided.

In order to satisfy these three requirements with simple technologies, Ishii devised the system architecture called the "drafter-mirror" architecture. The first prototype, ClearBoard-1 was implemented in November 1990 by Kobayashi.

5.1 ClearBoard-1 Architecture

Figure 5 illustrates the drafter-mirror architecture of ClearBoard-1. It looks like a "drafter" (a desk for architectural drawing), and it uses a half mirror to satisfy requirement (2). Each terminal is equipped with a tilted screen, a video projector, and a video camera. The screen is angled backward at about 45 degrees and is composed of a projection screen, a polarizing film, and a half-silvered mirror (which reflects half of the light reaching it and allows half to pass through). Video feedback between the two cameras and screen pairs is prevented by the polarizing filter placed over each camera lens and by the nearly orthogonal polarizing filter that covers the surface of each

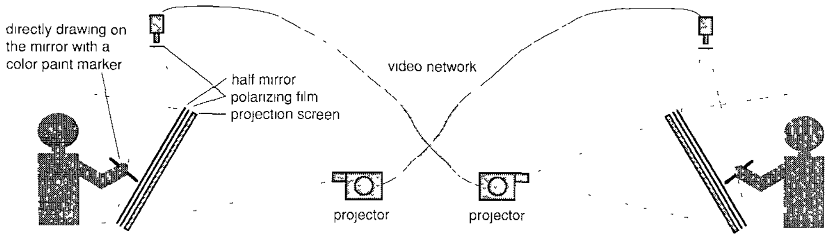


Fig. 5. System architecture of ClearBoard-1.

screen. Users can write and draw on the surface of the screen using color paint markers[3] and cloth erasers.

Figure 6 illustrates how this drafter-mirror architecture works. The video camera located above the screen captures the drawing marks on the screen surface and the image of the user reflected by the half mirror as a continuous video image. This image is sent to the other terminal through a video network and is projected onto the partner's screen from the rear. The partner can draw directly over this transmitted video image.[4]

The image of the partner and the partner's drawing are mirror-reversed so that ClearBoard-1 provides both users with a common drawing orientation on their screens. Since the user's image is also mirror-reversed, a right-handed partner will appear to be left-handed. The drafter-mirror architecture results in the video camera capturing double hand images as it draws—one being the direct image and the other being the image reflected by the half-mirror, as shown in Figure 6.

The drawing image captured by the camera is trapezoidally distorted due to perspective because the screen is at an angle to the camera. In order to support shared drawing on the screen, the drawing image must be recreated with the original shape and size on the partner's screen. In ClearBoard-1, the distortion is offset by the opposite distortion caused by projecting the image onto the tilted screen. In order to remove the distortion, the camera and the projector are symmetrically arranged with respect to the screen.

5.2 Results of ClearBoard-1 Experiments

Figure 7 shows snapshots of the ClearBoard-1 prototype in an experimental session that will be described later. In summary, we observed effortless focus switching between the task and the partner's face. Users could read their partner's facial expression, achieve eye contact, and utilize their awareness of the direction of their partner's gaze (we call this characteristic "gaze awareness" [Ishii and Kobayashi 1992]). These last two features are the novel aspects of the ClearBoard prototypes, and their importance is discussed later.

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[3] Water-based fluorescent paint markers were used in our experiment because these colors are easy to distinguish from the images of the user and the user's background.

[4] This shared-video drawing technique, which allows remote partners to draw directly over the video image of their coworkers' drawing surface, was originally demonstrated in VideoDraw [Tang and Minneman 1991a].

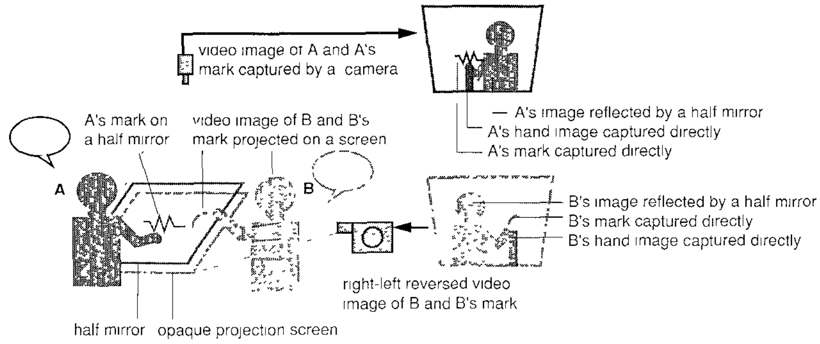


Fig. 6. How drafter-mirror architecture works.

