# A Study of Influential Factors on Effective Closely-Coupled Collaboration based on Single User Perceptions

Oliver Otto, Dave Roberts, Robin Wolff
The Centre for Virtual Environments,
University of Salford, Business House, UK
{o.otto, d.j.roberts, r.wolff}@salford.ac.uk

## Abstract

*The need for collaboration and cooperation across a distance is becoming equal to that between a co-located team. This means that cooperative working must be supported by systems that allow natural social human communication and interaction. A goal of tele-collaboration is to reproduce the effectiveness of co-located teamwork across a distributed team. Although many of today's systems support collaboration, only a subset can be said to support cooperation and no established solution comes close to reproducing the flexibility and efficiency of a face-to-face meeting. Previous work has demonstrated that accessing collaborative virtual environments through CAVE-like display systems provide a natural way of sharing space and objects within it that bring us closer to replicating a face-to-face meeting. Our previous research has demonstrated a link between level of immersion, task performance and feelings of collaboration and cooperation. It was, however, unclear if the advantage came from more natural interaction with objects or more natural interaction with others through objects.*

*The aim of this paper is to understand the impact of using a CAVE-like display has on user-to-object interaction so that we can isolate this from previous results to find the advantage given to collaboration. Task performance was measured and a questionnaire was used to identify the perceived impact of various display factors .The results from this study indicate that the major impact of immersion is on cooperative tasks. Results showed further a disparity between perceived and actual performance, which is discussed.*

## 1. Introduction

In an increasingly global economy many people are under the pressure to expand collaboration from co-located to geographically distributed groups. Cooperation between people is often centred around common interests. This point of interest may be embodied by some perceivable object. In virtual reality, such objects may represent some physical artefact, information or concept from the real world. It is important for all collaborators to perceive and understand the object in order to work with it. While we cooperate with other people through an object, we use a variety of communicational tools to demonstrate our opinion, desire and intention to others. Be it simply verbally with emotional nuances, with gestures and postures in a non-verbal way or by manipulating the object directly. When interacting remotely, these forms of social human communication (SHC), as well as the representation of the object, need to be mediated through tele-collaboration technology.

If we use a phone or text to communicate, progress can be slow due to possible misunderstandings arising from cues that cannot be communicated through this medium. The use of modern video-conferencing systems gives us more flexibility and support for non-verbal communication, such as pointing towards object attributes. Using video-conferencing systems, however, one only "looks into each other's world", which limits the operating range to move and to be seen. In addition, it is difficult for all participants to interact with a shared object. In particular, it is hard to see how someone is interacting with an object when the operator, observer and object are each in separate windows, as in Access Grid [1].

A collaborative virtual environment (CVE) allows remote people and objects to be situated in a shared synthetic environment, in which one can navigate around and interact with a computer-generated representation of objects and other participants. Thus, whereas tele-conferencing systems allow people to look into each other's space, CVEs allow people and data to be situated in a shared spatial and social context.

In a previous study focusing on closely coupled collaboration in CVEs [2], we found that the exclusive use of spatially immersive (CAVE-like) displays significantly improved task performance and feelings of collaboration & cooperation (Figure 1, Table 1).

**Table 1. Performance increase IPT / DT [2]**

| Sub-task | 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 % |

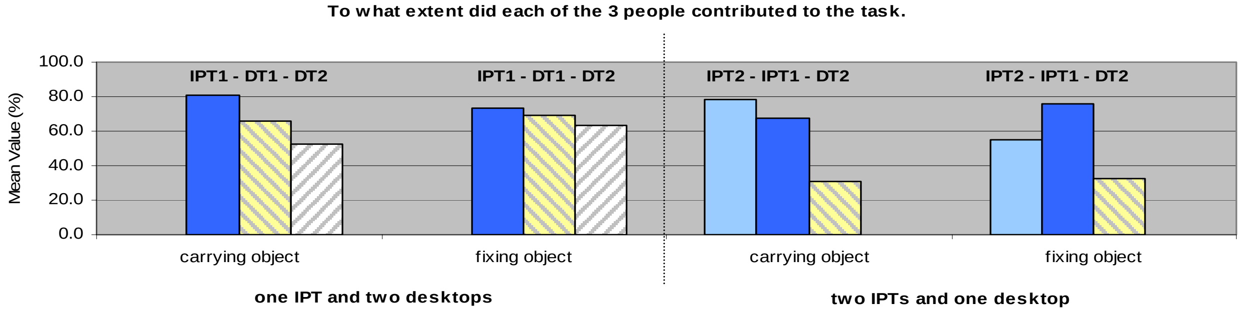


**Figure 1. perceived performance results of teamwork study [2] comparing IPT and desktop displays**

We were, however, uncertain if the improvements resulted from enhancements through user-to-object interaction or user-to-user collaboration around object interaction. To clarify this question, this study takes a closer look at display relevant factors, such as the field of view (FOV) and user interface, by performing similar tasks to previous trials, however excluding the social and team aspect. A single user trial with a number of volunteers was conducted, which measured the task performance, including time, task order and locomotion within the virtual environment. In addition the users were asked to fill out a questionnaire at the end of the test.

