A Review of Tele-collaboration Technologies with Respect to Closely Coupled Collaboration*

Robin Wolff[†], Dave J. Roberts[†], Anthony Steed[°] and Oliver Otto[†]
[†]The Centre for Virtual Environments, University of Salford, UK
[°]Department of Computer Science, University College London, UK

Abstract

Globalisation and an increasingly multi-disciplinary collaboration drive the need for efficient ways to collaborate within distant teams. Although existing computer-supported cooperative work (CSCW) systems, such as collaborative video-conferencing and shared desktops, are suitable for certain tasks, most of these systems have two major deficiencies. First they support the situation of face to face meetings poorly. With a few exceptions, they use a desktop metaphor and this metaphor loses many of the subtleties of interpersonal communication since this does not model or represent the spatial relationships of the participants. Second, again because of the imposition of a desktop metaphor, many systems deal badly with data sets and workspaces that are inherently 3D in nature. What is missing is the ability to naturally gesture towards and manipulate the objects of discussion, and to observe the body language of the collaborators in the spatial context that it is responsive to. Thus, we lose subtle gestures such as gaze being drawn to an object of common interest, or gaze being used by a speaker to indicate whom they want to speak next as they finish speaking.

This article serves two purposes. Firstly, it outlines the requirements for a class of CSCW tools that would focus on supporting closely coupled collaborative activity around shared

*Wolff, R., Roberts, D. J., Steed, A. & Otto, O., "A Review of Tele-collaboration Technologies with Respect to Closely Coupled Collaboration." To appear in International Journal of Computer Applications in Technology (IJCAT), Special Issue on: "Collaborative Multimedia Applications in Technology", Inderscience Publishers, Geneve, Switzerland, ISSN 0952-8091, 2005, (in press).

objects. These requirements include the ability to refer to a common model of the shared space through speech and gesture and for each person to be able to manipulate objects within that space. Secondly, this article describes the current state of the art in collaborative technologies with a critique of how well they support the required collaborative activities. These technologies span the range from audio conferencing through to spatially immersive (CAVE^{TM}-like) displays (SID). Essentially the article suggests that as of today only through collaborative virtual environment (CVE) based on SIDs are we close to being able to achieve the seamless collaboration that exists in a face to face meeting.

1 Introduction

The need for greater efficiency within and between both research and industrial teams leads many organisations to deploy one or more computer-supported collaborative work (CSCW) tools, such as groupware or video-conferencing. Supporting collaboration, however, is very complex. A group of people may need to interact in a number of ways. Ellis et al. (42) categorised group interactions according to a time/location matrix, illustrated in Figure 1. Within this matrix, a distinction is made between same time (synchronous) and different times (asynchronous), and between same place (face-to-face) and different places (distributed). The taxonomy reflects the diversity of closeness of coupling and of geographical spread within teamwork. This article particularly focuses on distributed synchronous teamwork.

Figure 1: Group interaction time/location matrix by Ellis et al. (42).

	Same Time	Different Times
Same Place	face−to−face interaction	asynchronous interaction
Different Places	synchronous distributed interaction	asynchronous distributed interaction

Tele-collaboration technologies have greatly reduced the need for co-located team meetings. Many teamwork tasks, however, rely on spatially oriented interactions around shared physical artefacts. Although some technologies, such as video-conferencing, can communicate the existence of gesture, posture and facial expression, they do not accurately reflect the potential target of the action or the relationship of the target to the viewer. For example, someone may gesture to a target that is off screen, as such systems do not usually integrate shared data within the collaborative space. Other systems, such as AccessGrid (AccessGrid), combine video streaming of participants with shared data applications, but people and data are separated and it is impossible to reference them without reverting to a shared cursor, thus losing some of the naturalness of the conversation.

Many issues have been studied extensively in the CSCW domain (58; 89; 103; 141). Research interests within this domain concern multi-user interfaces, concurrency control, shared information space and the support of a heterogeneous, open environment which integrates existing single-user applications. The primary key issues of CSCW are communication and coordination within the group, and group awareness (125). A persistent and important problem when collaborating over a distance is the delay or interruption within collaborative sessions (41; 64; 106). Recent work has additionally indicated significant deficiencies and problems in supporting social awareness between collaborators (23; 110; 116; 126; 136).

This article reviews work related to close collaboration over a distance in the scope of shared object manipulation. Current technologies are reviewed and compared with respect to their support offered for the two key factors of close collaboration: synchronous object sharing and the communication of references. In the following section we describe the requirements for closely coupled collaboration. In Section 3, we review the technologies that support such collaborations, which is followed by a discussion and the conclusion of the article.

2 Closely Coupled Collaboration around Shared Object Interaction

Much of collaborative work is based on conversational tasks or simple transactions of data, while others may require complex interaction between the team member and shared data. Some tasks may even explicitly require the team to tightly interact with shared physical artefacts. Often, it is not only necessary for the team to work closely around the objects, but also to communicate efficiently which object attribute is under discussion. The task may require object attributes to be explored through shared manipulations in real-time. It may take several iterations of manipulations and discussions to reach a common objective opinion. Throughout this process it is often necessary for the participants to build trust, to see nuances of how people react to changes due to the manipulation, to efficiently communicate their own opinion and to collaboratively interact with objects until agreement is found. In order to satisfy such needs for a distributed team, it seems reasonable that tele-collaboration technology should convey attention, interaction and emotion with reference to others, shared objects and the environment.

Whilst CSCW deals with collaboration in general, where key issues are communication, coordination and group awareness; this article focuses particularly on the situation of close collaboration around shared objects between team members at remote locations, where these key issues map to communication of references, coordination of shared object manipulation and a feeling of co-presence.

2.1 Communication of References

A large part of communication between humans occurs verbally, but in a co-located scenario, facial expressions, gaze, pointing, posture, gestures, and physical distance to others provide additional communication channels (119). Furthermore, shared objects and the environment around the participants can be used for communication. When collaborating, individuals rely on the gathering, incorporation and utilisation of environmental information to help them combine their unique knowledge and achieve their goals (126). Observational studies in the design sector found that thinking often depends upon and exploits physical artefacts (24; 77). People use objects to inspire, explain, demonstrate or evaluate. These objects may be handled directly or simply referred to through verbal and non-verbal means. Gergle et al. (54) present an empirical study that demonstrates how action replaces explicit verbal communication in a shared visual workspace. They found the communication of references to be essential for finding common ground when working with objects.

Communication may occur between two peers or in one-to-many or many-to-many relations (100). Instruction, for example, is primarily a one-to-many communication with real-time feedback. An instructor needs to communicate concepts and respond to questions and feedback while doing so, whereas the students consciously or unconsciously indicate their level of awareness or understanding. Democratic decision making in a boardroom meeting, on the other hand, occurs through many-to-many communication, where each of the participants must be able to demonstrate strength of opinion to all other participants. The most intense communication often occurs between two individuals. Many collaborations will combine these relations across the duration of the collaboration process.

2.2 Shared Object Manipulation

Shared object manipulation is the simultaneous action of modifying an object through its attributes, such as position or colour. Margery et al. (81) categorised cooperative tasks within virtual environments into three levels: users perceiving and communicating with each other within a shared environment; individual manipulations of the contents of a scene; and simultaneous manipulations on a shared object. Considering the timing of interactions, one can identify two classes of shared object manipulation: sequential and concurrent manipulation. Sequential manipulation occurs when attributes are modified in sequence, whereas concurrent manipulation occurs when attributes are modified simultaneously. Ruddle et al. (105) and Roberts et al. (101) distinguish further between scenarios where simultaneous actions are independent and co-dependent. Independent actions are those where distinct object attributes are modified. Co-dependent actions are modifications of the same object attribute. An example of independent action is when two people are together painting an object where one person controls the position attribute by holding the material in place, while another controls the colour attribute by painting it. An example of concurrent manipulation is the joint lifting of heavy object where the position attribute is dependent on both participants' actions.

To coordinate shared manipulation of common objects, it is essential to get a feedback of the effects of interactions with the objects, as well as of the actions and intentions of other participants. In many cases, a visual feedback that reflects the modification and can be perceived by all participants is sufficient as a response to an action. An aural feedback is often supportive, as it relaxes the requirement for visually focusing on the area of action (140). Recent studies, have shown that haptic (force) feedback significantly improves task performance and feeling of co-presence of the participants during shared object manipulation in virtual environments (12; 108). Shared object manipulation puts also high requirements on real-time response and consistency on the mediating tele-collaboration system.

2.3 Shared Context

Sharing the manipulation of objects requires a level of proximity between collaborators and objects within a shared workspace. Often, a level of mobility within the workspace is necessary in order to manipulate objects, or to reference towards attributes in a cluttered scene, in particular when working around large objects. In CSCW this is often echoed in the discussions of sharing of "place", rather than space, to emphasise in particular the sharing of context (94).

In CSCW, it has long been recognised that an awareness of the action of other participants is a fundamental feature in supporting cooperative work (38; 59; 104; 125). A commonly applied model for formalising awareness between objects and people is the spatial model using focus and nimbus (13; 104). Focus refers to the perception of actions and intentions of other people, as well as objects and the environment. In contrast, nimbus refers to the effect oneself has towards others through communication and articulation of actions, intentions or opinions, as well as the effects on objects or the environment. Thus, within scenarios of close collaboration around shared objects, awareness is supported by sharing both *social context* between collaborators, and *spatial context* between collaborators and the shared objects and environment.