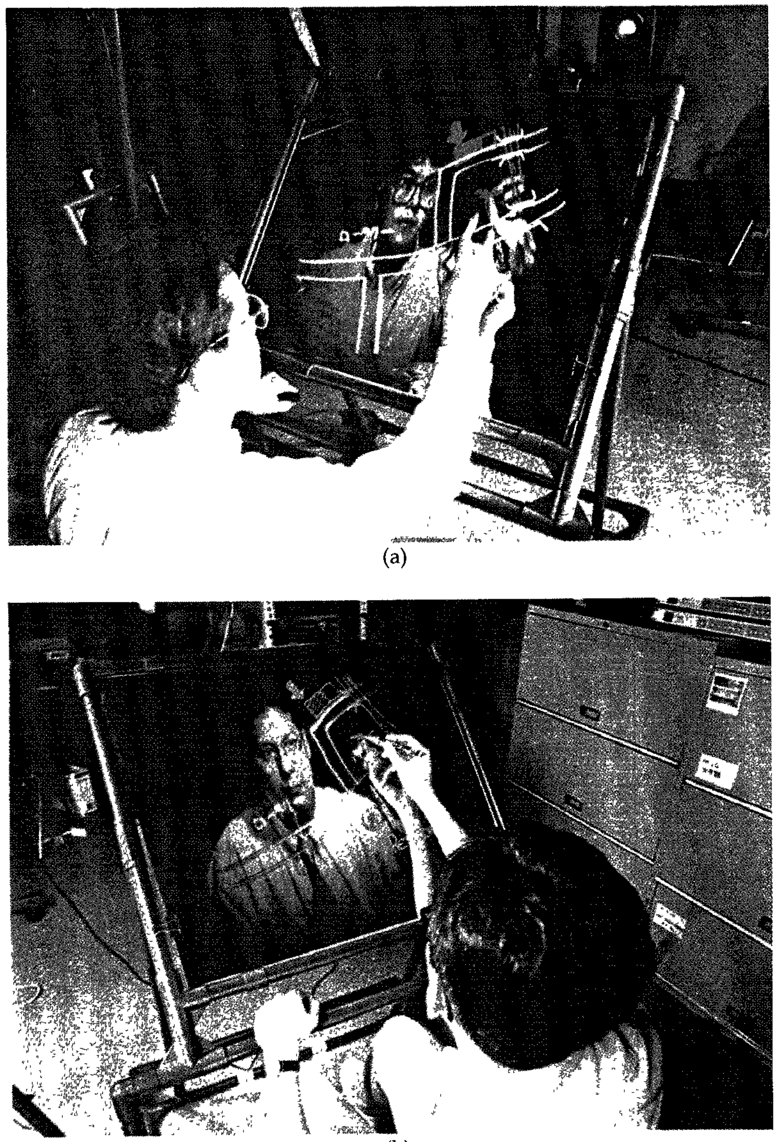
Most users did not notice double hand images. Some users, however, reported an initial period of distraction. No subjects reported difficulty with the mirror-reversal of the partner. This may be because our faces are quite symmetric or because our own images are reversed in mirrors.

An interesting and less critical confusion manifested itself when users directly drew over their partner's image, playfully adding eye glasses or mustache, for example. Clearly they had a "WYSIWIS" (what you see is what I see) expectation, not realizing that although the drawing is shared, the facial images are not, with each person seeing only the other's image. Thus, the metaphor of the ClearBoard is not always entirely assimilated.

We also encountered problems in using ClearBoard-1: the most frequently reported problem was that video images on the screen are darker and less clear than is desirable. This is because

(1) the brightness of the projected video image is reduced by the use of half-mirrors and polarizing films (more than half of the light is lost);
(2) the tilt of the screen places the bottom edge about 40 cm further from the camera than the top, making it hard to keep the entire drawing surface (and the drawer's face) in sharp focus;
(3) the video resolution was limited to the liquid crystal video projector's 90,000 pixels (in contrast to the approximately 400,000 pixels of the CCD camera).

The lack of video resolution forced the use of thick color paint markers; drawing with them is not precise and quickly uses up the available display space (50 cm $\times$ 55 cm). This problem is exacerbated by the low erasure efficiency with the cloth erasers and the difficulty of recording the resulting drawings. (We mainly used Polaroid™ cameras or video printers.) Another limitation of shared video drawing is that a user cannot erase the partner's drawing [Tang and Minneman 1991a]. Marks drawn by each user exist only on their respective screen surfaces. When users run out of free drawing space, they often hesitate to ask each other to erase marks or are embarrassed by



(a)

(b)

Fig. 7. ClearBoard-1 in use.

requests to erase their own marks because of the lack of appropriate recording and reusing capabilities.

It would be desirable to be able to bring both computer files and printed materials directly into the ClearBoard shared drawing space, as is possible in TeamWorkStation. Computer file access can be incorporated by using a computer-based groupware technology that permits shared drawing over the documents stored in computer files; the use of printed materials remains a problem if we stick to direct drawing. If user A puts a sheet of paper on his/her ClearBoard surface and marks on it, user B can see it, but subsequent marks by B will not be seen by A because the paper blocks the rear-projected image.

6. THE DESIGN OF CLEARBOARD-2 WITH TEAMPAINT

To overcome many of the problems of ClearBoard-1, we designed a new computer-based prototype, ClearBoard-2. Instead of video drawing with color paint markers, ClearBoard-2 provides users with digitizer pens and TeamPaint, a multiuser computer-based paint editor running on networked Macintosh™ computers.