## 1.1. Related work

Hindmarsh et al. studied collaborative interaction of two users through a set of objects using a desktop based CVE [3], in which the participants were asked to rearrange furniture. The authors found that the limited field of view (FOV) on desktop systems was of great hindrance due to problems with fragmentation of the workflow. It took an unnaturally long time (>20sec) for users to perceive each other's gestures and to reference them to the places and objects in their conversation. The authors concluded that this was caused from a lack of information about other's actions due to their limited window into the world. In addition the study found problems with slow applications and clumsy movements as well as the lack of parallelism for actions. A subsequent study tried to resolve some of the issues with peripheral lenses, which resulted in an enhanced FOV. Although this solution enhanced the awareness, it also showed that peripheral lens distortion can disrupt both a user's own sense, and their notion of the other's sense, of orientation to actions and features within the environment [4].

Large displays are often not placed at a distance due to space constraints. They are typically relatively closer and cast a larger retinal image, thus offer a wider FOV. It is generally agreed that a wider FOVs can increase "immersion" in VEs [5-7]. Large displays in these settings are easy for all users to see and interact with, providing a conduit for social interaction [8], and some researchers have begun to document performance increases for groups working on large displays [9, 10].

Advances in immersive display devices are increasing their acceptance in industry and research [11]. Their support of natural body and head movements may be used to view an object from every angle. An object can 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 their own body in the context of the virtual environment [12]. Schuemie concludes that little is known about what interaction has to do with presence [13]. It may be argued that even less is known about the relationship between effective interaction on common objects as a focus of interest and co-presence.

Desktop systems use various methods to interact with objects in a virtual environment, such as go-go, ray casting or occlusion techniques [14, 15]. These can be used in CAVE-like displays, but have been primarily developed using head-mounted displays (HMD). Desktop systems use 2D interface controls or virtual spheres or mouse picking, whereas immersive displays normally use one- or two-handed direct manipulation (virtual hand) using a tracking system. Evaluations of interaction techniques for immersive displays found that the virtual-hand is superior to ray casting for the selection and manipulation of objects [15, 16]. The VR community is looking into the use of various displays for various tasks, yet is unable to define which choice to make for specific tasks [11]. Comparisons of usability have been made between immersive and desktop displays [17, 18] and they tend to show an advantage for immersion in certain applications.

Kjeldskov et al. [19] found that non-tracked 3D interaction devices work fine for orientating and moving when using partial immersive displays, but are problematic when using fully immersive displays. In addition they argue that partial and fully immersive displays have different support for close-by interaction (virtual hand) and different affordances for pointing (virtual beam). An experiment by Bowman et al. [20] showed that HMD users are significantly more likely to use natural rotation in a VE than CAVE users. This produces higher levels of spatial orientation, and can make navigation more efficient.

This paper extends a previous study [2] that analysed factors affecting a collaborative task. The study presented in this paper analyses a similar task carried out by a single user, so that factors affecting collaboration can be isolated. The aim is to understand what impact of using a CAVE-like display has on user-to-object interaction, so that we can isolate this from previous results that showed an improvement in multi-user cooperation through shared objects. This will tell us if the advantage comes from more natural interaction with objects or more natural interaction with other participants through objects. Section 2 introduces the task and the setup for the various displays. The results are given in section 3, discussed in 4 in relation to previous studies and summarised in section 5.

## 2. Experimentation

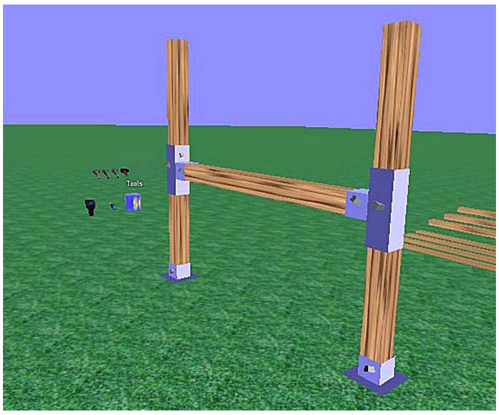

**Figure 2. A simple structure to build**

In order to understand how different display factors and interaction methods influence a task designed for closely-coupled collaboration, we modified our existing benchmark application, in which remote users are building a given structure (Figure 2) by interacting with simulated wooden beams, metal joiners, screws and a set of tools in a specific order [2, 21]. Objects have to be carried to the construction site and eventually fixed with the appropriate tools and materials. For example, a beam can be inserted into a metal joiner or foot and then fixed in place by drilling a hole and screwing in a screw. The original task required teamwork, as simulated gravity required two people to lift a beam and one person to hold a joiner to a beam while it was being fixed. The need for team work was removed by disabling the simulation of gravity. Our trial was then able to focus on single user interaction with objects. Clearly, interaction would be altered by the lack of gravity, but we considered the effect to be negligible.