Literature in the field of tele-collaboration often mentions the notion of presence and co-presence (111; 147). Although clear definitions and metrics for presence and co-presence have not yet been found (115; 128; 48), the term co-presence is often used to refer to the extent to which people have a feeling of “being there with them together” and that the interface becomes transparent, rather than their interaction being mediated by a computer interface (122). In this article, co-presence is seen as the perception of spatial and social togetherness between remote people when collaborating around shared objects.

2.4 Challenges

In order to satisfy the above needs of closely coupled collaboration around shared objects, tele-collaboration technology must convey interaction, attention and awareness with reference to others, shared objects and the environment. State of the art technologies should further offer a way of synchronously manipulating shared objects, as well as communicating references towards object attributes. The ultimate goal is to bring people together and to allow close collaboration as natural as in a co-located meeting.

2.4.1 Togetherness

When manipulating objects together, such as moving a large table, objects are synchronously shared. These objects must be both perceivable and reachable for all collaborators at the same time. This requires a level of spatial proximity within the environment between the participants and the manipulated object in a way that either collaborators are brought close to the objects or vice versa. Benford et al. (14) characterised shared-space systems in terms of the degree of spatiality, as it indicates the level of detail of mutual referencing between remote people. Additionally, the requirement for natural communication of referencing and pointing towards object attributes, implies a level of freedom and mobility, and thus the ability to move around objects and access them from any angle. Furthermore, efficient collaboration relies upon the two collaborators having compatible mental models of the task. The richness and utility of this model will be limited by the communication medium. Togetherness can be assessed on the extent of which successful exploitation of both social context (collaborator to collaborator) and spatial context (collaborators to objects and environment) can be achieved.

2.4.2 Naturalness

Naturalness of interactions is likely to increase performance, because people do not need to compensate for the technology, allowing the users to concentrate more on the task, not the interface. In some cases, specific interactions with objects and between team members may be enhanced through abstract interaction techniques or may be guided by pre-defined work-flows. On the other hand, mediating every-day groupwork tasks through tele-collaboration technology is likely to be more efficient when the task can be performed as natural and intuitively as in a co-located scenario. Poston and Serra (95) illustrate how natural referencing is intuitively preferred:

> "In the abstract, a mouse cursor seems far better than a finger, pointing more precisely at a point in the monitor screen. In practice, every screen has fingermarks." (95, p 39)

3 Tele-collaboration Technologies

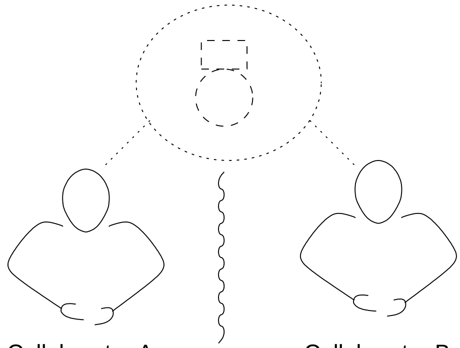
Many technologies have been established to support distant teamwork. To gain a better overview of the field, this section will provide an introductory review of current tele-collaboration technologies within the scope of closely coupled collaboration around shared objects. This survey does not intend to cover all the types of technologies in detail. The aim is to estimate to what extent the various technologies actually support closely coupled collaboration of a distributed group cooperating through shared objects. Particular interest is put towards the clarification of the extent to which shared, natural object manipulation is supported; to what extent natural non-verbal communication is supported; and finally, to what extent the sharing of spatial and social context can be perceived.

3.1 Audio-conferencing

The telephone is the most ubiquitous tool for communication today. Audio-conferencing technologies (2) span both fixed and mobile telephony services and Internet-based audio tools. Figure 2 a) illustrates an example scenario. Audio-only media are known to show limitations in supporting essential social cues (82; 118). As illustrated in Figure 2 b), people cannot see each other, and thus, interactions and social awareness are limited to what can be communicated verbally. Gestures and other non-verbal cues, such as posture, facial expressions and proxemics, are not transmitted. Conversations are difficult without established or agreed mechanisms for managing turn-talking. Additionally, audio-conferencing does not offer direct sharing of anything, but the audio properties of objects. ‘Sharing’ occurs only mentally through verbal discussion of the object properties. Therefore, the shared manipulation of objects, other than abstract ideas, is not supported. Although, the participants are aware of each other, the feeling of being together is very low.

Figure 2: Tele-collaboration through audio-conferencing.

(a) Two participants in an audio-conference.



(b) Concept of sharing space and data.

3.2 Groupware

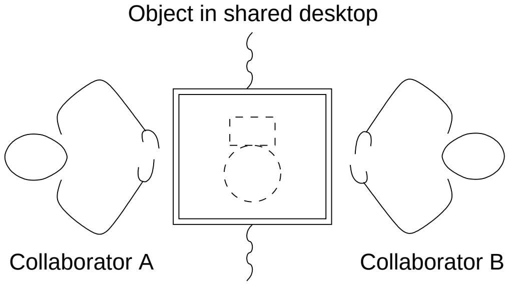
With the term groupware (42) we refer to window-based collaborative applications used on desktop computers. Groupware commonly provides a form of shared 2D desktop accessible for a group of people over a network. Conversational interaction is supported via text messages and sometimes live audio channels. Examples include application software, such as BSCW (137), JASMINE (37; 107), as illustrated in Figure 3 a), or Meeting Central (145).

The primary advantage over phone-conferencing is that groupware allows the sharing of objects. This is achieved through methods such as shared document handling and transactions or shared whiteboards. The concept of collaborating through groupware is illustrated in Figure 3 b).

Two primary problems have been identified: Firstly, groupware appears to commonly force the user's work into a "work-flow" (1) scheme. This is useful for guidance and coordination based on specific processes. However, it does not allow informal interactions or object manipulations that may be necessary to react to irregular actions within the team (4; 83). Most systems allow only asynchronous manipulations, which are often unnatural interactions through the desktop interface. Synchronous object manipulation is rarely supported. Secondly, users of groupware have noted limitations in perceiving an

Figure 3: Tele-collaboration through groupware.

(a) The JASMINE multimedia tele-collaboration system (Oliveira et al., 2003).



(b) Concept of sharing space and data.

awareness of the actions of others (18; 104; 110). While collaborating through groupware, actions of the participants can be tracked in change-logs or visualised in real-time with a shared cursor on the shared desktop. A limitation of groupware, however, is that communication of non-verbal cues is not well supported. Although some methods exist to capture a set of gesturing in shared desktops (43; 84), many studies and evaluations have shown limitations in a natural communication between remote people.

In summary, when collaborating through groupware systems, the feeling of working together is often low and natural communication, as well as natural object manipulations are very limited. Recent developments attempt to provide an understanding of awareness requirements within groupware systems (59), as well as add features for better communicating awareness, through gaze for example (139).

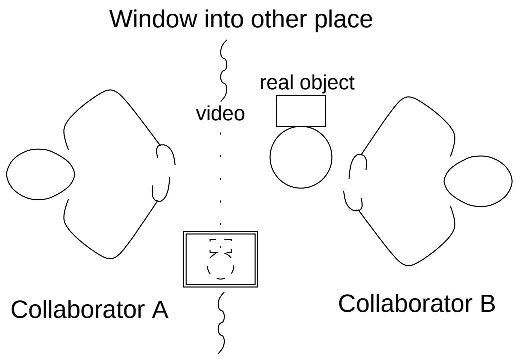
3.3 Video-conferencing

Video-conferencing allows multiple remote people to participate in a tele-conference by exchanging live audio and video data between remote sites (68; 88). Nowadays, many instant messaging software integrates audio and video transmission features free of charge. Together with low-cost web-cameras, tele-conferences can be set up quickly on any desktop computer in an office. A popular video-conferencing in the scientific area is Access-

Grid (AccessGrid), illustrated in Figure 4 a). The sharing of data and objects may be provided by merging groupware tools with video-conferencing technology (27; 53). The shared data is commonly displayed along with the video of remote collaborators in adjacent windows on one display. Additionally, physical objects may be located on one side, so that remote people may observe through video how a collaborator naturally demonstrates or references attributes of the actual object. Figure 4 b) illustrates this concept.

Figure 4: Tele-collaboration through video-conferencing.

(a) Typical AccessGrid session.



(b) Concept of sharing space and data.

The transmission of video signals enables face-to-face conversations between participants. Non-verbal cues, such as gesturing, can be transmitted via video, as long it is in the viewing field of the camera. This feature showed clear improvement over audio-only conferencing for acquiring common ground and trust (67; 72). Gaver (51), however, notes that the shared place in video-conferencing is significantly different than that from actual face-to-face meetings. The feeling of co-presence is low in that collaborators do not spatially share a space. Video-conferencing technology can be described as a ‘window’ into remote places occupied by other group members. Another problem often experienced is turn-taking in conversations. This is known already from audio-conferencing and often caused by delays in the transmission (106). As remote collaborators are often arranged on a single screen, the lack of gaze contributes to this problem (47).