6.1 ClearBoard-2 Architecture

Figure 8 illustrates the system architecture of ClearBoard-2. To improve the clarity of the screen image, we used a CRT-based rear-projection display with a transparent digitizer sheet. The digitizer is mounted to the surface of a flat panel display. The screen size is 80 cm × 60 cm, 1.7 times larger than the ClearBoard-1 screen. Although ClearBoard-2 is based on the same "drafter-mirror" architecture as ClearBoard-1, the digitizer pen and TeamPaint add the following capabilities:

(a) collaboratively created drawings can be saved as computer files and reaccessed later;
(b) documents created with other editors can be imported;
(c) it is easy to get a new blank sheet (drawing space); and
(d) it is easy to edit and erase marks.

The shared drawing image (RGB video) is overlaid onto the video image of the coworker (NTSC) using a special video overlay board, and the mixed RGB video image is projected onto the screen by a video projector. Chroma-keying in the overlay sharpens the drawing image against the image of the coworker.

6.2 TeamPaint: A Multiuser Paint Editor

TeamPaint is not a special component of ClearBoard-2; it is a groupware application that runs on AppleTalk™-networked Macintosh computers without any special hardware. It can be used by any number of users simultaneously, but performance drops off somewhat as the number of users increases. A mouse or tablet can be used for indirect drawing; the digitizer-screen supports direct drawing. Figure 9 shows an example of a TeamPaint screen. TeamPaint design is based on the following principles.

(1) *A simple human interface*: TeamPaint provides an intuitive interface based on the metaphor of drawing on a sketch pad with a color pencil. Scissors provide the functions of cutting, copying, and moving marks. A new blank sheet can be obtained by a single mouse click on the bottom left corner of the pad. To maximize transparency and speed of drawing, it

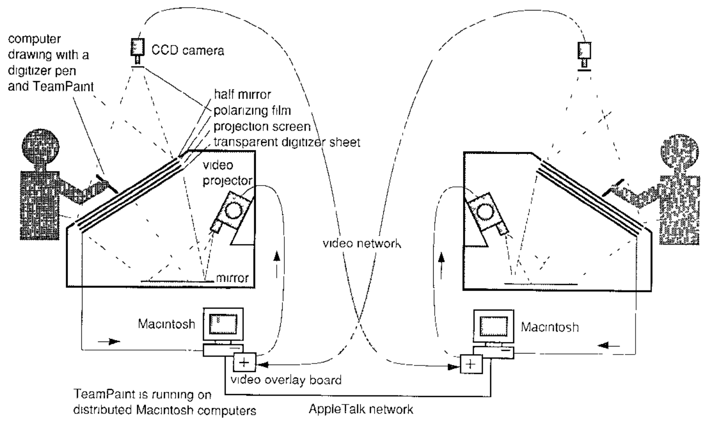


Fig. 8. System architecture of ClearBoard-2.

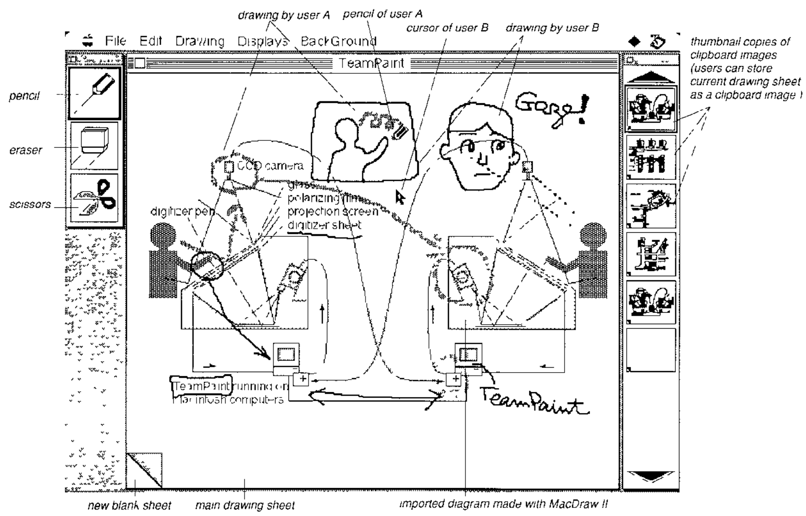


Fig. 9. Example of a TeamPaint screen.

is a simple bitmap paint editor, not an object-oriented drawing editor. TeamPaint enables simultaneous gesturing and drawing by multiple users.

(2) *Replicated architecture*: To support time-constrained design sessions, TeamPaint maximizes run-time performance by employing a replicated architecture [Lauwers et al. 1990]. It does not require a central server.