### 2.1. Measurements

For this task we asked 13 student volunteers to participate, each received multiple training sessions to familiarise them with the interface and the task. Earlier trials showed that after three short training sessions the user became familiar with the interface so that their performance reached that of an expert user [2, 21]. The trials needed no longer than 5-10 min per session and display, compared to almost 30-45 min of training and familiarisation per subject.

After evaluation of the results we found a significant difference in measured and perceived performance, which we partially related to the manipulation and navigation on the desktop. To better understand this relationship, we performed a subsequent trial with four people repeating the desktop trial with ray-casting as well as virtual-hand manipulation.

### 2.2. Display Configuration

We asked all participants to perform this task on a variety of distinct display configurations: a non-immersive desktop system, a partial immersive workbench system and a fully-immersive CAVE-like system (see Table 3). Each trial was first undertaken on a desktop and then repeated on the workbench and in the CAVE-like display. It was assumed that, as participants were practiced in doing the task on them and the trials were short, order was unlikely to impact on results.

**Figure 3. the workbench display**

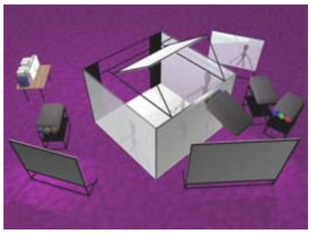

**Figure 4. the CAVE-like display**

DIVE [22] in version 3.3.5 was chosen as CVE platform for experimentation on all display devices, as it is an established benchmark [17, 23-27]. We extended this DIVE version with an event monitoring plugin that allowed us to monitor the user and object movements for a post-trial analysis.

**Table 2. display configurations**

| Display device | Input device | OS | Stereo | Field of view | Manipulation technique |
|---|---|---|---|---|---|
| Desktop | keyboard and mouse | Linux | No | 60 degree | ray-casting |
| Workbench (Figure 3) | tracked wand | Irix | Yes | 110 degree | virtual hand |
| CAVE-like (Figure 4) | tracked wand | Irix | Yes | 160 degree | virtual hand |

**Table 3. summery of some selected questions**

| Perception of | Desktop | | Workbench | | CAVE | | ANOVA |
|---|---|---|---|---|---|---|---|
| | mean | SD | mean | SD | Mean | SD | |
| performance carrying (%) | 68.8 | 12.5 | 75.3 | 11.2 | 81.4 | 13.6 | $F(2,29)= 2.70$, $MS_W=2.04$, $p=0.084$ |
| performance fixing (%) | 74.3 | 13.1 | 77.9 | 14.8 | 91.4 | 10.0 | $F(2,28)= 4.96$, $MS_W=4.02$, $p=0.014$ |
| interface hamper (%) | 61.0 | 23.1 | 49.4 | 20.6 | 37.7 | 17.2 | $F(2,30)= 3.59$, $MS_W=7.36$, $p=0.040$ |
| field of view (%) | 53.2 | 26.4 | 68.8 | 14.0 | 77.9 | 24.2 | $F(2,30)= 3.47$, $MS_W=8.39$, $p=0.044$ |
| missing sense of touch (%) | 41.6 | 28.2 | 54.5 | 21.0 | 59.7 | 27.7 | $F(2,30)= 1.44$, $MS_W=4.73$, $p=0.252$ |
| presence (%) | 28.6 | 18.1 | 66.2 | 9.6 | 85.7 | 14.3 | $F(2,30)= 44.67$, $MS_W=45.48$, $p=0.000$ |
| | | | | | | | |
| measured task time (min) | 6.1 | 1.4 | 7.0 | 1.8 | 7.3 | 2.1 | $F(2,30)= 1.33$, $MS_W=4.21$, $p=0.280$ |

## 2.3. Questionnaire

Thirteen questions were asked, in which the user compared the different display combinations. Errors arising from a user's misinterpretation of a question were reduced by asking sets of related questions. Answers could be given on a Likert-type scale [28] of 1-7, where 1 represented agreement to a very small extent and 7 to a very large extent. The questionnaire included questions concerning how subjects interacted with the object in the different configurations, as well as how they perceived the interaction with the objects. The questions were similar to those asked in previous studies allowing us to compare our earlier work [2, 21], but were mainly related to performance, field of view and presence.

# 3. Results

This section documents the results of this study, comparing user performance, manipulation technique, FOV and presence. We first describe the questionnaire results and then the observations and measurements of two selected cases.