Furthermore, when compared to face-to-face meetings, many users have found difficulties in noticing peripheral cues, pointing towards things or manipulating real-world objects

(67; 75; 76). The support for natural pointing or referencing of object details through non-verbal communication is limited, and is often only possible by holding objects into the camera. Efforts have been made to set up several cameras pointing at workspaces and artifacts forming so-called media-spaces (50). However, conventional video does not offer depth perception through stereo-vision and few cameras capture a high enough level of detail over a wide enough field of view to support a broad range of possible depth cues over a wide space. Cameras are mostly fixed in position and orientation and, thus, only offer limited range of exploration and mobility within the workspace (143).

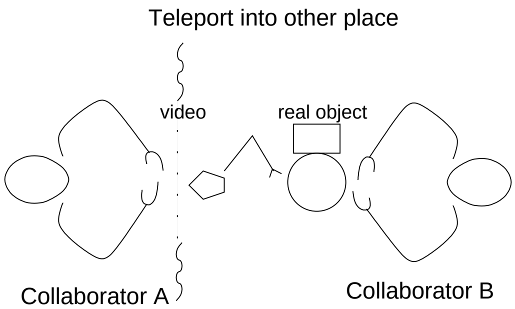
Recent development efforts in the field of video-conferencing try to increase the support of gesturing, for example by drawing gestures on tablet PCs (91), and gaze, for example through additional interfaces, such as head-mounted cameras with eye-tracker and scene oriented video (47) or separate cameras and windows per collaborator (113). One can also see a trend focusing toward 3D, as for example AGJuggler (56), a toolkit on top of AccessGrid, in which spatial information about participants is considered. A promising approach are semi-immersive tele-conferencing systems such as the “Office of the Future” by Raskar et al. (97) and variations (10; 34; 71; 127; 144), in which video is captured from various angles and integrated into a graphical three-dimensional environment.

3.4 Tele-presence

A related technology to video-conferencing is tele-operation, or tele-presence. The aim of tele-presence is to ‘teleport’ a person to a remote place, rather than providing a fixed ‘window’ as in conventional video-conferencing (31; 66). Sheridan (114) describes tele-presence as a “sense of being physically present with virtual objects at the remote tele-operator site.” Tele-presence was initially developed for application areas, such as hazardous exploration or remote inspection and operation, for example (3). Some developments concentrate on the support for human communication and interaction, and thus are suitable for remote collaboration. This is often achieved through a mobile platform with bi-directional audio and video support, as a tele-embodiment of the remote operator (69; 93), as illustrated in Figure 5 a). This is achieved by merging video-conferencing technology with tele-robotics, so that a local machine acts on behalf of the remote controlling person (146). One could describe this as a mobile 'window with hands'. Figure 5 b) shows a sketch of the concept of how the space and objects are shared.

Figure 5: Tele-collaboration through tele-presence.

(a) Tele-presence using PRoP (Paulos and Canny, 2001)



(b) Concept of sharing space and data.

Along with verbal communication via audio channels, non-verbal communication in form of gestures or gaze, may be realised through either video or controlled movements of parts of the robot (76). However, although a spatial context may be shared through tele-operation technology, and thus peripheral interaction with shared objects is given, the the level of sharing the manipulation of artifacts offered to the remote operator is limited and depend on the features of the robot.

In summary, the social separation, and thus co-presence, is lower than the previous technologies in respect to a spatial context. However, the naturalness of interaction with the remote participants is limited by the human realism of the robot. Apart from using robots to represent a remote human, other approaches make use of actuated environments to create a level of ambient presence and informal awareness about remote people through physical, "smart" objects integrated within the local workspace (17; 52; 96; 134).

3.5 Collaborative Mixed Reality

Milgram and Fumio (85) use the term “Mixed Reality” (MR) to refer to a large class of display technologies that span a continuum between completely real and completely virtual. A completely real environment solely consists of real objects that may be perceived either directly or through a window or (video) display. In contrast, a completely virtual environment consists solely consists of synthetic objects, such as computer graphics. A MR environment in which real and virtual objects may be perceived lies somewhere in between these extremes, for example (14; 29). The following sections will look closer at augmented and virtual reality.

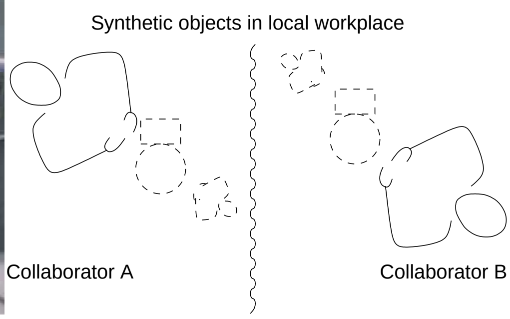
3.5.1 Distributed Collaborative Augmented Reality

Augmented reality (AR), aims to enhance the real world with virtual objects (8; 86). A user of AR usually wears a see-through head-mounted display (HMD) perceiving synthetic 3D objects overlaid on the surrounding real environment. In conjunction with motion tracking interfaces, this technology allows natural interactions with synthetic objects. A group of co-located people may share a set of projected virtual objects in a common place and manipulate them together (26; 109).

Collaboration between remote people is commonly enabled through additional videoconferencing technology (11; 20). The advantage of using AR technology is that remote collaborators and shared objects can be integrated into the actual workplace, and thus the remote is merged with the local workplace, as illustrated in Figures 6 a) and b). A stronger effect of co-presence can be achieved. However, limits in supporting non-verbal communication are inherited from videoconferencing, if not captured otherwise by a tracking system.

Figure 6: Tele-collaboration through augmented reality.

(a) Remote participants projected into local workspace (Billinghurst and Kato, 2002).



(b) Concept of sharing space and data.

3.5.2 Collaborative Desktop-based Virtual Reality

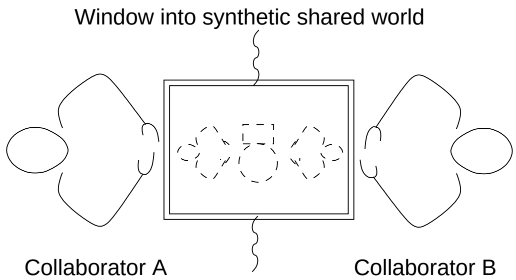
Virtual reality (VR) can be defined as a set of interfaces providing the sensory experience, which immerses the user in a completely synthetic environment (85). Such a "virtual" environment usually consists of computer generated geometric objects or other media, such as documents or video, inhabiting a three-dimensional space and may provide spatial sound or haptic (touch) feedback. Distributed VR system endpoints may be inter-connected with a collaborative virtual environment (CVE) software system and audio-conferencing tools. CVE systems allow a number of remote people to share the context of the virtual environment and to interact with each other and the inhabiting objects (15; 35; 120). Well documented CVE systems include: DIVE (33; 46; 45), NPSNET (80) and MASSIVE (57).

The difference to groupware and video-conferencing systems is that CVE systems offer "space-based presence", as they bring remote people together into a spatial proximity (21; 44). Typically, a human-like synthetic character (avatar) represents each remote participant within a CVE (16), as illustrated in Figure 7 a). This is seen to create a feeling of presence (39; 60; 124). Figure 7 b) shows the concept of collaborating through desktop CVE systems.

Many users of CVE systems who interact through desktop interfaces, however, still ex-

Figure 7: Tele-collaboration through desktop virtual reality.

(a) The Virtual Gazebo (Roberts, 2003) on a desktop system.



(b) Concept of sharing space and data.

perienced limitations in the support of non-verbal communication due to the limited field of view and the lack of natural avatar representation, as well as the lack of naturalness of object interactions (102; 129). Hindmarsh et al. (65) linked this to the fragmentation of activity caused by the low field of view offered by desktop interfaces and difficulties in communicating referencing towards objects.

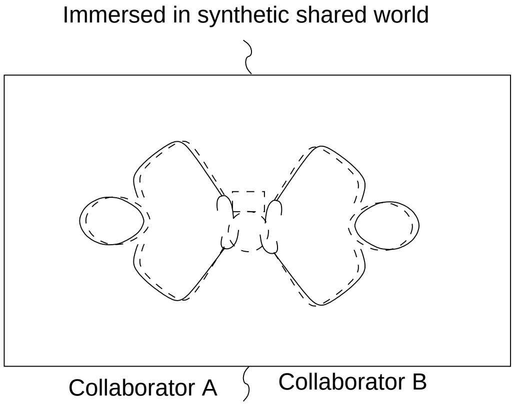
3.5.3 Collaborative Immersive Virtual Reality

In the VR field, there exist two primary classes of immersive displays: head mounded display (HMD) and spatially immersive display (SID). In contrast to desktop display systems and large flat or curved screens that may display three-dimensional graphics based on a user's tracked viewpoint, immersive displays provide a surrounding imagery of a virtual environment. The difference is that users are *inside*, rather than *in front* of the 3D environment (74). Body movement, often just head and dominant hand, is continuously tracked, allowing both conscious and subconscious non-verbal communication to be captured and mapped onto the tracked person's avatar. Figure 8 a) shows an example of a local user (left) collaborating with a remote participant (avatar on the right), while b) illustrates the concept of sharing space and objects using collaborative immersive VR technology.