(3) *Multilayer structure*: Each user is provided with individual transparent layers or drawing surfaces. The default is that users draw only on their own layers but see a composite of all layers. Members normally use different colors to distinguish the ownership of marks. Because each

layer is isolated from the others, no access control is necessary. It is also possible to share a layer, allowing other users to draw and erase the image on that layer. The usefulness of this multilayer architecture was originally demonstrated in TeamWorkStation using a translucent video overlay technique [Ishii and Miyake 1991]. We found that people respect the ownership of the drawing even in a close collaborative session and that the direct data-sharing and editing function is not always required. It is, however, still a research issue [Lu and Mantei 1991].

(4) *Gesture and process awareness*: Gestures in the form of cursor movements, and through them the drawing process, are visually shared by all members. This feature is important in enhancing the sense of a distributed group process[5] [Hayne et al. 1993].

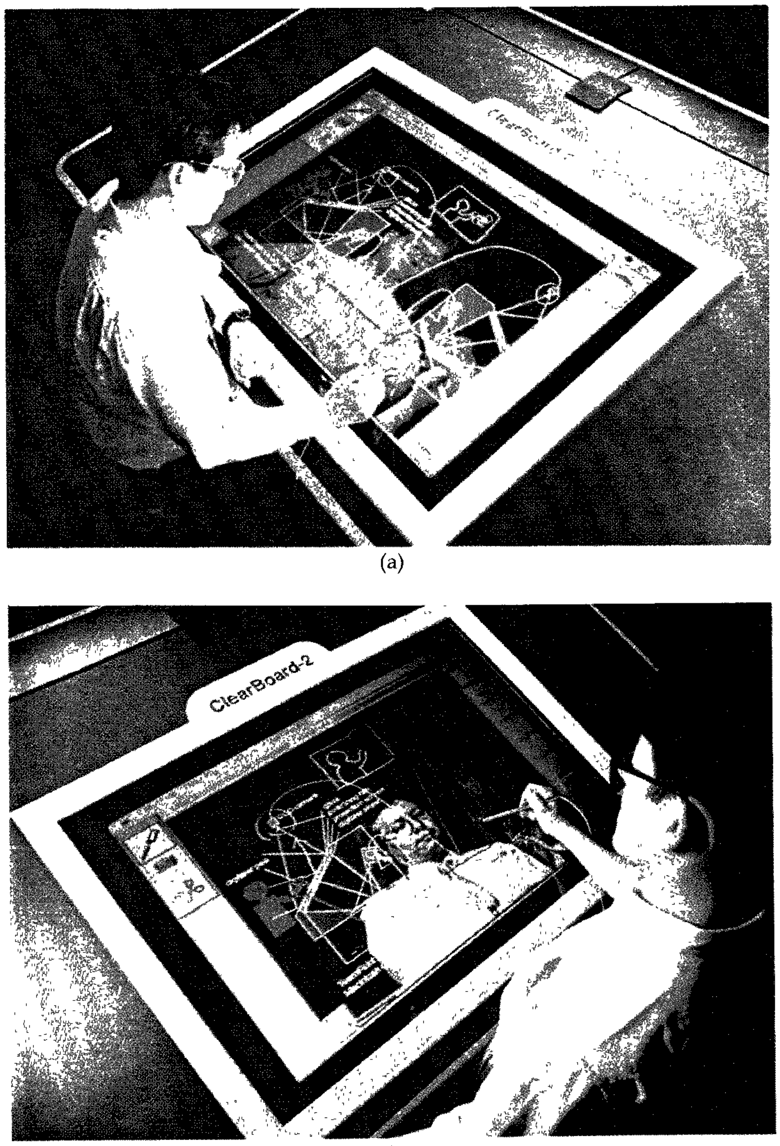
(5) *Data exchange via standard format file*: TeamPaint can store the shared-drawing results in the PICT file format that can be read by standard Macintosh programs. TeamPaint can also read PICT files created by other editors such as MacDraw II™.

6.3 Initial ClearBoard-2 Experience

We implemented an initial ClearBoard-2 prototype in February 1992. Figure 10 shows snapshots of the authors using ClearBoard-2 in a design session. Its ability to record results and reuse data from previous sessions or from other application programs promises to add tremendous value to an already practical tool. The use of RGB video and the chroma-keying overlay technique does increase image clarity. Since the partner's video image is seen in the background of the TeamPaint groupware, which runs in a Macintosh full-screen window, one has the feeling of interacting with the partner through a window instead of through a big glass board. The change of screen angle (45 degrees in ClearBoard-1 and 35 degrees in ClearBoard-2) decreases arm fatigue and prevents users from covering the screen with their body and hindering the camera view. It creates an impression that the partner is more *under* the screen than *behind* it as in ClearBoard-1.

We found that because ClearBoard-2 provides a precise shared drawing surface through the use of TeamPaint software, its video calibration needs not be as strict as that required by ClearBoard-1. It was often observed that the user's gaze follows the partner's pen movements. We confirmed that ClearBoard-2 supports *gaze awareness* as well as ClearBoard-1 did. A user can know what object in the TeamPaint screen the partner is looking at. The most serious problem of the current prototype is that drawing sometimes halted because of the poor sensitivity of the switch at the digitizer pen tip. Users complained about the situation, using the expression "out of ink."

