FORUM

Constructing a Gazebo: Supporting Teamwork in a Tightly Coupled, Distributed Task in Virtual Reality

Abstract

Many tasks require teamwork. Team members may work concurrently, but there must be some occasions of coming together. Collaborative virtual environments (CVEs) allow distributed teams to come together across distance to share a task. Studies of CVE systems have tended to focus on the sense of presence or copresence with other people. They have avoided studying close interaction between users, such as the shared manipulation of objects, because CVEs suffer from inherent network delays and often have cumbersome user interfaces. Little is known about the effectiveness of collaboration in tasks requiring various forms of object sharing and, in particular, the concurrent manipulation of objects.

This paper investigates the effectiveness of supporting teamwork among a geographically distributed group in a task that requires the shared manipulation of objects. To complete the task, users must share objects through concurrent manipulation of both the same and distinct attributes. The effectiveness of teamwork is measured in terms of time taken to achieve each step, as well as the impression of users. The effect of interface is examined by comparing various combinations of walk-in cubic immersive projection technology (IPT) displays and desktop devices.

1 Introduction

Many team-related tasks in the real world center around the shared manipulation of objects. A group of geographically remote users can be brought into social proximity to interactively share virtual objects within a collaborative virtual environment (CVE). CVEs are used extensively to support applications as diverse as military training, online games, and social meeting places (Roberts, 2003).

Advances in immersive display devices are ensuring their acceptance in industry as well as research (Brooks, 1999). Natural body and head movement may be used to view an object from every angle within an immersive display. The object may be reached for and manipulated with the outstretched hand, usually through holding some input device. The feeling of presence, and particularly the naturalness of interaction with objects, may be improved when the user can see his own body in the context of the virtual environment. Immersive projection technology (IPT) projects images onto one or more screens. Walk-in IPT displays, such as a CAVE or ReaCTor, surround the user with interactive stereo im-

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ages, thus placing the body in a natural spatial context within the environment.

By linking walk-in immersive displays through a CVE infrastructure, a user may be physically situated within a virtual scene representing a group of remote users congregated around a shared object. This allows each team member to use their body within the space to interact with other members of the team and virtual objects. The spoken word is supplemented by nonverbal communication in the form of pointing to, manipulating, and interacting with the objects as well as turning to people, gesturing, and other forms of body language. This offers unprecedented naturalness of interaction and remote collaboration. As described in the related work subsection (1.2), for several years, CVEs have successfully supported representation of remote users and shared observation of interactive environments. For example, one person can manipulate an object while others observe. However, generally, they do not support closely coupled tasks, such as two people concurrently interacting with the same object.

This paper investigates concurrent interaction with shared objects by users of a variety of display system configurations. We describe two ways of sharing the manipulation of objects, that is, through the same and distinct attributes. An example application, requiring both these forms of concurrent manipulation, is introduced. Collaboration is measured within this application, both in terms of team performance and user perception.

1.1 Principles of Distribution in Collaborative Virtual Environments

A key requirement of virtual reality (VR) is the responsiveness of the local system. For example, delays in representing a perspective change following a head movement can lead to disorientation and feelings of nausea. A CVE system supports a potentially unlimited environment across a number of resource-bounded computers interconnected by a network that induces perceptible delays. To make a CVE attractive and productive to use, it must support interaction that is sufficiently intuitive, reactive, responsive, detailed, and consistent. A virtual environment is composed of objects, which may be brought to life through their behavior and interaction. Some objects will be static and have no behavior. Some will have behavior driven from the real world, such as users. Alternatively, object behavior may be procedurally defined in some computer program. Key goals of a CVE are to maximize responsiveness and scalability while minimizing latency. This is achieved through localization and scaling (Roberts, 2003). Localization replicates objects on machines local to users. Early systems replicated object states but not their behavior. Each state change to any object is sent across the network to every replica of that object. In more advanced systems, the load on the network may be reduced by communicating parametric behavior definitions from which states may be derived. Scaling limits the number and complexity of objects held on each machine and is generally driven by user interest (Greenhalgh, 1999).

1.2 Related Work

Various forms of interaction with shared objects have been considered. Four classes of shared behavior: autonomous behaviors, synchronized behaviors, independent interactions and shared interactions are introduced (Broll, 1997). A special case of shared interaction is the concurrent manipulation of a shared object, which was found not to be possible with the CVE technology that was available in 1995 (Broll, 1995). Advances in this technology, driven by applications such as games and military training, have addressed some of the shortcomings. These allow today's CVEs to support limited real-time sharing of objects. A virtual tennis game was played (Molet et al., 1999) in which the position attribute of the ball was shared sequentially between two sites. Prediction was shown to overcome the effect of network delays in a simple ball game between the United Kingdom and Germany (Roberts, Strassner, Worthington, & Sharkey, 1999). This included advanced ownership transfer to allow instantaneous exchange of a ball between players in competitive scenarios. The simulation interoperability standard (IEEE 1516.2, 2000) defined concurrency control that allows concurrent manipulation of distinct attributes of a given