## 3.1. Overall Findings

For the analysis of the questionnaire we used the statistical approach of analysis of variance (ANOVA) to verify the significance of the results. The limit of significant deviance was $\alpha=0.05$. The results are given with $MS_W$ as the mean square within groups, $F(a,b)$ as the variance between groups/$MS_W$ and p as the actual deviance, with four decimal places. A posthoc Tukey test was applied if a significant difference could be found to verify where those differences appear.

We asked the users *"how well they performed the task of carrying / fixing an object using the different displays"* and an ANOVA showed that there is a significant difference between the desktop and the immersive displays (performance carrying and fixing: $F(2,60)= 7.25$, $MS_W=5.80$, $p=0.002$). On a desktop, performance was perceived to be less effective than it was in the CAVE or workbench. In addition, this contrast was stronger for fixing an object than for carrying it (Figure 5, Table 3).

The question of "*how much did the interface hamper the task*" showed a clear difference between desktop and immersive displays. The keyboard/mouse combination on the desktop system with its, for CVEs typical, complicated combination of shortcuts was clearly perceived to hamper the task much more than the tracking / joystick combination in the CAVE or workbench (Figure 5, Table 3).

Another question was "*how important was the field of view during the interaction*" and again a clear difference can be seen between the desktop and the immersive display (Figure 5, Table 3).

None of our displays had a haptic interface and when asking: "*how much did you miss the feel of touch*" it showed that it was missed more within the immersive displays than at the desktop system. One of the users expressed it as: "The sense of touch was not expected when using the desktop, whereas it was when on the workbench and particularly in the CAVE." (Figure 5, Table 3).

The results above show that the user in the immersive display felt more natural and present in the task. This was confirmed by their answer to our questions regarding presence. The questions "*of their sense of being there*", "*realistic appearance of interaction*" and "*feeling of physical space*" show all a very low perception of presence on the desktop, but a high perception on the immersive displays (Figure 5, Table 3).

Although the questionnaire was used to measure the user's perception of their performance, the time taken by each subject to complete a test-run was taken independently. The performance measured by time appeared to contradict the subject's perception measured from the questionnaire, as shown in Table 3. Average task completion times were 370, 410 and 445 seconds for desktop, workbench and cave respectively. An ANOVA for the measured time showed no significant difference for any of the displays ($F(2,30)= 1.33$, $MS_W=4.21$, $p=0.280$).

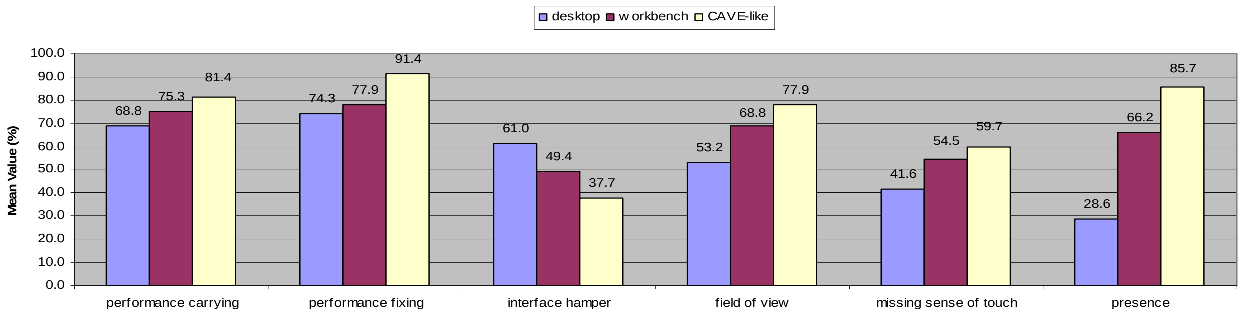


**Figure 5. summery questionnaire overview to perception of …**

## 3.2. Comparing two extremes in Detail

The results above show that the users perceived the use of immersive displays as more efficient and suitable than the use of a desktop display. However, these results contradict the task performance measurements. The average time to complete the task was similar for each display, but slightly proportional to the level of immersion. We will discuss this contradiction later in this paper, but first we will look at two opposite cases (Table 4). In the first case (case1) the user had an equally fast time on all displays and in the second case (case2) the desktop time was faster than on the immersive displays. The main difference between the two has been observed in how they used the display interfaces. The former was taking advantage of the display's properties (movability, view frustum, interaction technique), whereas the later used all displays as if he was fixed in his position (Figure 9, Figure 11, Table 5).

The CVE platform used in this trial allows manipulation of objects through ray-casting on the desktop display, whereas a user must physically reach for an object before it can be manipulated through the immersive displays. This has the effect that the desktop user can manipulate objects from a distance, whereas in the immersed setting they must first approach the object. The advantage on the desktop is an apparent increase in the "field of view" when the building site is viewed from a distance. However, this would only work well in an open environment, as it is the case in the experimental setting in this trial. In a normal sized room, surrounded by walls, it would be difficult to see the whole room, and subsequently this would make it necessary to turn around. The effect of a large open environment can be seen in Figure 8a (traces show navigation through environment) where the desktop user moved very little and performed the object manipulation from a distance.