[5] Awareness based on such a tele-pointer may have limitations. Actual hand gestures have much more power of expression, and with ClearBoard-2, the real hand and pen gesture images that lie behind the tele-pointer augment the awareness provided by TeamPaint. This video-augmented computer drawing technique was originally demonstrated in VideoCom, presented by Minneman and Bly at CHI 91. In VideoCom, however, the hand image and face image are separated and presented in different displays.



(a)

(b)

Fig. 10. ClearBoard-2 in use.

7. AN ALTERNATIVE ARCHITECTURE BASED ON LIQUID CRYSTAL SCREEN

The half-mirror and polarizing film still block the projected light and darken the ClearBoard-2 display. Moreover, overhead light sources are reflected by the half-mirror, which degrades the visibility of the projected image. Fully overcoming this problem and increasing the robustness against the lighting conditions will require us to abandon the drafter-mirror architecture. To address this, we are designing a new architecture based on a liquid crystal screen (LCS) that can be rapidly switched between transparent and light-scattering states by the application of a suitable control voltage. Figure 11 illustrates the new system architecture.

The architecture works by switching between the (1) light-scattering (opaque) and (2) transparent states. In state (1), the screen works as a rear-projection screen on which the image of a coworker and his or her drawing is displayed. In state (2), the user's image is captured by a video camera behind the now-transparent screen. The timing of image capture and image display is synchronized to the cycling of the LCS states. This technique was originally a means of enabling eye contact [Shiwa and Ishibashi 1991]. By allowing users to draw directly on the screen, this architecture can be extended to implement the ClearBoard concept.

Today, this LCS architecture is limited by an undesirable *flickering* that increases with the screen size; the transition frequency of the liquid crystal screen depends on its size. The expected evolution of LCS technologies should overcome this problem and realize the ClearBoard concept at a reasonable performance-to-price ratio in the near future.

8. EMPIRICAL RESEARCH USING CLEARBOARD PROTOTYPES

We have used the ClearBoard prototypes in work or work-like situations and in tasks constructed to explore certain aspects of the technology. In some cases we ourselves have been the users; in others the users were people not involved in the development of the technology. This section outlines some of the purposes of these studies and gives examples of the results.

One purpose of our experiments was to obtain a quick first impression of the usability of the prototypes and of any obvious technical or behavioral problems. Many of the ClearBoard-1 problems and resulting ClearBoard-2 requirements described earlier were discovered through such use. A second purpose was to explore in more detail the way in which users react to the new aspects and capabilities of the technology. More careful study is needed to see how people react to overlaid images and to remote collaboration with eye contact and awareness of gaze direction, for example. A third purpose was to gain increased understanding of how people work together and how technology might ideally support such work. Basic research questions must be addressed before we can understand how our technologies affect or could affect collaboration.

8.1 Results from Informal Studies of Use

The authors and six colleagues not involved in this research used the ClearBoard-1 prototype in conceptual design exercises (the limited marker resolution prevented the detail required by complicated electronic-circuit diagrams, for example). We found that users easily and frequently glanced at each other's face and achieved eye contact while conversing and while drawing. Switching focus from the drawing to the partner's face required almost

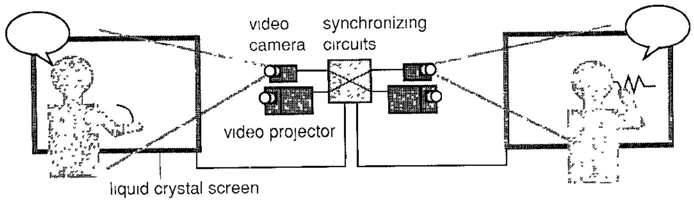


Fig. 11. Liquid crystal screen architecture.

no head movement. The effect seemed to be an increased feeling of intimacy and copresence. These impressions were addressed more quantitatively in experiments described later.

Ishii and Arita [1991] found that users of ClearFace hesitated to draw over the image of the partner's face, where the partner's image was in a translucent small window that appeared to be superimposed on a larger drawing image. With ClearBoard, users seemed to see the partner as *behind* the drawing and thus were not reticent in drawing on the board *in front of* the partner. This may be attributable to the transparent-glass metaphor and to the relatively large size of the partner's image and head movements. Even with overlapping images, users did not report having trouble distinguishing drawing marks from the video background.

8.2 River-Crossing Problem Solving and Gaze Awareness

The importance of eye contact is often discussed in the context of video communication tools [Acker and Levitt 1987]. However, we found that even more important may be the more general capability we call "gaze awareness": the ability to monitor the direction of a partner's gaze and thus his or her focus of attention. A ClearBoard user can tell what screen objects the partner is gazing at during a conversation more easily than is possible in an ordinary meeting environment with a whiteboard.