Table 1. *Comparison to Schroeder et al. (2001)*

	Rubik's Cube	Gazebo
Sequential object sharing	Supported	Necessary
Concurrent object sharing	Counterproductive	Necessary
Sharing through distinct attributes	Not necessary	Necessary
Collaboration	Improves performance	Improves performance of all activities and is necessary for some
Human communication	Necessary: intent and action Supported: complex plans including responsibilities and steps	Necessary: intent, action, complex plans including roles, responsibilities, and steps
Team size	2	2/3

object. The implementation of advanced ownership transfer (Roberts, Richardson, Sharkey, & Lake, 1998) allowed control of an attribute to be passed to a remote user with little or no delay. The importance of haptic interfaces for collaborative tasks in virtual environments was investigated by Basdogan, Ho, Srinivasan, and Slater (2000). The authors state that finding a general solution to supporting various collaborative haptic tasks over a network may be "too hard." The authors made a distinction between concurrent and sequential interaction with shared objects, but this is not discussed further. As with Choi, Choi, and Ryew (1997), a spring model is used to overcome network latencies to support concurrent manipulation of a shared object. Causal surface manipulation allows two users to carry a shared object while hiding the effects of latency through gradual deformation (Ryan & Sharkey, 1998). For example, a wooden beam held between two users would bend as the local user moves, and then straighten as the remote user is seen to follow.

The DIVE system (Frécon & Stenius, 1998) is an established testbed for experimentation of collaboration in virtual environments and, after three major revisions, remains an effective benchmark. The COVEN project (Frécon, Smith, Steed, Stenius, & Stahl, 2001) undertook network trials of large-scale collaborative applications run over the DIVE CVE infrastructure. This produced a detailed analysis of network-induced behavior in CVE applications (Greenhalgh, Bullock, Frécon, Lloyd, & Steed, 2001). DIVE was ported to CAVE-like display systems (Steed, Mortensen, & Frécon, 2001), and consequently an experiment on a non-coupled interaction task with two users in different walk-in displays was found to be very successful (Schroeder et al., 2001). Another application was implemented above DIVE that investigated the carrying of a stretcher by allowing the material to follow the handles (Mortensen et al., 2002). The work concludes that, although the Internet-2 has sufficient bandwidth and levels of latency to support joint manipulation of shared objects, the CVE did not adequately address the consistency issues arising from the network characteristics.

Several studies have investigated the effect of linking various combinations of display system on collaboration. It was found that immersed users naturally adopted dominant roles (Slater, Sadagic, Usoh, & Schroeder, 2000). A recent study by Schroeder et al. (2001), again using DIVE, investigated the effect of display type on collaboration of a distributed team. This work extended the concept of a Rubik's cube by splitting the composite cube such that two people could concurrently interact with individual component cubes while observing each other's actions. The study compared three conditions based on display combinations: two linked walk-in displays, face-to-face, and a walk-in display linked to a desktop. An important finding was that the asymmetry between users of the different systems affects their collabo-

Table 2. *Examples of Object Sharing*

Subtask	Scenario	Method of sharing
Moving a beam (Figure 3)	A wooden beam is too heavy to lift alone, requiring one user to lift each end	Concurrent sharing of an object through the same attribute
Fixing a beam (Figure 4)	A wooden beam must be held in place by one user, while another fixes it by drilling a hole and inserting a screw	Concurrent sharing of an object through distinct attributes

ration, and that the copresence of one's partner increases the experience of the virtual environment (VE) as a place.

To aid comparison to previous studies (Frécon et al., 2001; Frécon & Stenius, 1998; Greenhalgh et al., 2001; Mortensen et al., 2002; Schroeder et al., 2001; Steed et al., 2001), we have adopted the same CVE—that is, DIVE. We extend Schroeder's Rubik study in a number of ways. (See Table 1.)

2 Experiment

To examine distinct scenarios of sharing the manipulation of an object, we have designed the structured task of building a gazebo. This section starts by describing the gazebo application. We then reduce the task to remove redundancy, and divide it into subtasks that provide various collaboration scenarios requiring shared manipulation of an object. Various device configurations used throughout the experiment are detailed.

The methodology for evaluating the task is explained both for team performance and subject perception. Team performance measures the time taken to complete the task and each component subtask. User evaluation details the responses to a questionnaire on the perception of collaboration.

2.1 Gazebo

A gazebo (Figure 1) is a simple structure that is often found at a vantage point or within a garden. Our application places users in a virtual garden setting that contains both materials and tools for construction, both of which must be shared in a variety of ways. Screws fix beams in place, and planks may be nailed to beams. Tools (Figure 2) are used to drill holes, tighten screws, hammer nails, and the like. Although some aspects of the construction can be undertaken independently, the simulation of gravity ensures that collaboration is necessary for others. For example, a single person can place a metallic foot on the ground or drill a hole in a beam while it lies on the ground, whereas two people are required to carry or fix a beam.

To complete the gazebo, tools and materials must be shared in various scenarios of shared object manipulation, some of which are distinct in the method of sharing attributes. (See Figures 3 and 4 and Table 2.) A pair of carry tools are used to pick up a beam. When lifted by two carry tools, one at each end, the end of the beam is attracted towards the closest carry tool, as if by magnetism. This solution overcomes the issue of multiple parenting in the scene graph and helps users to conceptualize the effects of network delays as magnetic attraction and inertia.