Traditionally, HMDs have offered a low field of view that has been associated with motion

Figure 8: Tele-collaboration through immersive virtual reality.

(a) The Virtual Gazebo (Roberts, 2003) in a SID.



(b) Concept of sharing space and data.

sickness (6; 70), and reduction in the feeling of presence (63). This is likely to impact on observing and following the awareness, attention and actions in the periphery of view. The other class of immersive displays are those that spatially surround the user with fixed screens, rather than following the head movement. The most common form of SID is based on the CAVE^{TM}(36) principle.

It has been shown that within a tracked, stereo, real-time environment, a user's ability to comprehend large-scale data is substantially improved (92; 135; 138). Several studies have investigated the effect of linking various combinations of display systems for collaboration. Leigh et al. (79) present an overview of collaboration in immersive tele-collaboration (tele-immersion) applications. Many of these applications have had a significant impact on their respective fields and provided effective collaboration. In a study by Mortensen et al. (87), where a pair of remote participants was required to negotiate the task of handling a stretcher object together and moving a few meters into a building, it was found that co-presence was significantly and positively correlated with task performance. Heldal et al. (63) showed in a comparative study that SID devices seem to support object-focused interaction in a very efficient manner. Very few disturbances of the form as reported by Hindmarsh et al. (65) were seen. Another study by Heldal et al. (61, 62) the authors investigated the effect of display type on collaboration through combinations of SID, HMD and desktop systems, and compared this to a face-to-face setting.

The primary finding was that immersed users felt more present and were more effective than non-immersed users, as well as that asymmetric settings can lower these benefits. In related studies (7; 121; 132), based on a similar experimental task, it has been found that immersed users naturally adopted dominant roles versus desktop users. Steed et al. (133) conducted a study, in which subjects collaborated over an extended period of time through cubic surround screens. The authors found that subjects collaborated intuitively and the networked environment lent itself particularly well to highly spatial and highly interactive tasks. Roberts et al. (101) have demonstrated an increased task performance within closely coupled collaborative tasks when interacting through a SID device. The natural interaction has enabled novice users to adapt their task performance of that expert users within just three test runs.

4 Discussion

The previous section has reviewed a number of tele-collaboration technologies. All have shown advantages and disadvantages in regard to supporting close interaction. The features reached by means from simply ‘connecting remote people’, over ‘projecting people into remote sites’, up to ‘placing people into a common virtual space’. As documented in the sections above, failures and limits of these technologies for supporting distant work have long been noted. Many studies have shown limitations in supporting highly interactive tasks in a natural manner. A common critique of users is the lack of social and situational awareness within the collaborating team. Two primary problems can be identified: a spatial separation between team and data when sharing the manipulation of objects; and limitations in communicating mediating non-verbal communication. An overview of the extent of supporting closely coupled collaboration that may be achieved using the reviewed technologies is summarised in Table 1.

Conventional video-conferencing is commonly found to naturally support aspects of face-to-face communication, as it communicates a high fidelity and highly faithful image of

Table 1: Extent of supporting closely coupled collaboration through tele-collaboration technologies.

Technology	Shared Object Manipulation	Communication of references	Shared spatial context	Shared social context	Mobility within the shared space
Audio-conferencing	not supported	not supported	separated	separated	not supported
Groupware	unnatural	unnatural	separated	separated	not supported
Video-conferencing	unnatural	natural	separated	partially shared	limited
Tele-presence	unnatural	unnatural	fully shared	partially shared	unlimited
Augmented Reality	natural	natural	partially shared	partially shared	unlimited
Desktop-based CVE	unnatural	unnatural	fully shared	partially shared	unlimited
Immersive CVE	natural	natural	fully shared	partially shared	unlimited

the face. However, these systems show limitations in close collaboration around shared objects, in that they suffer from a spatial separation between collaborators and shared objects, and they restrict movement within the space. Collaborative virtual environments bring shared objects and remote people together into a spatial and social proximity by means of VR interfaces. This can increase closeness and naturalness within interactions, and thus allows better communicating awareness, attention and interaction in an unconstrained space. In the presented review of related work, it has been shown that linking immersive VR interfaces enables the communication of important cues such as referencing, gestures or proxemics. Leigh et al. (78) note that, relative to other tele-collaborative technologies, such as groupware and video-conferencing, using immersive VR technology for remote collaboration is found to provide the closest emulation of physical co-location possible. Very strong scientific evidence supports this view that VR works (induces presence), because it triggers exactly the same perceptive mechanisms as reality (123, p. 26).

The primary advantage of using SID systems is that the user is aware of his own body movement in relation to the environment through the linked senses of vision, proprioception (the feeling of one's body state), and sometimes haptics (force feedback) implying self-haptics, which matches proprioception. While users of desktop or HMD interfaces see only a virtual body (if represented at all), users of SID interfaces feel and see their own body. Hence, linking of vision and proprioception is not affected by technology, as it is in other display types (5; 30; 63). Additionally, spatially surrounding the users in data, not only improves the sense of immersion, but enables the use of both their focal (or central) vision and their peripheral vision. The wide field of view encourages natural head and body movement for both focused and general observation. This allows for a better understanding of the three-dimensional structure of the dataset, as well as the spatial scale of features within it. Further, natural body movement may be used to walk around an object, move the body and head to examine it from every angle, manipulate it with the hand and interact naturally with remote users. A significant characteristic is that subconscious gestures, such as gaze or gesturing with the hand during conversations, are also communicated between distributed team members (99).

Nevertheless, a particular technology may not necessarily be the best choice for all types of applications. A study by Axelsson et al. (7), for example, showed in a collaborative molecular visualisation task that, although the perceived co-presence was higher and communication found to be slightly more natural within a SID, collaboration between the pairs was found to be higher when using desktop display systems. Bowman et al. (22) found that HMD may be better suited than SID systems in applications involving navigation through enclosed spaces and frequent turning, as the direct mapping of surrounding imagery head movements detected by head tracking increases efficiency and spatial orientation to users. Steed and Parker (130) found that performance on selection tasks is much better on a SID than a HMD, while manipulation tasks show only little differences between the two immersive display technologies. Brooks noted in his review of the state of the art in virtual environments, an important task in the field of VR is "choosing which display best fits each application" (28, p 27).

5 Conclusion

Remote collaboration and distant teamwork have become a strategic factor for many organisations. Supporting social awareness about the actions of others within closely coupled collaboration is an important feature that many tele-collaboration technologies miss. Conventional technologies lack effective support for close collaboration around shared objects between remote people. The essential requirements of close collaboration, shared object manipulation and natural communication of references, are often limited or not supported.

The overview we have presented suggests that linked immersive display technology will be of great benefit to spatially unconstrained tele-collaboration, especially where users collaborate around shared information artefacts. Immersive display devices place a user in a spatial and social context allowing natural first person observations of remote users while interacting with objects. This is shown to improve human communication and the collaborative work within such an environment. It has been shown that, especially in spatially immersive surround screen displays (SID), the remote users increase their feeling of co-presence and team performance, compared to those of HMD and desktop displays.

Much research has been done in the sector of remote collaboration through SID interfaces. Many have recognised the advantages of using this technology. There are, however, still issues that need to be addressed. The four most significant challenges that remain for in future systems are (1) supporting consistent synchronous object manipulations between remote sites; (2) the feeling of touch when interacting with virtual objects; (3) a more realistic representation of human embodiments; and (4) integrating tele-collaboration technology into workplaces.

Early research (25) has shown that concurrent remote interaction with a shared object was not possible with CVE technology in 1995, as sharing the manipulation of objects over a distance put high requirements on the underlying software platform maintaining responsive interaction and a consistent shared state. Clearly, consistency control affects the responsiveness, as well as throughput in terms of fidelity, of a distributed interactive system. This problem is well known as the "consistency-throughput trade-off" (19; 120). Hence, the ultimate goal is to find a sufficient balance between throughput and consistency above user requirements. A study of the characteristics of supporting shared object manipulation and communication of references (142) have shown how immersion increases the processing load for the underlying software platform. Shirmohammadi and Georganas (117) present an architecture that allows timely-reliable communication of vital key messages within the interaction stream while supporting tightly-coupled collaborative tasks. Task-oriented consistency control (98) may help to better balance the requirements of both responsiveness and consistency based on situational requirements.

The sense of touch obviously plays a unique and important role in human interaction. Many people complain about the lack of feeling weight or other forms of force feedback when manipulating objects in virtual environments. It further appears that touching and manipulating objects in virtual environments increases the general sense of presence (12; 40). Kim et al. (73) successfully demonstrate a handshake with force feedback over a network connection across the Atlantic. A related study (90) documents the technical challenges related to supporting responsive interaction with haptic devices and noted performance issues when implementing force feedback in a conventional CVE system. Seelig et al. (112) have shown how some of these issues may be overcome by using dedicated resources for haptic rendering and the virtual environment.