We conducted collaborative problem-solving experiments on ClearBoard-1 using the river-crossing problem[6] [Ishii and Kobayashi 1992]. It has been shown that the success of this game depends heavily on the *points of view* of the players [Hutchins and Levin 1981]. It is thus advantageous for the collaborative players to know what the partner is gazing at. Figure 12 shows a snapshot of one such experiment. Participant A is gazing at one side of the river, and Participant B is looking at A's face to read his gaze. These experiments confirmed that it is easy for the players to tell which side of the

[6] The "river-crossing problem" is a puzzle in which the challenge is to devise a plan for getting the members of two groups, A and B, across a river in a boat. (Traditionally, the groups were missionaries and cannibals.) The boat can hold only two members at a time and must have one person in it to cross the river. Members of group A can never outnumber members of B on either bank. We played the puzzle by drawing the river on ClearBoard and using Post-it™ notes to represent people.

(a)

(b)

Fig. 12. ClearBoard-1 used for solving the river-crossing problem.

river their partner is gazing at and that this information seems to help them understand and guide the partner.

We believe that the concept of gaze awareness is more general and thus a more important concept than eye contact. Gaze awareness lets viewers know what their partners are looking at, whether it be someone's face or anything else in the shared workspace. You can tell when your partner is looking at you, and when your partner looks at an object in the shared workspace, you can see what the object is. Eye contact is a special case of gaze awareness.

We think that providing gaze awareness will be an important goal of the next generation of shared-drawing tools. It cannot be easily obtained in conventional meeting environments; only CSCW technology can provide it. ClearBoard enables distributed users to establish gaze awareness.

8.3 Backgammon Instruction and Gaze Pattern

More extensive experiments were carried out by videotaping backgammon instruction sessions on a modified game board using ClearBoard-0, ClearBoard-1, and an ordinary table top as a control. The backgammon positions were laid out in a square as shown in the photographs from a ClearBoard-0 session in Figure 13. By confining the instructional activity to the periphery, we could differentiate patterns of visual attention to the workspace and to the partner, as seen in Figure 13. The backgammon game succeeded in engaging the subjects and motivated them to focus on the task. We observed complex uses of gaze awareness. For example, in the left picture of Figure 13, the instructor continues to point to a position on the display while monitoring the gaze of the student. This enables him to verify that the student is looking at the correct position.

In one experiment a teacher instructed a student in different backgammon tactics in three settings: ClearBoard-0, ClearBoard-1, and with a table. Neither the teacher, a backgammon expert, nor the student were involved in the research effort. Each session took about 20 minutes, with the first half mainly being used for teaching rules and tactics and the latter half spent playing a game using the knowledge acquired by the student. In the game-playing phase, both teacher and student were often absorbed in the game and rarely looked at each other's faces in any of the settings. In the teaching phase, however, we found a big difference in the patterns of focus shifting.

We observed the patterns of gaze, gesture, and speaking in each of the three teaching phases, and we found that there was considerably more shifting of focus between shared workspace and interpersonal space in ClearBoard-0 and ClearBoard-1 settings than when using the table. Figure 14 shows a coded transcript of the patterns of conversation, gesture, and gaze in sample 140-second segments in each setting. The experiment was designed to minimize random eye contact, and in finding that the pattern of eye contact varied markedly with the task, we are confident that it did not result from random glances.

In this experimental setting, the participants showed a greater incidence of eye contact and focus shift between shared workspace and interpersonal space with the ClearBoard technologies. There is a decrease with ClearBoard-1, perhaps because the partner's face is less clear than with ClearBoard-0, but the incidence is still considerably greater than the tabletop, where the separation of workspace and interpersonal space is greater. Of course, results from a single pair of subjects are more suggestive than definitive. Although the value of monitoring a partner's gaze direction seems clear, the uses of eye

Fig. 13. Gaze awareness in backgammon instruction with ClearBoard-0.

contacts in such settings are matters for further research. Nevertheless, this and other trials with ClearBoard have been very encouraging.

9. FUTURE WORK

We have described the designs and experiments of the shared-drawing media ClearBoard-1 and ClearBoard-2, which seamlessly integrate shared workspace and interpersonal space. Many interesting technical and behavioral issues remain to be investigated.

Fig. 13. Continued.

9.1 Multiuser and Multipoint ClearBoard

One interesting design question is how to extend the ClearBoard concept to support multiple users and multiple points. Although we originally designed ClearBoard-2 for a pair of users, often two or three users gathered in front of a terminal and worked together with remote users. The larger screen size of ClearBoard-2 allows multiple users to join a ClearBoard-2 session comfortably. We think the use of wall-size screens will make ClearBoard-2 a practical multiuser medium with which to connect two distributed meeting rooms. ClearBoard-2 extensions will support the simultaneous use of multiple elec-