2.1.1 Task Breakdown. Variations of the gazebo have been built during several collaborative sessions involving walk-in displays at Reading and London in the United Kingdom and Linz in Austria. (See Figure 5.) As in the real world, building a gazebo can take several hours of often repetitive work. Thus, for detailed evaluation, we reduced the task to constructing a simpler structure, removing unnecessary repetition, but still requiring both forms of object sharing along with varied human communication (Figure 6). The detailed breakdown of the new task is given in Table 3, where we show an example of how two users might construct the simple structure. A third user may assist by, for example,

Table 3. *Detailed Task Breakdown Showing an Example Collaboration*

Subtask	Description	User 1	User 2
ST1	Place foot	Fetch foot and place squarely on the ground.	
ST2	Carry beam	Fetch carry tools and use one to lift each end of the beam. When both ends are lifted, carry the beam to the foot.	
ST3	Place beam in foot	Place one end of the beam in the foot.	Then lift the other end so that the beam is vertical.
ST4	Drill hole	Fetch the drill and drill a hole through foot and beam.	Hold the beam in place.
ST5	Insert screw	Fetch a screw and insert it in hole.	Hold the beam in place.
ST6	Tighten screw	Fetch a screwdriver and tighten screw.	Hold beam in place until screw is tightened.
ST7	Place T joiner	Fetch the T joiner and hold it in place on the upright beam.	
ST8	Drill hole	Hold the T joiner in place.	Fetch drill and drill a hole through foot and T joiner.
ST9	Insert screw	Hold the T joiner in place.	Fetch a screw and insert it in the hole.
ST10	Tighten screw	Hold the T joiner in place until screw is tightened.	Fetch screwdriver and tighten screw.

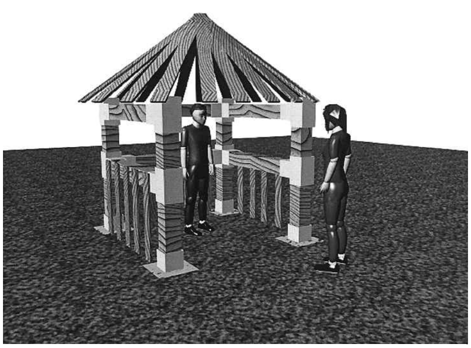

Figure 1. *Ideal gazebo.*

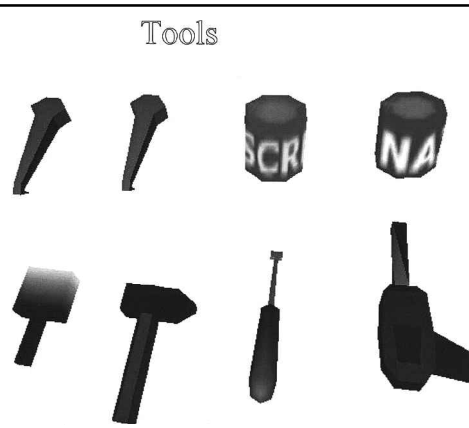

Figure 2. *Tools.*

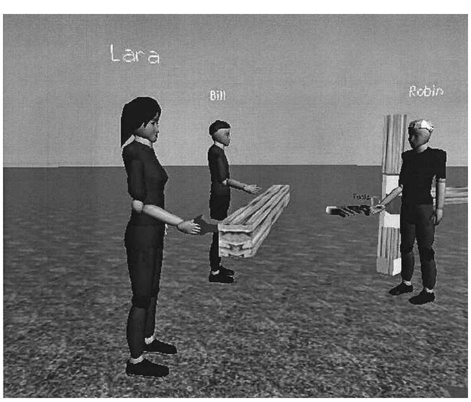

Figure 3. *Concurrent sharing of an object through the same attribute.*

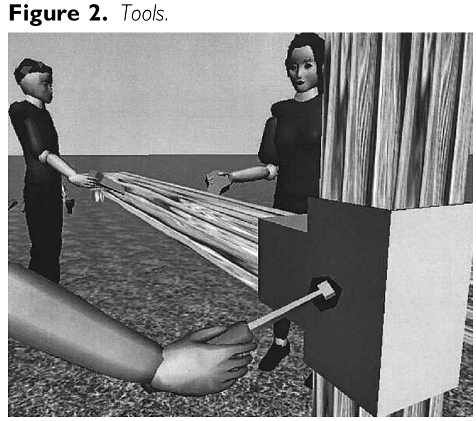

Figure 4. *Concurrent sharing of an object through distinct attributes.*

Table 4. *Display Configurations*

Name	Display Type	View	Input	Audio	Avatar*	Location
IPT1	Walk-in	Stereo	Tracked head and hand	Yes	Medium realism, dynamic body	Reading
IPT2						London
DT1	Desktop	Mono	Mouse and keyboard	Yes	Low realism, static body	Reading
DT2				No	Medium realism, static body	Reading

*The remote representation of the local user.

fetching a tool while two others are carrying the beam or by helping with task planning and execution.