In contrast, in our configuration, the immersive displays required direct manipulation, hence the large amount of movements for both users in Figure 8b and Figure 8c. In addition, a larger amount of movements in a contained space have been recorded for the CAVE-like display compared to the workbench. From observations, we believe this to be due to the difference in modes of interaction across the display types. The CAVE-like display was a 3x3 m room in which the user can freely walk due to the tracking of the body, allowing natural precise and fast movements around an object, if it is close enough (within the 3x3m). This includes the ability to swing the body around, using peripheral vision and eye cascades to control an effective turn to an object of interest, when displayed on another projection wall. The joystick controller is only needed for larger movements. In contrast, on the workbench the user is more restricted (space of 1x1.5m) by the physical space as well as the smaller FOV, making it necessary to use the joystick controller more often for navigation. This can be seen in comparing the fairly straight lines of Figure 8b (using joystick navigation) with curved lines of Figure 8c (user walking within the spatial display). The figures 8a-8c show in addition that the user of case1 is moving less and shorter than the user of case2. This is in harmony with the observations that in case2 the joystick was used more often than in case1, where the user made more use of his physical space to move. The result is an increase of measured completion time of the task for case2.

**Table 4. comparison of two opposite cases, using 7-point Likert-type scale**

| perception of | Desktop | Work-bench | CAVE-like |
|---|---|---|---|
| **case1** | | | |
| measured task time | 6 min | 6 min | 6 min |
| main observations | - good use of all walls in the CAVE<br>- "10min ago I was working on the wall, now I am in the middle and that makes a difference" | | |
| **case2** | | | |
| measured task time | 6 min | 7 min | 9 min |
| main observations | - a mental picture of the scene seems to be missing<br>- stayed in one place in the immersive display, but lots of joystick movements | | |

Observations have shown that taking advantage of the natural interface of the immersive display it could increase the feeling of presence and performance (Table 4) as well as reducing the frustration factor, because one may "overshoot" the target when trying to get there with the joystick. Similar observations have been made in previous trials during closely-coupled interaction [21], where