Steed et al. (131) suggest that much more of the subtle non-verbal behaviour of users needs to be captured or simulated in order to have collaborative interactions that are more similar to those in the real world. Most of the current immersive tele-collaboration systems represent the participants as a computer generated character (avatar) within the virtual environment, as it is difficult to map live video of a participant into a dynamic 3D environment. Increasing the realism in representing synthetic humans is found to have an impact on proxemics, and thus the way how people deal with avatars (9; 122). Articulated human-like figures have proven well in representing the actions of remote people

(32). Additionally, facial impressions or eye gaze may be represented through an avatar to increase realism, which is found to impact on the user's impression (49).

In the next few years we expect that advances in real-time computer vision capture systems will rapidly remove the problem of realistic representations. Video avatars can provide high level of detail and realism to faithfully reflect actions and emotions of participants and their interactions with objects. The required mobility and accuracy when manipulating objects, however, makes it difficult to capture live video of collaborators and mapping this into a dynamic 3D environment in real-time without disturbing the interaction itself. Using multiple cameras, as for example the Blue-C (127), behind a switching semi-transparent screen of an immersive display in a way so that the interacting user is captured from various angles. Besides the advantages, current SID systems are expensive, large and time-consuming to set up. Future systems eventually have to be cheap and deployable in the office environment. Examples of pioneering research in this area are the "Office of the Future" system (97) or the TelePort system (55) that make use of full-wall display surfaces, "merging" of real and virtual environments, viewer tracking, and real-time compositing of live video with synthetic backgrounds and surfaces within the actual workspace.

Acknowledgements

The authors would like to thank Emmanuel Frécon at the Swedish Institute of Computer Science and Information Technology in Sweden for fundamental ideas and thoughts. Special thanks to Dieter Kranzlmüller and Christoph Anthes at the Institute of Graphics and Parallel Processing of the Johannes Kepler University in Linz, Austria, as well as Vassil Alexandrov and Ali Al-Khalifah at the Department of Computer Science of the University of Reading in UK for collaboration and discussions. Special thanks also to Ralph Schroeder at the Department of Technology and Society at Chalmers University in Sweden for fruitful discussions. Thanks also to Maria Limniou of the Chemistry Department of Aristotle University of Thessaloniki, Greece.

References

[1] Abbott, K. R. and Sarin, S. K. (1994). Experiences with workflow management: issues for the next generation. In *CSCW '94: Proceedings of the 1994 ACM conference on Computer supported cooperative work*, pages 113–120, New York, NY, USA. ACM Press.

[AccessGrid] AccessGrid. http://www.accessgrid.org.

[2] Ackerman, M. S., Starr, B., Hindus, D., and Mainwaring, S. D. (1997). Hanging on the 'wire: A field study of an audio-only media space. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 4(1):39–66.

[3] Ansar, A., Rodrigues, D., Desai, J. P., Daniilidis, K., Kumar, V., and Campos, M. F. (2001). Visual and haptic collaborative tele-presence. *Computers and Graphics*, 25(5):789–798.

[4] Antunes, P., Guimarães, N., Segovia, J., and Cardenosa, J. (1995). Beyond formal processes: Augmenting workflow with group interaction techniques. In *COCS '95: Proceedings of Conference on Organizational Computing Systems*, pages 1–9, New York, NY, USA. ACM Press.

[5] Arnold, P. and Farrell, M. J. (2003). Embodiment and spatial behavior in virtual environments: Comments on durlach et al. (2000). *Presence: Teleoperators and Virtual Environments*, 12(6):658–662.

[6] Arthur, K. (1996). Effects of field of view on task performance with head-mounted displays. In *Human Factors in Computing Systems*, pages 29–30, Vancouver, Canada.

[7] Axelsson, A.-S., Abelin, Å., Heldal, I., Nilsson, A., Schroeder, R., and Wideström, J. (1999). Collaboration and communication in multi-user virtual environments: A comparison of desktop and immersive virtual reality systems for molecular visualization. In *Sixth UKVRSIG Conference*, pages 107–117, Salford University. Terence Fernando (ed.).

[8] Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, 6(4):1–38.

[9] Bailenson, J., Beall, A., Blascovich, J., Weisbuch, M., and Raimmundo, R. (2001). Intelligent agents who wear your face: Users reactions to the virtual self. In *Lecture Notes in Artificial Intelligence*, pages 86–99.

[10] Baker, H. H., Bhatti, N., Tanguay, D., Sobel, I., Gelb, D., Goss, M. E., MacCormick, J., Yuasa, K., Culbertson, W. B., and Malzbender, T. (2003). Computation and performance issues in coliseum: An immersive videoconferencing system. In *MULTIMEDIA '03: Proceedings of the eleventh ACM international conference on Multimedia*, pages 470–479, New York, NY, USA. ACM Press.

[11] Barakony, I., Frieb, W., and Schmalstieg, D. (2003). Augmented reality videoconferencing for collaborative work. Presented at the 2nd Hungarian Conference on Computer Graphics and Geomtery, Budapest, Hungary, May.

[12] Basdogan, C., Ho, C.-H., Srinivasan, M. A., and Slater, M. (2000). An experimental study on the role of touch in shared virtual environments. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 7(4):443 – 460.

[13] Benford, S. and Fahlén, L. E. (1993). A spatial model of interaction in large virtual environments. In *3rd European Conference on Computer Supported Cooperative Working*, Millan, Italy.

[14] Benford, S., Greenhalgh, C., Reynard, G., Brown, C., and Koleva, B. (1998). Understanding and constructing shared spaces with mixed-reality boundaries. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 5(3):185–223.

[15] Benford, S., Greenhalgh, C., Rodden, T., and Pycock, J. (2001). Collaborative virtual environments. *Communications of the ACM*, 44(7):79–85.

[16] Benford, S. D., Bowers, J. M., Fahlén, L. E., Greenhalgh, C. M., and Snowdon, D. N. (1997). Embodiments, avatars, clones and agents for multi-user, multi-sensory virtual worlds. *Multimedia Systems*, 5(2):93–104.

[17] Bentley, F., Tollmar, K., Demirdjian, D., Koile, K., and Darrell, T. (2003). Perceptive presence. *IEEE Computer Graphics and Applications*, 23(5):26–36.

[18] Berlage, T. and Sohlenkamp, M. (1999). Visualizing common artefacts to support awareness in computer-mediated cooperation. *Computer Supported Cooperative Work*, 8(3):207–238.

[19] Bhola, S., Banavar, S., and Ahmad, M. (1998). Responsiveness and consistency tradeoffs in interactive groupware. In *the seventeenth annual ACM Symposium on Principles of Distributed Computing*, pages 324–334, Puerto Vallarta, Mexico. ACM Press New York, NY, USA.

[20] Billinghurst, M. and Kato, H. (2002). Collaborative augmented reality. *Communications of the ACM*, 45(7):64–70.

[21] Bowers, J., O'Brien, J., and Pycock, J. (1996). Practically accomplishing immersion: Cooperation in and for virtual environments. In *CSCW '96: Proceedings of the 1996 ACM conference on Computer supported cooperative work*, pages 380–389, New York, NY, USA. ACM Press.

[22] Bowman, D., Datey, A., Ryu, Y., Farooq, U., and Vasnaik, O. (2002). Empirical comparison of human behavior and performance with different display devices for virtual environments. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, pages 2134–2138.

[23] Bradner, E. and Mark, G. (2002). Why distance matters: effects on cooperation, persuasion and deception. In *CSCW '02: Proceedings of the 2002 ACM Conference on Computer Supported Cooperative Work*, pages 226–235, New York, NY, USA. ACM Press. isbn 1-58113-560-2.

[24] Brereton, M. and McGarry, B. (2000). An observational study of how objects support engineering design thinking and communication: Implications for the design of tangible media. In *CHI '00: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 217–224, New York, NY, USA. ACM Press.

[25] Broll, W. (1995). Interacting in distributed collaborative virtual environments. In *VRAIS '95: Proceedings of the Virtual Reality Annual International Symposium*, pages 148–155, Washington, DC, USA. IEEE Computer Society.

[26] Broll, W., Meier, E., and Schardt, T. (2000). The virtual round table - a collaborative augmented multi-user environment. In *CVE '00: Proceedings of the Third International Conference on Collaborative virtual Environments*, pages 39–45, New York, NY, USA. ACM Press.

[27] Brooke, J., Eickermann, T., and Woessner, U. (2003). Application steering in a collaborative environment. In *SC '03: Proceedings of the 2003 ACM/IEEE conference on Supercomputing*, page 61, Washington, DC, USA. IEEE Computer Society.

[28] Brooks, F. P. (1999). Whats real about virtual reality? *IEEE Computer Graphics and Applications*, 19(6):16–27.

[29] Brown, B., MacColl, I., Chalmers, M., Galani, A., Randell, C., and Steed, A. (2003). Lessons from the lighthouse: Collaboration in a shared mixed reality system. In *CHI '03: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 577–584, New York, NY, USA. ACM Press.

[30] Burns, E., Razzaque, S., Panter, A. T., Whitton, M. C., McCallus, M. R., and Frederick P. Brooks, J. (2005). The hand is slower than the eye: A quantitative exploration of visual dominance over proprioception. In *VR '05: IEEE Virtual Reality*, pages 3–10. IEEE.