2.1.2 Display Configurations. The tests involved distinct display configurations, all different in their ability to facilitate interaction with the other two participants as shown in Table 4. Two basic display types were used: a walk-in cubic IPT and a desktop. All of the configurations restricted the user to one-handed interaction within our application. Collaboration would still have been necessary for two-handed input because of the effect of gravity on "heavy" beams.

2.1.3 CVE. The DIVE CVE was used for experimentation as it is an established benchmark (Frécon et al., 2001; Frécon & Stenius, 1998; Greenhalgh et al., 2001; Mortensen et al., 2002; Schroeder et al., 2001; Steed et al., 2001). DIVE version 3.3.5 was used on all devices, but we extended this DIVE version with an event-monitoring plug-in and an event filter. The event monitor timed event callbacks with synchronized clocks (Anthes, 2002). Event filtering reduced the frequency of events generated by the tracking system. Throughout our tests, the tracking system was filtered to produce only events for movements greater than 1 cm. In extensive testing, this level of filtering was found to produce the optimal balance between system performance and usability.

2.1.4 Network Conditions. Tests were undertaken over a six-month period. Typical network latencies during this period were as follows.

- Reading to London: 19 ms
- Reading to Reading: 17 ms (through slow switch to simulate national Internet latency)
- Reading to Linz: 43 ms

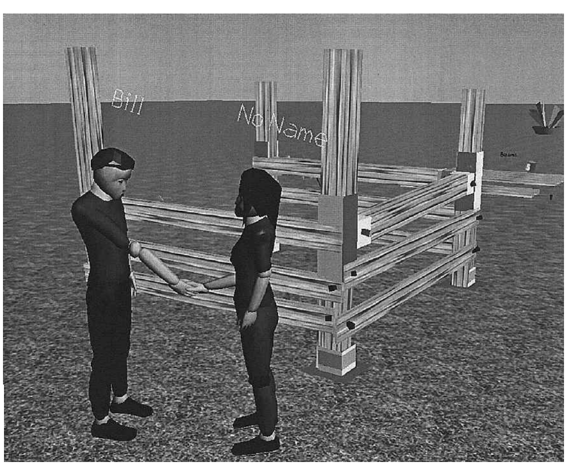

Figure 5. *Completed work after 1 hr collaboration of two IPTs.*

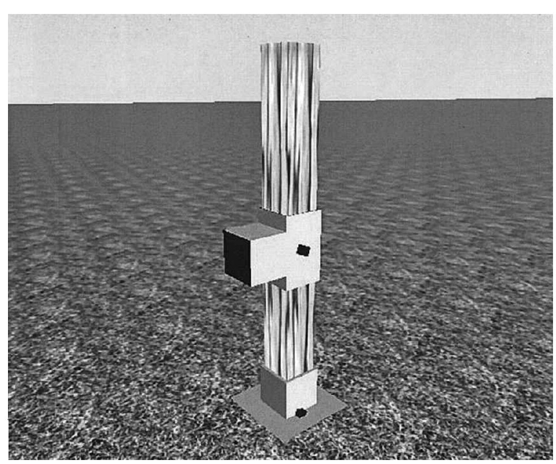

Figure 6. *Simple structure used for detailed analysis.*

2.2 Team Performance

Team performance was measured both in terms of the time taken to complete the task and each component subtask to gauge the support for collaboration offered by various display configurations. Multiple test runs compared the performance of both expert and novice teams across the display configurations IPT1, DT1, and DT2. (See Table 4.) The teams were left to determine their own organization of roles in a natural way as the task progressed. The only constraint was the order of the subtasks ST1 to ST10 as described in Table 3.

2.2.1 Collaboration Between Novice Subjects. We started our trials with a set of twelve novice users, each of whom undertook the trials voluntarily and were students of undergraduate programs in computer science and cybernetics. None had previous experience of working in an immersive display or of the gazebo application. Teams of three subjects performed the task in three test runs using IPT1, DT1, and DT2. All of these display systems were at Reading. By changing places between test runs, each subject interacted through the entire set of display configurations in the same geographical location.

2.2.2 Effect of Display Configuration on Expert Users. Performance measurements for novice subjects vary greatly. Consequently, to better gauge the effect of device combinations, we repeated the test runs between pairs of expert subjects. The set of expert subjects had three members, each with several months of regular experience of both the gazebo application and the interface. We first compared display configurations as before and then repeated the runs constraining subject roles. The latter was done to gain a clearer understanding of the effect of role on subject performance for a given display. The constrained roles were divided into primary and supporting, the former undertaking the more difficult parts of subtasks, such as fixing, while the latter held material in place. Table 5 distinguishes the test runs undertaken by expert teams.

Table 5. *Overview of Roles in Expert Users Test Runs*

Test Run	IPT1	DT1	DT2
TRA	Unconstrained	Unconstrained	—
TRB	—	Unconstrained	Unconstrained
TRC	Primary	Supporting	—
TRD	Supporting	Primary	—

2.3 User Evaluation

The perceived effectiveness of collaboration involving shared objects and the perceived effect of display type were investigated, using a user evaluation questionnaire. Fifty-six volunteers were split into teams of three for each test. Within every task, each user interacted through a distinct display device and was questioned on his perception of the effectiveness of teamwork. Various test conditions defined both device combination and perspective (See Table 6). For example, condition C1 questioned how the user of IPT1 perceived the effectiveness of collaboration with the users of DT1 and DT2.