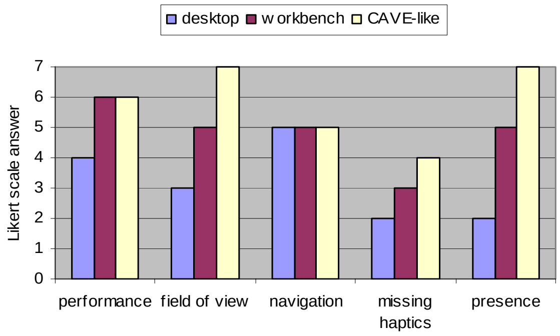


**Figure 6. user perception of case1 (with observed flexible interaction pattern)**

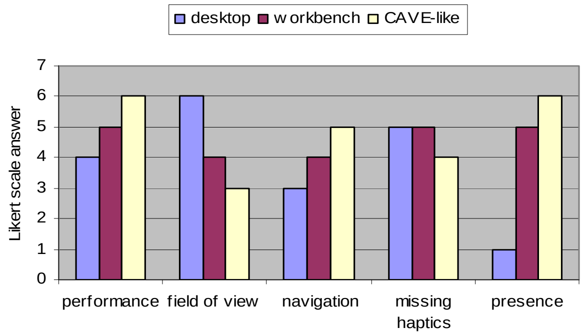


**Figure 7. user perception of case2 (with observed ridged interaction pattern)**

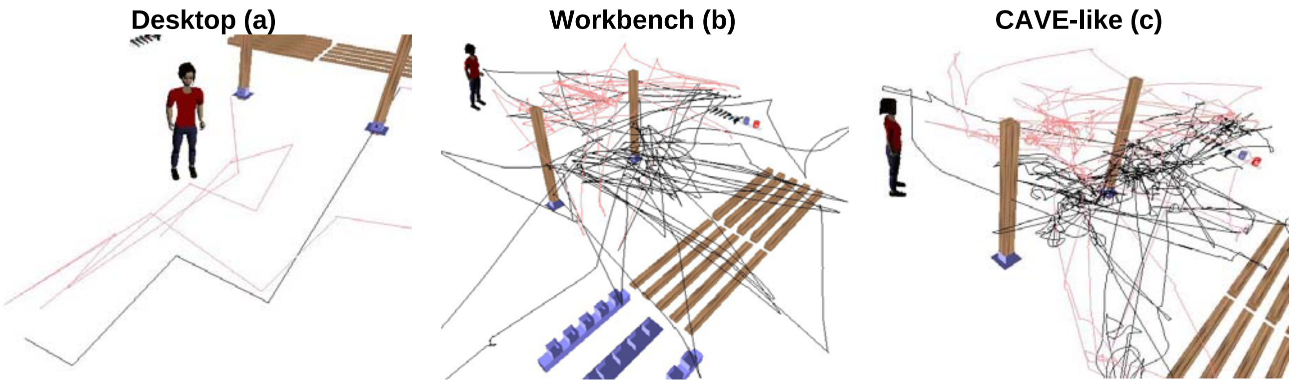


**Figure 8. traces of the moving avatar during the task, case1: dark line, case2: bright line**

overshooting led to some observed distress when a user needed more time to adjust their position. Thereby the other user had to wait if one's action was needed to finish a cooperative subtask.

## 4. Discussion

This section discusses why perceived and measured performance was different, what the FOV has to do with user locomotion & navigation and why the interaction technique influences the user collaboration and performance.

One clear observation was the difference between the perceived performance and the time needed to complete the task (see Figure 5, Table 3). The contradiction of these results may be explained through the relationship of the perception of being there, immersiveness and interaction technique (Figure 9). The results of this study (Figure 5) show significant differences in perceived presence for all displays. The same tendency can be seen for performance, FOV, missing touch and interface problems. Although those tendencies are not as strong as for presence, they show that the more one becomes immersed and engaged the higher is the feeling of being there. Presence is not something that can be clearly measured, but is a feeling created by a number of factors [29]. Those factors, like immersiveness, naturalness of interface and ease of interaction, all appear to contribute to a feeling of being there. Small differences of perception (between displays) for all those factors have a profound influence on the perceived presence. This also explains the difference between perceived and measured performance. If one feels more engaged and present, time will seem to pass quicker and the user's own activity will enhance the feeling of performance. This can also be seen in the reaction of users, who consistently mentioned that the use of the immersive display was much more enjoyable than the desktop.

One objective in this study was to determine how much the FOV would influence task performance. Our hypothesis was that with a wider view frustum the task would become easier and increase performance as the scene is more visibly accessible and therefore objects can be faster spotted. In contrast to the desktop, both immersive displays are similar in the way the user interacts, however the FOV is their main difference. Differences can be seen in the data and observations gathered during this trial. At the workbench, Figure 8b shows clearly longer ways for locomotion in comparison to Figure 8c. In addition, the observation during the trial was that on the workbench the joystick was used more often to attain an object as compared to the CAVE, where physical walking toward an object was easier and only longer distances needed the use of the joystick (Figure 11a and Figure 11b).

From observations, we estimate the relationship between FOV and locomotion as a curve as shown in Figure 11b. An exception is the HMD, which has natural rotation (360°), independent of the FOV. This means that with an HMD the user may not need to use a joystick to

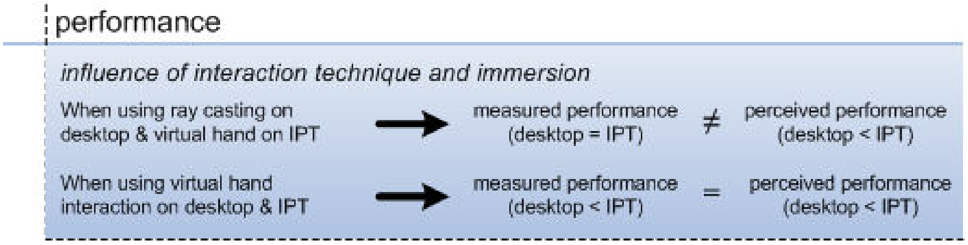


**Figure 9. correlation diagram of perceived and measured performance**

rotate, but rather uses its own body [30]. In contrast, the desktop has the smallest FOV of all the tested displays, yet the locomotion recorded during the trial was very low. The reason for this appears to be based upon the ray-casting manipulation of objects. The user did not need to get close to the object, but could do everything from a remote place, from which the whole scene could be observed. However, in previous trials this behaviour was reason for complaint as other collaborating users could not see the correlation between a user and the object they were interacting with [3, 21]. In addition, working from a remote place is only possible if the given environment supports such behaviour, for example - a world without walls or very large rooms.


**Figure 10. correlation diagram of manipulation technique**

Therefore, in a subsequent trial to this study we asked users to repeat the task on the desktop, first from a remote location (using ray-casting) and second from a location close to the object (virtual-hand). The result was that the time taken to perform the task doubled for the close-up trial (mean of 9.4min). Therefore we can hypothesise that if we try to improve the collaboration between users by allowing only close-object interaction, time-performance for desktop user will drop due to their limitation in FOV hence resulting in extended locomotion time to orientate (see Figure 9). In addition, a study from Steed et al. [16], that compared ray casting and virtual-hand interaction on HMD and CAVE displays, found that virtual-hand is superior for selection and manipulation of objects (Figure 10).