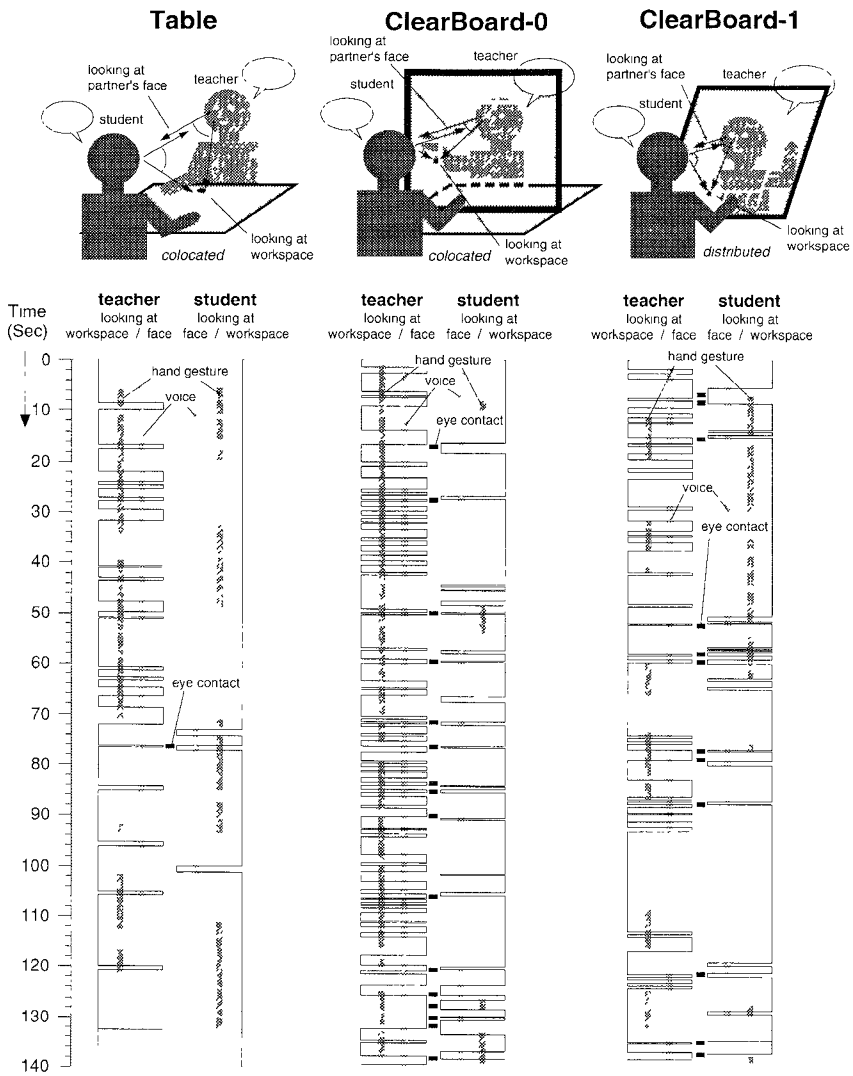


Fig. 14. Time chart of gaze, gesture, and speaking patterns in backgammon-teaching phase

tronic pens at each terminal for this purpose. TeamPaint software will also be extended to support multiple inputs that correspond to multiple pens at each computer.

How to extend ClearBoard to connect three or more points is a more challenging question. Severe technical and usability limitations prohibit us from overlaying many more video images. The metaphor of ClearBoard is to connect two distributed spaces through a virtual glass board; to support three or more points seems to require a major change in the metaphor itself. In multiuser and multipoint situations, it is more difficult to know who is watching whom, and eye contact confusion is a potential problem. Hydra, designed by Buxton, provides an ingenious solution to this multiuser gaze problem in multipoint video conferencing, although it does not provide a shared workspace [Buxton 1992]. We are exploring ways to extend the ClearBoard metaphor seamlessly to support multiple users at more than two points without losing its simplicity and the virtue of gaze awareness.

9.2 New Display Technology

Implementation of the ClearBoard prototypes convinced us that the invention of new display technologies is critical for the wide acceptance of the ClearBoard concept. For example, the multiuser ClearBoard-2 indicates the need for wall-size flat display technology with the following functions:

(1) to display the overlaid image of computer screen and the video at very high resolution and with enough brightness for ordinary office environments;
(2) to input concurrent gestures of drawing and pointing at display surfaces with multiple electronic pens; and
(3) to capture a bright video image of users in front of the display surface.

To implement the prototypes described in this article, we used a variety of commercially available components, such as half-silvered mirrors, polarizing films, transparent digitizer sheets, video overlay boards, video projectors, and video cameras. We manually integrated them into a system based on the new architecture we had invented. However, the limitation of this approach is apparent. We feel it is necessary to start from the electronic engineering design of a new device that satisfies the display requirements just described.

Bitmap displays played a crucial role in the development of GUI (Graphical User Interface); head-mounted displays did the same for VR (Virtual Reality). We expect ClearBoard to provide a new goal for display technologies that may change our concept of a wall from being a passive partition to being a dynamic collaboration medium.

9.3 Interpersonal Distance

Interpersonal distance is an interesting issue in the ClearBoard design. Edward T. Hall studied interpersonal distance and developed the categories of *intimate distance* (0–18 inches or 0–46 cm), *personal distance* (1.5–4 feet, 46–122 cm), *social distance* (4–12 feet, 1.22–3.66 m), and *public distance* (more than 12 feet, 3.66 m) [Hall 1966].