Table 6. *Test Conditions*

Condition	Questioned User	User 2	User 3
C1	IPT1	DT1	DT2
C2	DT1	IPT1	DT2
C3	DT2	IPT1	DT1
C4	IPT1	IPT2	DT1

2.3.1 Questionnaire. The questionnaire was aimed at ascertaining the user's subjective perception of collaboration, both generally and for each specific task. Questions were based on those of Usoh and colleagues (Usoh, Catena, Arman, & Slater, 2000). Answers could be given on a scale of 1–7, where 7 represents total agreement and 1 total disagreement. Errors arising from a user's misinterpretation of a question were reduced by asking sets of related questions. For example, "to what extent did the two of you collaborate" was contrasted with "to what extent did each user hinder the task." The entire questionnaire of more than thirty questions is too long to reproduce here, as are the detailed responses to each question. The summary findings are given in the next section, where we describe those answers relating directly to the shared manipulation of objects that were found to be statistically significant.

3 Results

This section first examines the results of the team performance tests and then the user evaluation.

3.1 Team Performance Results

The effect of interface on team performance is given here, first for novice and second for expert users. Performance is measured in terms of the time taken to complete each subtask.

3.1.1 Collaboration of Novice Users. Figure 7 shows the measured timing of teams of novice users for each completed subtask. A strong correlation was observed between the experience of users and the time taken to complete the task. Subjects that faced our test environment for the first time appeared to have difficulty recognizing the constraints of the application and the handling of the interface. However, both were learned quickly, resulting in a doubling of performance by the third attempt.

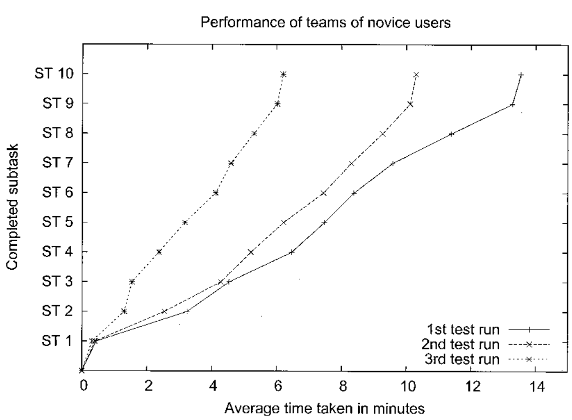

Figure 7. *Timing of novice teams.*

3.1.2 Effect of Display Configuration on Expert Users. Figure 8 shows the timing of the team of expert users. For unconstrained roles, the expert teams took approximately half of the time of the average of the novice teams.

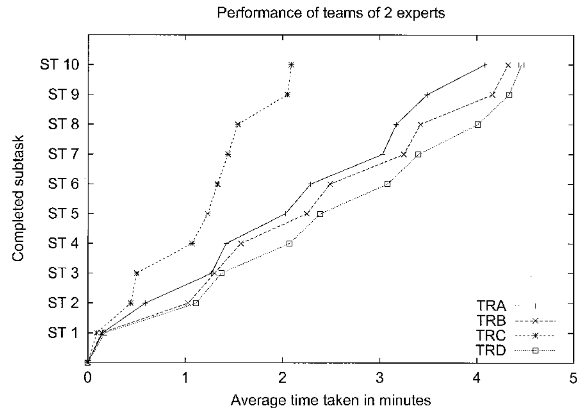

Figure 8. *Timing of expert teams.*

Graphs TRA and TRB in Figure 8 reveal that the type of display does not make a clear difference when the organization of role is unconstrained. However, giving the primary role to the walk-in display user, results in a considerable performance increase (TRC and TRD in Figure 8).

The taking of the primary role by the immersed user results in a clear performance increase for most subtasks. This can be seen more clearly in Figure 9, which illustrates the timing advantage for each subtask. The advantage appears to relate more to the suitability of each interface to a given form of object manipulation rather than to the method of object sharing. The advantage gained when the immersed user leads the carrying is approximately half of that gained by leading the placement, ST2 and ST3, respectively. A clear advantage is seen for all subtasks that require accurate 3D placement over those that require approximate movement. This can be seen by comparing ST3, ST5, ST7, and ST9 to ST1 and ST2 over TRC and TRD in Figure 9. In contrast, the average improvement gained is equal when sharing an object through the same, or distinct, attributes: average (ST2, ST3) == average (ST4, ST5, ST6). Table 7 summarizes the performance increase