[31] Buxton, W. A. S. (1992). Telepresence: Integrating shared task and person spaces. In *Proceedings of the Conference on Graphics Interface '92*, pages 123–129, San Francisco, CA, USA. Morgan Kaufmann Publishers Inc.

[32] Capin, T. K., Pandzic, I. S., Magnenat-Thalmann, N., and Thalmann, D. (1999). *Avatars in Networked Virtual Environments*. Wiley.

[33] Carlsson, C. and Hagsand, O. (1993). Dive - a platform for multi-user virtual environments. *Computers and Graphics*, 17(6):663–669.

[34] Chen, W.-C., Towles, H., Nyland, L., Welch, G., and Fuchs, H. (2000). Toward a compelling sensation of telepresence: Demonstrating a portal to a distant (static) office. In *VIS '00: Proceedings of the Conference on Visualization '00*, pages 327–333, Los Alamitos, CA, USA. IEEE Computer Society Press.

[35] Churchill, E. F., Snowdon, D., and Munro, A. J. (2001). *Collaborative Virtual Environments. Digital Places and Spaces for Interaction*. Springer Verlag.

[36] Cruz-Neira, C., Sandin, D. J., and DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: The design and implementation of the cave. In *SIGGRAPH '93: Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques*, pages 135–142, New York, NY, USA. ACM Press.

[37] de Oliveira, J. C., Hosseini, M., Shirmohammadi, S., Malric, F., Nourian, S., Saddik, A. E., and Georganas, N. D. (2003). Java multimedia telecollaboration. *IEEE MultiMedia*, 10(3):18–29.

[38] Dourish, P. and Bellotti, V. (1992). Awareness and coordination in shared workspaces. In *CSCW '92: Proceedings of the 1992 ACM Conference on Computer-Supported Cooperative Work*, pages 107–114, New York, NY, USA. ACM Press.

[39] Draper, J. V., Kaber, D. B., and Usher, J. M. (1998). Telepresence. *Human Factors*, 40(3):354–375.

[40] Durlach, N. and Slater, M. (2000). Presence in shared virtual environments and virtual togetherness. *Presence: Teleoperators and Virtual Environments*, 9(2):214 – 217.

[41] Egido, C. (1988). Video conferencing as a technology to support group work: a review of its failures. In *CSCW '88: Proceedings of the 1988 ACM conference on Computer Supported Cooperative Work*, pages 13–24, New York, NY, USA. ACM Press.

[42] Ellis, C. A., Gibbs, S. J., and Rein, G. (1991). Groupware: Some issues and experiences. *Communications of the ACM*, 34(1):39–58.

[43] Everitt, K. M., Klemmer, S. R., Lee, R., and Landay, J. A. (2003). Two worlds apart: Bridging the gap between physical and virtual media for distributed design collaboration. In *CHI '03: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 553–560, New York, NY, USA. ACM Press.

[44] Fahlén, L. E., Brown, C. G., Ståhl, O., and Carlsson, C. (1993). A space based model for user interaction in shared synthetic environments. In *CHI '93: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 43–48, New York, NY, USA. ACM Press.

[45] Frècon, E. (2003). DIVE: A programming architecture for the prototyping of IIS. In Snowdon, D. and Churchill, E. F., editors, *Inhabited Information Systems*, pages 211–231. Springer-Verlag.

[46] Frécon, E., Smith, G., Steed, A., Stenius, M., and Ståhl, O. (2001). An overview of the coven platform. *Presence: Teleoperators and Virtual Environments*, 10(1):109 – 127.

[47] Fussell, S. R., Setlock, L. D., and Kraut, R. E. (2003). Effects of head-mounted and scene-oriented video systems on remote collaboration on physical tasks. In *CHI '03: Proceedings of the SIGCHI Conference on Human factors in Computing Systems*, pages 513–520, New York, NY, USA. ACM Press.

[48] Garau, M. (2003). The impact of avatar fidelity on social interaction in virtual environments. PhD thesis, University College London.

[49] Garau, M., Slater, M., Vinayagamoorthy, V., Brogni, A., Steed, A., and Sasse, M. A. (2003). The impact of avatar realism and eye gaze control on perceived quality of communication in a shared immersive virtual environment. In *CHI 2003*, volume 5 (1), Ft. Lauderdale, Florida, USA.

[50] Gaver, W., Sellen, A., Heath, C., and Luff, P. (1993). One is not enough: Multiple views in a media space. In *InterCHI '93: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 335–341, New York. ACM Press.

[51] Gaver, W. W. (1992). The affordances of media spaces for collaboration. In *CSCW '92: Proceedings of the 1992 ACM Conference on Computer Supported Cooperative Work*, pages 17–24, New York, NY, USA. ACM Press.

[52] Gellersen, H.-W. and Beigl, M. (1999). Ambient telepresence: Colleague awareness in smart environments. In Nixon, P., Lacey, G., and Dobson, S., editors, *MANSE '99: International Workshop on Managing Interactions in Smart Environments*, pages 80–88. Springer Verlag, London.

[53] George Chin, J. and Lansing, C. S. (2004). Capturing and supporting contexts for scientific data sharing via the biological sciences collaboratory. In *CSCW '04: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, pages 409–418, New York, NY, USA. ACM Press.

[54] Gergle, D., Kraut, R. E., and Fussell, S. R. (2004). Action as language in a shared visual space. In *CSCW '04: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, pages 487–496, New York, NY, USA. ACM Press.

[55] Gibbs, S. J., Arapis, C., and Breiteneder, C. J. (1999). Teleport- towards immersive copresence. *Multimedia Systems*, 7(3):214–221.

[56] Gonzalez, D. A. (2005). Agjuggler: An architecture for virtual reality within a collaboration environment. Master's thesis, Purdue University, West Lafayette, IN 47907, USA.

[57] Greenhalgh, C. M. and Benford, S. D. (1995). Massive: A virtual reality system for tele-conferencing. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 2(3):239–261.

[58] Greif, I. (1988). *Computer Supported Cooperative Work: A Book of Readings*. Morgan Kaufmann.

[59] Gutwin, C. and Greenberg, S. (2002). A descriptive framework of workspace awareness for real-time groupware. *Computer Supported Cooperative Work*, 11(3):411–446.

[60] Heeter, C. (1992). Being there: the subjective experience of presence. *Presence: Teleoperators and Virtual Environments*, 1(2):262–271.

[61] Heldal, I., Schroeder, R., Steed, A., Axelsson, A., Spante, M., and Wideström, J. (2005a). Immersiveness and symmetry in copresent scenarios. In *VR '05: Presented at the IEEE Virtual Reality 2005 Conference*, pages 171–178.

[62] Heldal, I., Steed, A., and Schroeder, R. (2005b). Evaluating collaboration in distributed virtual environments for a puzzle-solving task. Presented at HCI International 2005, the 11th International Conference on Human Computer Interaction, Las Vegas. Heldal I., Steed A., Schroeder R., "Evaluating Collaboration in Distributed Virtual Environments for a Puzzle-solving Task", HCI International 2005, the 11th International Conference on Human Computer Interaction, 22-27 July 2005, Las Vegas.

[63] Heldal, I., Steed, A., Spante, M., Schroeder, R., Bengtsson, S., and Partanan, M. (2005c). Successes and failures in co-present situations. *Presence: Teleoperators and Virtual Environments*, 14(5):(in press).

[64] Herbsleb, J. D., Mockus, A., Finholt, T. A., and Grinter, R. E. (2000). Distance, dependencies, and delay in a global collaboration. In *CSCW '00: Proceedings of the 2000 ACM Conference on Computer Supported Cooperative Work*, pages 319–328, New York, NY, USA. ACM Press.

[65] Hindmarsh, J., Fraser, M., Heath, C., Benford, S., and Greenhalgh, C. (2000). Object-focused interaction in collaborative virtual environments. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 7(4):477–509.

[66] Hollan, J. and Stornetta, S. (1992). Beyond being there. In *CHI '92: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 119–125, New York, NY, USA. ACM Press.

[67] Isaacs, E. and Tang, J. C. (1994). What video can and cannot do for collaboration. *Multimedia Systems*, 2:63–73.

[68] Johansen, R. (1984). *Teleconferencing and Beyond: Communications in the Office of the Future*. McGraw-Hill.

[69] Jouppi, N. P. (2002). First steps towards mutually-immersive mobile telepresence. In *CSCW '02: Proceedings of the 2002 ACM Conference on Computer Supported Cooperative Work*, pages 354–363, New York, NY, USA. ACM Press.

[70] Kalawsky, R. S. (1993). Physiology of visual perception. In *The Science of Virtual Reality and Virtual Environments*, pages 44–68. Addison-Wesley.

[71] Kauff, P. and Schreer, O. (2002). An immersive 3d video-conferencing system using shared virtual team user environments. In *CVE '02: Proceedings of the 4th International Conference on Collaborative Virtual Environments*, pages 105–112, New York, NY, USA. ACM Press.