This study looked into influences on a single user task. Those influences sustain in a co-presence situation and may even enhance. For example, problems with interface and manipulation of objects can interrupt the workflow in a closely-coupled situation [31]. The previous studies showed that people have a higher perception of the performance of an immersed user, independent of the assessment of themselves or others [2]. They also show a significant difference between two immersed users and a desktop user, which was related to the ease of manipulation and navigation.

## Conclusion

The measurement of performance is always difficult to achieve, as it depends on the way we measure and how measurable a task is. This applies as well for performance in a virtual environment. We may be able to measure the time it takes to finish a task, but as this study shows this is not necessarily reconciled with perceived performance.

In previous studies we *measured* an increase of performance in a collaborative task for CAVE-like displays [2], yet no such difference could be measured on a single user task. At the same time both showed an increase of *perceived* performance. Since the display and application properties were identical for the studies, it can be concluded that the *measured performance increase is due to the collaboration*. It seems that CAVE-like displays are better at representing contribution of others, but can trick a single user into thinking they are achieving more than they truly are.

This study has shown that different factors lead to an increasing perception of presence and performance. Factors, such as FOV, manipulation technique and navigation, may as well influence a user's interaction and its effect on other participants in a collaborative task (e.g. no fragmented workflow).

Our studies have focused on a structured task designed for closely coupled collaboration; it remains to be seen how our results affect other task designs.

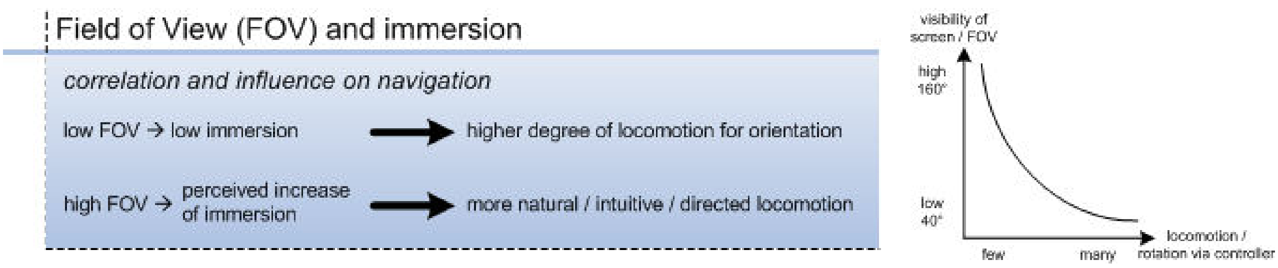


**Figure 11 a & 11 b. correlation diagram of field of view and its influence on navigation**

## Reference


[1] "Access Grid" URL:www.accessgrid.org, 2005.

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

[3] Hindmarsh, J., Fraser, M., Heath, C., Benford, S., and Greenhalgh, C., "Object-Focused Interaction in Collaborative Virtual Environments", *ACM Transactions on Computer-Human Interaction (ToCHI)*, vol. 7 (4), pp. 477-509, 2000.

[4] Fraser, M., Benford, S., Hindmarsh, J., and Heath, C., "Supporting Awareness and Interaction through Collaborative Virtual Interfaces", *In Proceedings of 2th Annual ACM Symposium on User Interface Software and Technology (UIST'99)*, pp. 27-36, 1999.

[5] Lapointe, J.-F. and Vinson, N. G., "Effects of Joystick Mapping and Field-of-View on Human Performance in Virtual Walkthroughs", *In Proceedings of the 1st International Symposium on 3D Data Processing Visualization and Transmission*, Padova, Italy, pp. 490-493, 2002.

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

[7] Tan, D. S., Gergle, D., Scupelli, P. G., and Pausch, R., "With Similar Visual Angles, Larger Displays Improve Spatial Performance", *In Proceedings of Conference on Human factors in Computing Systems (CHI)*, Ft. Lauderdale, Florida, USA, pp. 217-224, 2003.

[8] Guimbretière, F., "Fluid interaction for high resolution wall-size displays". Stanford University, Stanford, CA, 2002.

[9] Dudfield, H. J., Macklin, C., Fearnley, R., Simpson, A., and Hall, P., "Big is better? Human factors issues of large screen displays with military command teams", *In Proceedings of People in Control*, pp. 304-309, 2001.

[10] Mortensen, J., Vinagayamoorthy, V., Slater, M., Steed, A., Lok, B., and Whitton, M. C., "Collaboration in Tele-Immersive Environments", *In Proceedings of Eighth Eurographics Workshop on Virtual Environments*, Barcelona, 2002.

[11] Brooks, F. P., "What's Real About Virtual Reality?" *IEEE Computer Graphics & Applications*, vol. 19 (6), pp. 16-27, 1999.