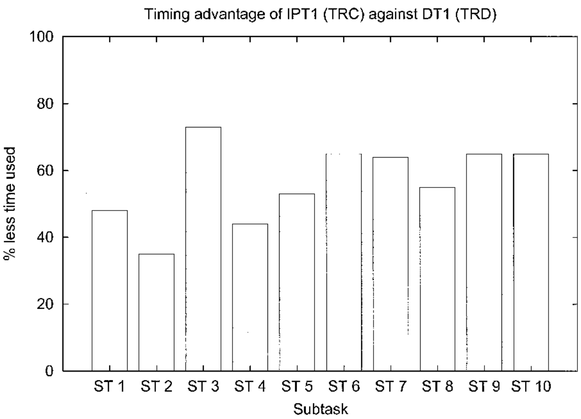

Figure 9. *Timing advantage of IPT in TRC and TRD.*

Table 7. *Performance Increase IPT/DT*

Subtask	Description	Predominant activity	Performance increase IPT/DT
ST1	Place foot	Moving	48%
ST2	Carry beam	Moving	35%
ST3	Place beam	Positioning	73%
ST4	Drill hole	Use tool	44%
ST5	Insert screw	Positioning	53%
ST6	Fix beam	Use tool	65%
ST7	Place T joiner	Positioning	64%
ST8	Drill hole	Use tool	55%
ST9	Insert screw	Positioning	65%
ST10	Fix T joiner	Use tool	65%

during TRC and reviews the predominant activity of each subtask. Over the whole task, a cumulative performance increase of 55% was measured for the walk-in display against the desktop.

3.2 User Evaluation

We now summarize the responses to the questionnaire.

3.2.1 Contributions to Carrying a Beam. For the response to the first question, "To what extent did each person contribute to the task while carrying a beam?" an analysis of variance (ANOVA) showed that there was a significant difference between the conditions (Table 8). Conditions C1, C2, and C4 all showed a clear statistical significance, whereas C3 showed a close statistical significance. An ANOVA across the combined questions, for conditions C1 to C3, showed that all users held an objective impression of the effectiveness of collaboration ($F(2, 41) = 0.18$, $MS_W = 14.9$, $p = .840$). Thus, the answers may be united, across conditions C1 to C3, to gain a better statistical certainty of device importance. The ANOVA for this showed that there is a significant difference and a post hoc test showed that the difference lies between all three devices. These results show that asymmetry in linked devices affects perceived contribution. Immersive users are considered by all to contribute more than desktop users. Furthermore, when a team comprised two immersed and one desktop user, the latter was left out of most of the activity. The significance of this finding is demonstrated through the ANOVA of C4 that returned an actual deviance of 0.003.

3.2.2 Contributions to Fixing a Beam. We asked the same question for the task of fixing a beam. (See Table 9.)

An ANOVA across the combined questions ($F(2, 40) = 0.92$, $MS_W = 14.1$, $p = .405$), of the conditions C1 to C3, showed that all users held an objective impression of the effectiveness of collaboration. Thus, to gain a better statistical certainty of device importance, the answers may again be united across conditions C1 to C3. The ANOVA for this showed that there is only a close significant difference, and a post hoc test showed that the difference lies between IPT1 and DT2. These results show that the effect of asymmetric devices is perceived to play considerably less of a role in the level of contribution when *fixing* a beam than *carrying* it. The actual deviance for fixing is 0.097 compared to 0 for carrying.

3.2.3 Comparison of Perceived Contribution for Carrying and Fixing. The difference of the effect of asymmetric devices observed when carrying as opposed to fixing the beam is confirmed in Figure 10, which combines the preceding results.

Table 8. *ANOVA Results for Contribution to Carry a Beam*

Condition	ANOVA results ($\alpha = 0.05$)	Significant difference*	Mean and *SD* results, sorted as in Table 6
C1	$F(2, 48) = 5.12$, $MS_W = 2.79$, $p = .010$	IPT1 and DT2	IPT1 ($M = 81.0$, $SD = 17.7$) DT1 ($M = 67.5$, $SD = 23.9$) DT2 ($M = 54.3$, $SD = 29.7$)
C2	$F(2, 34) = 4.67$, $MS_W = 3.21$, $p = .016$	IPT1 and DT2	DT1 ($M = 65.5$, $SD = 28.2$) IPT1 ($M = 83.5$, $SD = 20.9$) DT2 ($M = 52.4$, $SD = 27.5$)
C3	$F(2, 30) = 2.65$, $MS_W = 3.40$, $p = .087$	IPT1 and DT2	DT2 ($M = 51.4$, $SD = 31.0$) IPT1 ($M = 77.9$, $SD = 25.0$) DT1 ($M = 65.5$, $SD = 23.2$)
C4	$F(2, 19) = 8.29$, $MS_W = 2.44$, $p = .003$	(IPT1, IPT2) and DT2	IPT1 ($M = 67.9$, $SD = 29.3$) IPT2 ($M = 78.6$, $SD = 20.2$) DT1 ($M = 31.0$, $SD = 10.8$)
C1–C3	$F(2, 118) = 12.96$, $MS_W = 2.94$, $p = .000$	IPT1 and (DT1, DT2)	IPT1 ($M = 81.0$, $SD = 20.4$) DT1 ($M = 66.3$, $SD = 24.4$) DT2 ($M = 52.9$, $SD = 28.5$)

Where: α is the limit of significant deviance, MS_W is the mean square within groups, F(a, b) is the variance between groups/MS_W, p is the actual deviance, with four decimal places, M is mean, and SD is standard deviation.
*As found by the post hoc test (Tukey).