[72] Kethers, S., Hargreaves, D., and Wilkinson, R. (2004). Remote meetings between farmers and researchers: A case study on asymmetry. In *CSCW '04: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, pages 624–627, New York, NY, USA. ACM Press.

[73] Kim, J., Kim, H., Tay, B. K., Muniyandi, M., Srinivasan, M. A., Jordan, J., Mortensen, J., Oliveira, M., and Slater, M. (2004). Transatlantic touch: a study of haptic collaboration over long distance. *Presence: Teleoperators and Virtual Environments*, 13(3):328–337.

[74] Kjeldskov, J. (2001). Interaction: Full and partial immersive virtual reality displays. In *IRIS24*, pages 587–600.

[75] Kraut, R. E., Miller, M. D., and Siegel, J. (1996). Collaboration in performance of physical tasks: Effects on outcomes and communication. In *CSCW '96: Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*, pages 57–66, New York, NY, USA. ACM Press.

[76] Kuzuoka, H., Oyama, S., Yamazaki, K., Suzuki, K., and Mitsuishi, M. (2000). Gestureman: a mobile robot that embodies a remote instructor's actions. In *CSCW '00: Proceedings of the 2000 ACM conference on Computer supported cooperative work*, pages 155–162, New York, NY, USA. ACM Press.

[77] Larsson, A. (2003). Making sense of collaboration: The challenge of thinking together in global design teams. In *GROUP '03: Proceedings of the 2003 International ACM SIGGROUP Conference on Supporting Group Work*, pages 153–160, New York, NY, USA. ACM Press.

[78] Leigh, J., Johnson, A., Brown, M., Sandin, D. J., and DeFanti, T. A. (1999a). Visualization in teleimmersive environments. *Computer*, 32(12):66–73.

[79] Leigh, J., Johnson, A., and DeFanti, T. (1999b). A review of tele-immersive applications in the cave research network. In *IEEE VR '99*, pages 180–187, Houston, TX.

[80] Macedonia, M. R., Zyda, M. J., Pratt, D. R., Barham, P. T., and Zeswitz, S. (1994). Npsnet: A network software architecture for large-scale virtual environment. *Presence: Teleoperators and Virtual Environments*, 3(4):265–287.

[81] Margery, D., Arnaldi, B., and Plouzeau, N. (1999). A general framework for cooperative manipulation in virtual environments. In Gervautz, M., Hildebrand, A., and Schmaltsieg, D., editors, *Virtual Environments '99*, pages 169–178. Springer Verlag.

[82] Mark, G., Grudin, J., and Poltrock, S. E. (1999). Meeting at the desktop: An empirical study of virtually collocated teams. In *ECSCW'99: Sixth European Conference on Computer Supported Cooperateive Work*. Kluwer Academic Publishers.

[83] Markus, M. L. and Connolly, T. (1990). Why cscw applications fail: Problems in the adoption of interdependent work tools. In *CSCW '90: Proceedings of the 1990 ACM Conference on Computer Supported Cooperative Work*, pages 371–380, New York, NY, USA. ACM Press.

[84] Matsushita, N. and Rekimoto, J. (1997). Holowall: designing a finger, hand, body, and object sensitive wall. In *UIST '97: Proceedings of the 10th annual ACM symposium on User interface software and technology*, pages 209–210, New York, NY, USA. ACM Press.

[85] Milgram, P. and Fumio, K. (1994). A taxonomy of mixed reality displays. *IEICE Transactions on Information Systems*, E77-D(12).

[86] Milgram, P., Takemura, H., Utsumi, A., and Kishino, F. (1995). Augmented reality: A class of displays on the reality-virtuality continuum. In *Proceedings of SPIE Volume: 2351, Telemanipulator and Telepresence Technologies*, pages 282–292. Hari Das, Jet Propulsion Lab.

[87] Mortensen, J., Vinayagamoorthy, V., Slater, M., Steed, A., Lok, B., and Whitton, M. C. (2002). Collaboration in tele-immersive environments. In *Proceedings of the workshop on Virtual environments 2002*, pages 93 – 101, Barcelona, Spain. Eurographics Association Aire-la-Ville, Switzerland, Switzerland.

[88] Nardi, B. A., Schwarz, H., Kuchinsky, A., Leichner, R., Whittaker, S., and Sclabassi, R. (1993). Turning away from talking heads: The use of video-as-data in neurosurgery. In *CHI '93: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 327–334, New York, NY, USA. ACM Press.

[89] Neale, D. C., Carroll, J. M., and Rosson, M. B. (2004). Evaluating computer-supported cooperative work: Models and frameworks. In *CSCW '04: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, pages 112–121, New York, NY, USA. ACM Press.

[90] Oliveira, M., Mortensen, J., Jordan, J., Steed, A., and Slater, M. (2002). The pitfalls in system design for distributed virtual environments: A case study. Presented at the International Workshop on Immersive Telepresence, Juan Les Pin.

[91] Ou, J., Fussell, S. R., Chen, X., Setlock, L. D., and Yang, J. (2003). Gestural communication over video stream: Supporting multimodal interaction for remote collaborative physical tasks. In *ICMI '03: Proceedings of the 5th International Conference on Multimodal Interfaces*, pages 242–249, New York, NY, USA. ACM Press.

[92] Patrick, E., Cosgrove, D., Slavkovic, A., Rode, J. A., Verratti, T., and Chiselko, G. (2000). Using a large projection screen as an alternative to head-mounted displays for virtual environments. In *CHI '00: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 478–485, New York, NY, USA. ACM Press.

[93] Paulos, E. and Canny, J. (2001). Social tele-embodiment: Understanding presence. *Autonomous Robots 11*, pages 87–95.

[94] Pekkola, S. (2002). Critical approach to 3d virtual realities for group work. In *NordiCHI '02: Proceedings of the Second Nordic Conference on Human-Computer Interaction*, pages 129–138, New York, NY, USA. ACM Press.

[95] Poston, T. and Serra, L. (1996). Dextrous virtual work. *Communications of the ACM*, pages 37–45. issn 0001-0782, publisher ACM Press.

[96] Prante, T., Stenzel, R., Röcker, C., van Alphen, D., Streitz, N. A., Magerkurth, C., and Plewe, D. A. (2004). Connecting remote teams: Cross-media integration to support remote informal encounters. Presented at the Sixth International Conference on Ubiquitous Computing (UBICOMP '04), Nottingham, England, September 7-10.

[97] Raskar, R., Welch, G., Cutts, M., Lake, A., Stesin, L., and Fuchs, H. (1998). The office of the future: A unified approach to image-based modeling and spatially immersive displays. In *SIGGRAPH '98: Proceedings of the 25th Annual Conference on Computer Graphics and Interactive Techniques*, pages 179–188, New York, NY, USA. ACM Press.

[98] Roberts, D. and Wolff, R. (2004). Controlling consistency within collaborative virtual environments. In *The Eighth IEEE International Symposium on Distributed Simulation and Real Time Applications, DS-RT 2004*, pages 46–52.

[99] Roberts, D., Wolff, R., Otto, O., Kranzlmueller, D., Anthes, C., and Steed, A. (2004). Supporting social human communication between distributed walk-in displays. In ACM, editor, *VRST 2004*, pages 81–88.

[100] Roberts, D. J. (2003). Communication infrastructures for inhabited information spaces. In Snowdon, D. and Churchill, E. F., editors, *Inhabited Information Systems*, pages 233–268. Springer-Verlag.

[101] Roberts, D. J., Wolff, R., and Otto, O. (2003). Constructing a gazebo: Supporting team work in a tightly coupled, distributed task in virtual reality. *Presence: Teleoperators and Virtual Environments*, 12(6):644–668.

[102] Robinson, M., Pekkola, S., Korhonen, J., Hujala, S., Toivonen, T., and Saarinen, M.-J. (2001). *Extending the Limits of Collaborative Virtual Environments*, pages 21–42. Springer Verlag.

[103] Rodden, T. (1991). A survey of cscw systems. *Interacting with Computers*, 3(3):319–353.

[104] Rodden, T. (1996). Populating the application: A model of awareness for cooperative applications. In *CSCW '96: Proceedings of the 1996 ACM conference on Computer Supported Cooperative Work*, pages 87–96, New York, NY, USA. ACM Press.

[105] Ruddle, R., Savage, J., and Jones, D. (2002). Symmetric and asymmetric action integration during cooperative object manipulation in virtual environments. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 9(4):285–308.

[106] Ruhleder, K. and Jordan, B. (1999). Meaning-making across remote sites: How delays in transmission affect interaction. In *Proceedings of the Sixth European Conference on Computer Supported Cooperative Work*, pages 411–429, Norwell, MA, USA. Kluwer Academic Publishers.

[107] Saddik, A. E., Shirmohammadi, S., Georganas, N. D., and Steinmetz, R. (2000). Jasmine: Java application sharing in multiuser interactive environments. In *Proceedings of the 7th International Workshop on Interactive Distributed Multimedia Systems and Telecommunication Services*, pages 214–226.

[108] Sallnäs, E.-L., Rassmus-Gröhn, K., and Sjöström, C. (2000). Supporting presence in collaborative environments by haptic force feedback. *ACM Transactions on Computer-Human Interaction (ToCHI)*, 7(4):461–476.