[12] Mine, M. R., Brooks, F. P. J., and Sequin, C. H., "Moving Objects In Space: Exploiting Proprioception In Virtual-Environment Interaction", *In Proceedings of SIGGRAPH 97*, Los Angeles, CA, 1997.

[13] M.J.Schuemie, P. v. d. S., M.Krijn. C.A.P.G.van der Mast, "Research on Presence in VR: a Survey", *Cyberpsychology and Behavior*, vol. 4 (2), pp. 183-202, 2001.

[14] Bowman, D. A., Johnson, D. B., and Hodges, L. F., "Testbed Evaluation of Virtual Environment Interaction Techniques", *Presence: Teleoperators and Virtual Environments*, vol. 10 (1), pp. 75-95, 2001.

[15] Poupyrev, I., Weghorst, S., Billinghurst, M., and Ichikawa, T., "Egocentric object manipulation in virtual environments: empirical evaluation of interaction techniques", *Computer Graphics Forum*, vol. 17 (3), pp. 41-52, 1998.

[16] Steed, A. and Parker, C., "Evaluating Effectiveness of Interaction Techniques across Immersive Virtual Environment Systems", *forthcoming in Presence: Teleoperators and Virtual Environments*, vol. 14 (5), 2005.

[17] Schroeder, R., Steed, A., Axelsson, A. S., Heldal, I., Abelin, A., Widestroem, J., Nilsson, A., and Slater, M., "Collaborating in networked immersive spaces: as good as being there together?" *Computers and Graphics*, vol. 25, pp. 781-788, 2001.

[18] Bowman, D. A., Gabbard, J. L., and Hix, D., "A Survey of Usability Evaluation in Virtual Environments: Classifcation and Comparison of Methods", *Presence: Teleoperators and Virtual Environments*, vol. 11 (4), pp. 404 - 424, 2002.

[19] Kjeldskov, J., "Interaction: Full and partial Immersive Virtual Reality Displays", *In Proceedings of IRIS24*, pp. 587-600, 2001.

[20] Bowman, D., Datey, A., Ryu, Y., Farooq, U., and Vasnaik, O., "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*, pp. 2134-2138, 2002.

[21] Roberts, D., Wolff, R., Otto, O., Kranzlmueller, D., Anthes, C., and Steed, A., "Supporting Social Human Communication between Distributed Walk-in Displays", *In Proceedings of VRST 2004*, pp. 81-88, 2004.

[22] Carlsson, C. and Hagsand, O., "DIVE - A platform for multi-user virtual environments", *Computers & Graphics*, vol. 17 (6), pp. 663-669, 1993.

[23] Frécon, E., Smith, G., Steed, A., Stenius, M., and Stahl, O., "An Overview of the COVEN Platform", *Presence: Teleoperators and Virtual Environments*, vol. 10 (1), pp. 109 - 127, 2001.

[24] Frécon, E. and Stenius, M., "DIVE: A Scalable network architecture for distributed virtual environments", *Distributed Systems Engineering Journal (special issue on Distributed Virtual Environments)*, vol. 5 (3), pp. 91-100, 1998.

[25] Greenhalgh, C. M., Bullock, A., Frécon, E., Lloyd, D., and Steed, A., "Making Networked Virtual Environments Work", *Presence: Teleoperators and Virtual Environments*, vol. 10 (2), pp. 142-159, 2001.

[26] Mortensen, J., Vinayagamoorthy, V., Slater, M., Steed, A., Lok, B., and Whitton, M. C., "Collaboration in tele-immersive environments", *In Proceedings of Proceedings of the workshop on Virtual environments 2002*, Barcelona, Spain, pp. 93 - 101, 2002.

[27] Steed, A., Mortensen, J., and Frécon, E., "Spelunking: Experiences using the DIVE System on CAVE-like Platforms", in *Immersive Projection Technologies and Virtual Environments*. Wien: Springer-Verlag, 2001, pp. 153-164.

[28] Sitzman, K., "Likert type questions may be helpful for baseline inquiry", *AAOHN Journal*, vol. 51 (7), pp. 320, 2003.

[29] Slater, M., "Measuring Presence: A Response to the Witmer and Singer Presence Questionnaire", *Presence: Teleoperators and Virtual Environments*, vol. 8 (5), pp. 560-565, 1999.

[30] Bowman, D., Datey, A., Ryu, Y., Farooq, U., and Vasnaik, O., "Empirical Comparison of Human Behavior and Performance with Different Display Devices for Virtual Environments", *In Proceedings of Human Factors and Ergonomics Society Annual Meeting*, pp. 2134-2138, 2002.

[31] Hindmarsh, J., Fraser, M., Heath, C., and Benford, S., "Virtually Missing the Point: Configuring CVEs for Object-Focused Interaction", in *Collaborative Virtual Environments. Digital Places and Spaces for Interaction*. London, UK: Springer Verlag, pp. 115-139, 2001