3.2.4 User Hindrance of the Task. In answer to the question "To what extent did each user hinder the task?" an ANOVA unveiled that there is no significant difference between the conditions: $p = .699$ for carrying a beam and $p = .846$ for fixing a beam. Therefore, we can accept the null hypothesis. The results for carrying a beam ($M = 44.9$, $SD = 23.4$) and for fixing a beam ($M = 46.2$, $SD = 21.1$) show clearly that the participants did not excessively hinder each other.

3.2.5 Collaboration Between Users. Carrying and fixing a beam requires collaboration between two users. When it comes to the evaluation of "To what extent did the two of you collaborate?" and "How well did you and the other person together perform the task?" an ANOVA showed only a significant difference ($p = .002$) in C4 for carrying the beam ($M = 80.4$, $SD = 25.3$), whereas there was no significant difference in one of the other trials, neither for carrying nor for fixing a beam. (See Figure 11.) These results show that, from the perspective of immersed users, collaboration is considerably easier with a symmetric user. However, desktop users found the type of remote display to play little part in the level of collaboration.

4 Conclusion

A degree of copresence has long been supported by CVEs; however, the realism of shared object manipulation has, in the past, been hampered by interface and network delays. We have shown that a task requiring various forms of shared object manipulation is achievable with today's technology. This task has been undertaken successfully between remote sites on many occasions, sometimes linking up to three remote walk-in displays and multiple desktops. Detailed analysis has focused on team performance and user evaluation.

Table 9. *ANOVA Results for Contribution to Fix a Beam*

Condition	ANOVA results (α = 0.05)	Significant difference*	Mean and *SD* results, sorted as in Table 6
C1	$F(2, 50) = 2.05$, $MS_W = 2.66$, $p = .140$	None	IPT1 (M = 78.2, SD = 17.6) DT1 (M = 64.7, SD = 25.4) DT2 (M = 63.9, SD = 25.8)
C2	$F(2, 33) = 0.97$, $MS_W = 2.78$, $p = .389$	None	DT1 (M = 73.8, SD = 24.2) IPT1 (M = 77.4, SD = 18.7) DT2 (M = 64.3, SD = 27.6)
C3	$F(2, 32) = 0.25$, $MS_W = 2.05$, $p = .777$	None	DT2 (M = 61.9, SD = 26.8) IPT1 (M = 64.9, SD = 17.3) DT1 (M = 67.9, SD = 15.1)
C4	$F(2, 13) = 4.30$, $MS_W = 2.69$, $p = .037$	IPT1 and DT1	IPT1 (M = 76.2, SD = 14.8) IPT2 (M = 54.8, SD = 30.5) DT1 (M = 32.1, SD = 21.4)
C1–C3	$F(2, 121) = 2.38$, $MS_W = 2.48$, $p = .097$	IPT1 and DT2	IPT1 (M = 74.3, SD = 18.4) DT1 (M = 68.1, SD = 22.4) DT2 (M = 63.4, SD = 26.0)

*as found by the post hoc test (Tukey)