ClearBoard creates the impression of participants standing about *one meter* apart, because both sit (or stand) close enough to the screen to draw directly on its surface. This virtual distance belongs to the *personal distance* in Hall's classification. When people use ClearBoard with close friends or colleagues, this distance seems appropriate. However, for a formal meeting with a person of much higher rank, this virtual interpersonal distance might seem too small, and the participants might be uncomfortable. Therefore, we would like the media to provide users with some control over the virtual interpersonal distance. We are planning to provide an option of indirect drawing using a wireless tablet or pen-based personal computer for that purpose.

9.4 Studies of Visual Behavior

Interpersonal distance is an example of a behavioral issue that can be explored using ClearBoard technology and that will be important in governing how it is received and used. We have noted that awareness of gaze direction is potentially very important. This has clear uses in identifying the context for spoken remarks and gestures. More ambiguous is the role of direct eye contact. ClearBoard makes eye contact easy to establish and may even make it more difficult to avoid. It has been shown that the use of eye contact varies with the culture (for example, Argyle [1975]); these are issues for further exploration in ClearBoard settings.

Another important behavioral issue is that of visual attention in the context of overlaid images. For example, it has been shown that while people can selectively attend to one of two overlaid visual images, they may have trouble monitoring two unrelated images even when they try to do so [Neisser and Becklen 1975]. ClearBoard presents two images in the context of an overarching task; how that will affect behavior remains to be explored. Depth is another variable to be considered. In ClearBoard-0, the shared workspace and the partner were at different focal planes. The subsequent ClearBoard prototypes place both images on the same focal plane.[7]

We are planning to study visual behavior further in the context of overlaid images. Existing work on the roles of visual attention and eye contact indicate the need for further research into the effects of facilitated eye contact and gaze awareness provided by these technologies.

10. CONCLUSION

We have described the design of the novel collaboration media ClearBoard-1 and ClearBoard-2. These media seamlessly integrate a shared workspace and interpersonal space, and transitions of focus between the spaces are smooth. ClearBoard is based on the metaphor of talking through and drawing on a transparent glass window, while providing a common right-left orientation.

Our studies suggest that ClearBoard realizes *gaze awareness*, which includes eye contact and monitoring the partner's direction of gaze. Gaze awareness may be crucial to the next generation of collaboration media and is a potentially useful capability that CSCW technology can greatly enhance. ClearBoard offers a means to further explore the role of eye contact and gaze awareness in collaborative work, by making them possible in new situations

[7] Kobayashi and Ishii [1992] are developing a new display technology called "DispLayers" that can place multiple video images on different focal planes using multiple liquid crystal screens. A user can see the composite of all video images at different distances We plan to use the DispLayers technology to place the drawing image and the partner's image on different focal planes and to study the effect of selective attention in a ClearBoard environment.

that are amenable to study. The use of gaze awareness is reported by athletes, teachers, and others, who may position themselves to take advantage of it. How extensive its use is and when eye contact might be disruptive are topics for exploration. Our observation that eye contact occurred more often in instruction than in competing suggests that there will be differences and also suggests that ClearBoard users can avoid eye contact when it is not needed. Our users did not report disruptive eye contact, but in some situations it could be an issue.

We see the evolution from ClearBoard-1 to ClearBoard-2 as being very important. Computer and video communication technologies have, until now, evolved independently. Although they have been loosely coupled using arbitrary multiwindow interfaces in many desktop multimedia conferencing systems, they have never been integrated seamlessly from the users' cognitive point of view. We feel ClearBoard-2 is the first system that fully succeeds in naturally integrating the technology of computer-based groupware with that of video conferencing. We expect that the seamless integration of computer and video communication technologies will realize the next generation of collaboration media.

Moreover, ClearBoard-2 can be seen as one instance of the paradigm shift from traditional HCI (Human-Computer Interaction) to HHI (Human-Human Interaction mediated by computers). We are interacting not *with* computers, but *through* computers. ClearBoard design is not only "beyond being there" [Hollan and Stornetta 1992] but also a step beyond the traditional desktop metaphor based on a multiwindow interface. We expect ClearBoard to be useful both as a collaboration medium and as a vehicle to investigate the nature of dynamic human interaction.

ACKNOWLEDGMENT

William Buxton at the University of Toronto must be mentioned for his stimulating discussions with Ishii on the shared workspace/interpersonal space framework. We thank Naomi Miyake at Chukyo University for her insightful comments on the role of gaze and her participation in the river-crossing experiments on ClearBoard-1. We thank Saul Greenberg at the University of Calgary for his detailed comments to a draft of this article. Thanks are also due to A. Sasaki and Y. Hanamoto for their collaboration in developing TeamPaint software, and to Takaya Endo and Takahiko Kamae for supporting this research.

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Received January 1993; accepted July 1993