[109] Schmalstieg, D., Fuhrmann, A., Hesina, G., Szalavári, Z., Encarnação, L. M., Gervautz, M., and Purgathofer, W. (2002). The studierstube augmented reality projects. *Presence: Teleoperators and Virtual Environments*, 11(1):33–54.

[110] Schmidt, K. (2002). The problem with 'awareness': Introductory remarks on 'awareness in cscw'. *Computer Supported Cooperative Work*, 11(3):285–298.

[111] Schuemie, M., der Straaten, P., M.Krijn, and der Mast, C. (2001). Research on presence in VR: a survey. *Cyberpsychology and Behavior*, 4(2):183–202.

[112] Seelig, M., Roberts, D., Harwin, W., Otto, O., and Wolff, R. (2004). A haptic interface for linked immersive and desktop displays: Maintaining sufficient frame rate for haptic rendering. In *17th International Conference on Parallel and Distributed Computing Systems (PDCS 2004)*, pages 478–483, San Francisco, CA, USA.

[113] Sellen, A., Buxton, B., and Arnott, J. (1992). Using spatial cues to improve videoconferencing. In *CHI '92: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 651–652, New York, NY, USA. ACM Press.

[114] Sheridan, T. B. (1992). Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments*, 1(1):120–126.

[115] Sheridan, T. B. (2000). Interaction, imagination and immersion some research needs. In *VRST '00: Proceedings of the ACM symposium on Virtual reality software and technology*, pages 1–7, New York, NY, USA. ACM Press.

[116] Shirmohammadi, S., de Oliveira, J. C., and Georganas, N. D. (1998). Applet-based telecollaboration: A network-centric approach. *IEEE Multimedia*, 5(2):64–73.

[117] Shirmohammadi, S. and Georganas, N. (2001). An end-to-end communication architecture for collaborative virtual environments. *Computer Networks Journal*, 35(2-3):351–36.

[118] Short, J., Williams, E., and Christie, B. (1976). *The Social Psychology of Telecommunications*. Wiley, New York.

[119] Short, J., Williams, E., and Christie, B. (1993). *Visual Communication and Social Interaction*, pages 153–164. Morgan Kaufmann.

[120] Singhal, S. and Zyda, M. (1999). *Networked Virtual Environments: Design and Implementation*. ACM Press.

[121] Slater, M., Sadagic, A., Usoh, M., and Schroeder, R. (2000). Small group behaviour in a virtual and real environment: A comparative study. *Presence: Teleoperators and Virtual Environments*, 9(1):37–51.

[122] Slater, M. and Steed, A. (2002). Meeting people virtually: Experiments in shared virtual envrionments. In Schroeder, R., editor, *The Social Life of Avatars*, pages 145–171. Springer-Verlag.

[123] Slater, M., Steed, A., and Chrysanthou, Y. (2001). *Computer Graphics and Virtual Environments: From Realism to Real-Time*. Addison Wesley Publishers.

[124] Slater, M. and Usoh, M. (1993). The influence of a virtual body on presence in immersive virtual environments. In *Virtual Reality International 93: Proceedings of the third annual conference on Virtual Reality*, pages 34–42. Meckler.

[125] Sohlenkamp, M. and Chwelos, G. (1994). Integrating communication, cooperation, and awareness: The diva virtual office environment. In *CSCW '94: Proceedings of the 1994 ACM Conference on Computer Supported Cooperative Work*, pages 331–343, New York, NY, USA. ACM Press.

[126] Sonnenwald, D. H., Maglaughlin, K. L., and Whitton, M. C. (2004). Designing to support situation awareness across distances: an example from a scientific collaboratory. *Information Processing & Management*, 40(6):989–1011.

[127] Spagno, C. P. and Kunz, A. M. (2003). Construction of a three-sided immersive telecollaboration system. In *IEEE Virtual Reality 2003*, page 37, Los Angeles, CA.

[128] Spante, M., Heldal, I., Axelsson, A. S., and Schroeder, R. (2003). Is there a trade-off between presence and copresence? Presented at the 6th International Workshop on Presence, Aalborg, Denmark, October 6-8.

[129] Ståhl, O. (1999). Meetings for real-experiences from a series of vr-based project meetings. In *VRST '99: Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, pages 164–165, New York, NY, USA. ACM Press.

[130] Steed, A. and Parker, C. (2005). Evaluating effectiveness of interaction techniques across immersive virtual environment systems. *Presence: Teleoperators and Virtual Environments*, 14(5):(in press). MIT Press.

[131] Steed, A., Roberts, D., Schroeder, R., and Heldal, I. (2005). Interaction between users of immersion projection technology systems. Presented at HCI International 2005, the 11th International Conference on Human Computer Interaction, Las Vegas. A. Steed, D. Roberts, R. Schroeder, I. Heldal, "Interaction Between Users of Immersion Projection Technology Systems", HCI International 2005, the 11th International Conference on Human Computer Interaction, 22-27 July 2005, Las Vegas.

[132] Steed, A., Slater, M., Sadagic, A., Tromp, J., and Bullock, A. (1999). Leadership and collaboration in virtual environments. In *IEEE Virtual Reality*, pages 112–115. IEEE Computer Society.

[133] Steed, A., Spante, M., Schroeder, R., Heldal, I., and Axelsson, A. (2003). Strangers and friends in caves: An exploratory study of collaboration in networked ipt systems for extended periods of time. In *ACM SIGGRAPH 2003 Symposium on Interactive 3D Graphics*, Monterey, California, USA.

[134] Streitz, N., Prante, T., Rd'ż˝ker, C., van Alphen, D., Magerkurth, C., Stenzel, R., and Plewe, D. A. (2003). Ambient displays and mobile devices for the creation of social architectural spaces: Supporting informal communication and social awareness in organizations. In O'Hara, K., Perry, M., Churchill, E., and Russell, D., editors, *Public and Situated Displays: Social and Interactional Aspects of Shared Display Technologies*, pages 387–409. Kluwer.

[135] Tan, D. S., Gergle, D., Scupelli, P. G., and Pausch, R. (2004). Physically large displays improve path integration in 3d virtual navigation tasks. In *CHI '04: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 439–446, New York, NY, USA. ACM Press.

[136] Tollmar, K., Sandor, O., and Schömer, A. (1996). Supporting social awareness @work design and experience. In *CSCW '96: Proceedings of the 1996 ACM conference on Computer Supported Cooperative Work*, pages 298–307, New York, NY, USA. ACM Press.

[137] Trevor, J., Koch, T., and Woetzel, G. (1997). Metaweb: Bringing synchronous groupware to the world wide web. In John F. Hughes, Wolfgang Prinz, K. S., editor, *Proceedings of the Fifth European Conference on Computer-Supported Cooperative Work*, pages 65–80. Kluwer Academic Publishers.

[138] Tyndiuk, F., Lespinet-Najib, V., Thomas, G., and Schlick, C. (2004). Impact of large displays on virtual reality task performance. In *AFRIGRAPH '04: Proceedings of the 3rd International Conference on Computer Graphics, Virtual Reality, Visualisation and Interaction in Africa*, pages 61–65, New York, NY, USA. ACM Press.

[139] Vertegaal, R. (1999). The gaze groupware system: Mediating joint attention in multiparty communication and collaboration. In *CHI '99: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 294–301, New York, NY, USA. ACM Press.

[140] Watts, J. C., Woods, D. D., Corban, J. M., Patterson, E. S., Kerr, R. L., and Hicks, L. C. (1996). Voice loops as cooperative aids in space shuttle mission control. In *CSCW '96: Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*, pages 48–56, New York, NY, USA. ACM Press.

[141] Wilson, P. (1991). *Computer Supported Cooperative Work : An Introduction*. Intellect Books, Oxford, England Norwell, MA.

[142] Wolff, R., Roberts, D., and Otto, O. (2004). A study of event traffic during the shared manipulation of objects within collaborative virtual environments. *Presence: Teleoperators and Virtual Environments*, 13(3):251–262.

[143] Yamaashi, K., Cooperstock, J. R., Narine, T., and Buxton, W. (1996). Beating the limitations of camera-monitor mediated telepresence with extra eyes. In *CHI '96: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 50–57, New York, NY, USA. ACM Press.

[144] Yang, R., Nashel, A., and Towles, H. (2004). Interactive 3d teleconferencing with user-adaptive views. In *ETP '04: Proceedings of the 2004 ACM SIGMM Workshop on Effective Telepresence*, pages 50–51, New York, NY, USA. ACM Press.

[145] Yankelovich, N., Walker, W., Roberts, P., Wessler, M., Kaplan, J., and Provino, J. (2004). Meeting central: Making distributed meetings more effective. In *CSCW '04: Proceedings of the 2004 ACM Conference on Computer Supported Cooperative Work*, pages 419–428, New York, NY, USA. ACM Press.

[146] Zhai, S. and Milgram, P. (1992). Human-robot synergism and virtual telerobotic control. Published in Proc. Annual Meeting of Human Factors Association of Canada.

[147] Zhao, S. (2003). Toward a taxonomy of copresence. *Presence: Teleoperators and Virtual Environments*, 12(5):445–455.