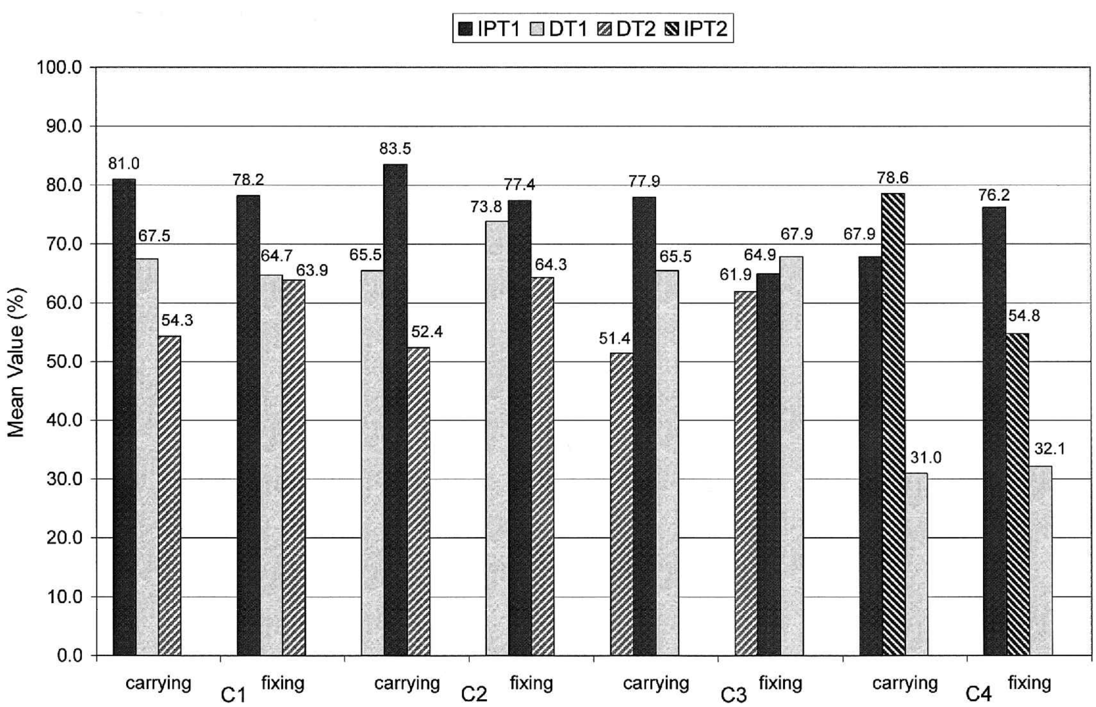

Figure 10. *Perceived contribution while both carrying and fixing the beam.*

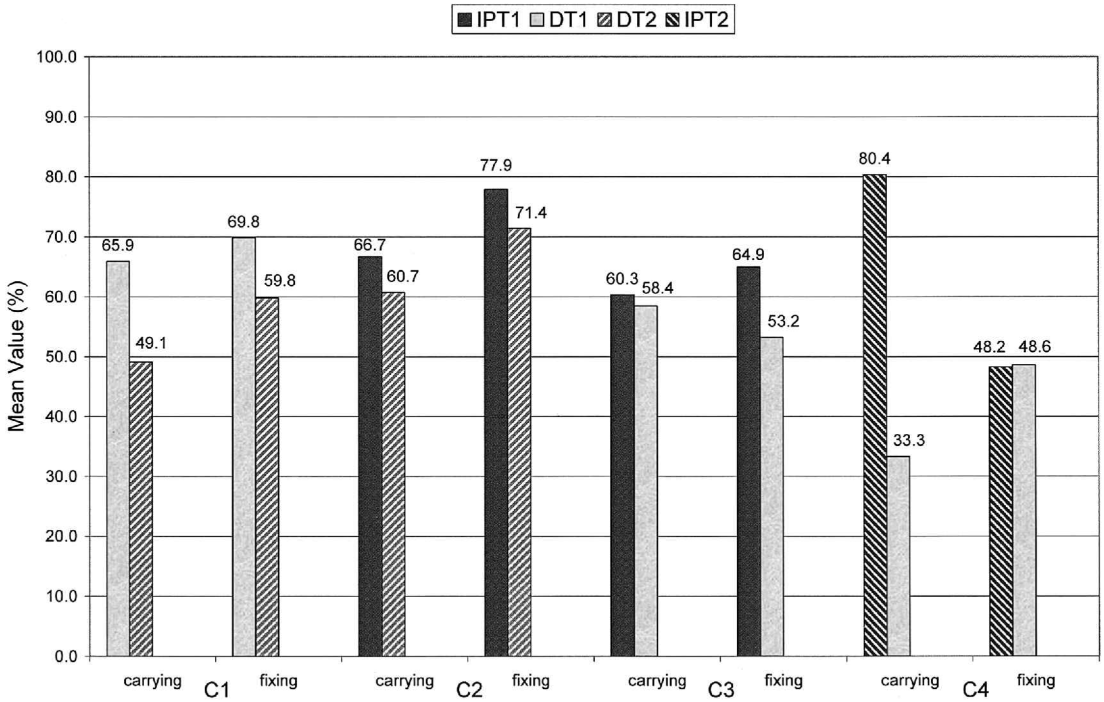

Figure 11. *Perceived collaboration while both carrying and fixing the beam.*

4.1 Team Performance

Using the gazebo application, novice users adapt quickly to remoteness of peers and the interface. Typically, after three sessions their performance doubles and approaches that of expert users. Immersive users can undertake most parts of the task far more efficiently than their desktop counterparts. The gazebo task requires collaboration at numerous points. This means that a faster user must often wait for the slower one to catch up before beginning the next step. Schroeder et al. (2001) found that the perception of collaboration is affected by asymmetry between users of the different systems. Our results show that the time taken to complete a collaborative task is also affected. When roles in the gazebo task are ill defined, the performance of the team approaches that of the weakest member. However, the performance is greatly increased when the immersed user undertakes the more difficult part of every task.

4.2 User Evaluation

The user evaluation is summarized in Table 10. The findings of our questionnaire confirm that the perception of contribution is affected by asymmetry of linked displays when carrying a beam. However, this is clearly not the case when fixing a beam, which suggests that the interface plays a major role during the sharing of an object's attribute and a minor role when sharing an object through distinct attributes. Surprisingly, neither the interface nor the form of object sharing is per-

Table 10. *Summary of User Evaluation*

Type	Same attribute	Distinct attribute
Contribution	IPT > Desktop	IPT == Desktop
Hindrance	IPT == Desktop	IPT == Desktop
Collaboration	IPT: IPT > Desktop Desktop: IPT == Desktop	IPT == Desktop

ceived to affect the level to which the remote user hindered the task. This appears to contradict the results of the preceding performance analysis. From the perspective of immersed users, collaboration is considerably easier with a symmetric user. However, a desktop user found the type of remote display to play little part in the level of collaboration.

4.3 Further Work

We are now advancing this work on a number of fronts:

- *alternative platform:* implementing the same experiment above CAVERNsoft
- *other display configurations:* linking workbench, walk-in, and desktop displays
- *consistency management:* managing the reliability, ordering, and timeliness of event communication
- *social human communication:* mapping fundamental principles from psychology into avatar design
- *shared manipulation of volumetric data:* supporting real-time shared interaction of large volumetric models between remote walk-in displays

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