Sometimes, there are moments in our life when it is hard to believe that the goal that you were aiming for has finally been reached. For me, such a moment was the journey towards a PhD degree. It was not always a smooth and easy way, but thanks to a lot of people I am finally there. So now it is time to look back and to express my sincere gratitude to all who supported me in these last four years and without whom this journey would not even be possible at all.

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Abstract

Collaboration between people is an essential component of daily life. With the growing use of computer technology in the last decades, it has become possible to interact with other people not only in real life but also virtually through collaborative virtual environments. Collaborative virtual environments are computer-based virtual spaces that enable users, although geographically dispersed, to be present in the same environment and to collaborate with each other.

When creating a collaborative virtual environment one of the main challenges is to provide users with the ability to interact with each other in a natural and realistic manner. A lot of research has been done in this area; however, this primarily focused on the realism of modern applications that is mainly achieved by the provision of advanced three-dimensional visualization and audio. Although common in real life, collaboration in which people are directly depending on each other, remains quite limited in virtual environments. In our research, we explore ways to enhance the collaborative user experience in virtual environments with the main goal of achieving a more realistic and satisfying interaction between users.

The first part of this dissertation studies collaboration in virtual environments in general. Through a number of formal experiments, we determine which factors contribute to a satisfactory user experience when performing highly interactive tasks in virtual environments. Firstly, we explore the applicability of different levels of collaboration, that occur in real life, in a multi-user virtual environment. In particular, we analyze and compare the influence of loosely-coupled and closely-coupled collaboration when working together in a virtual environment, and how these two levels of collaboration affect user experience. Afterwards, we address several challenges that have to be taken into account when creating collaborative user environments. In particular, we investigate to what extent the combination of different technologies used by the collaborators to interact with the environment influences the collaborative user experience. Besides the technological differences, users themselves may have varying abilities and prefer-
ences when working together. Therefore, as a next step we study how to accommodate the user diversity in order to enhance group performance.

The second part of this dissertation is dedicated to study what contributes to the collaborative user experience in a specific domain – multiplayer games. Based on the positive reaction towards closely-coupled interaction in 3D virtual environments observed in the first part of our research, we now investigate to what extent it is beneficial in the context of multiplayer games. Afterwards, we discuss the issues arising when integrating closely-coupled collaboration in games, namely the impact of different network impairments on collaboration and the communication between players. Our research on collaboration in games is concluded by looking into the solutions to achieve an improved collaborative user experience in a co-located gameplay, i.e. games for a tabletop surface. Throughout the second part of the dissertation, by performing several user experiments with existing and custom developed games we highlight the main factors that facilitate a better collaborative experience among players.

By studying collaboration between users in virtual environments and multiplayer games, we have shown several important implications with regards to providing natural collaboration. We believe that applying these findings will lead to designing better collaborative virtual environments and as a result to more satisfied users.
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Chapter 1

Introduction

1.1 Motivation

The social nature of humans dictates that many of their daily activities require collaboration with others. There are multiple reasons and scenarios for these social interactions: working together, sharing knowledge and expertise and performing tasks that are hard or even impossible to accomplish individually. Besides these serious matters, there is also a clear desire towards social entertainment, for example by attending parties or playing games. It is not surprising that, with the pervasive use of computer technology and advanced means of communication offered by state of the art networks, interaction with others in an efficient or fun manner is regarded by many as a universal and primary need, regardless of physical location. Collaborative virtual environments (CVEs), which are the primary topic of research in this dissertation, can satisfy this demand in a number of situations.

Collaborative virtual environments are computer-based, distributed, virtual spaces where users can meet and interact with others (Churchill et al., 2001). Similar to single-user virtual environments (VEs), they aim to make users perceive themselves to be in another place than where they actually are. Enabling numerous users to be present in the same environment, CVEs provide tools that allow users to collaborate with each other. Collaboration in virtual environments refers to the interaction between two or more people through a virtual environment and its objects in order to achieve a common goal (Collins English Dictionary, 2012). The development of
three-dimensional (3D) collaborative virtual environments has been growing vastly and matured over the last years. This fact can be demonstrated by a considerable amount of significant research and real applications in various fields, such as architecture and design, medical and health care, military, and entertainment (Steed and Oliveira, 2009).

Despite this growing number of CVE applications, there are still many open questions motivating researchers in the field. One of the biggest challenges is related to the *realism* of such collaborative environments, the tendency to represent things as they really are in life. Many researchers are trying to make virtual worlds seem as realistic as possible. A multitude of visual and other sensory input and output devices, as well as processing techniques, are used to achieve these goals. Powerful graphical applications, along with e.g. 3D sound systems, can truly immerse the person into the ‘reality’ of the virtual world. On the other hand, relatively little attention is paid to the topic of natural and intricate interactions within this environment. Supporting realistic collaboration in virtual environments is a very complex task as a group of people may interact in a number of ways. Due to this complexity, interaction in multi-user applications is often reduced to merely communication or an individual contribution to the overall goal. Although common in real life, collaboration in which people are directly depending on each other is very limited in virtual environments. Therefore in this dissertation, we are motivated to explore ways on how to enhance collaboration in virtual environments by integrating simultaneous interaction between users in order to achieve more satisfying.

### 1.2 Towards Realistic Interaction in Collaborative Virtual Environments: Problem Statement and Research Questions

Supporting natural interaction between users in virtual environments is not a trivial task. To achieve a realistic and efficient collaboration, it is important to determine the factors that contribute to the user experience in multi-user virtual environments. As mentioned earlier, realism in modern applications is mainly achieved by the provision of advanced three-dimensional visualization and audio while the interaction, typical in real life, remains quite limited. In particular, several people can collaborate at different levels, e.g. more independently from each other or, oppositely, cohesively, interacting with the same objects simultaneously. Furthermore, this simultaneous interaction in a 3D environment is more complex compared to real life situations due to the amount of different 3D interaction techniques and interactive tasks that may not always be
1.2 Towards Realistic Interaction in Collaborative Virtual Environments: Problem Statement and Research Questions

Intuitive for users. These tasks can be performed using special 3D devices, and thus causing extra difficulties for the users being not always straightforward or easy to learn. Collaboration between users in virtual environments may also be restrained by the variety between the users themselves. Similarly to real life collaboration, people with different abilities, preferences and experiences may be working together.

These challenges determine the main goal of our research: to define and understand the factors that contribute to the simultaneous collaboration in virtual environments, where actions of users are directly influenced by others, in order to facilitate natural and realistic interaction between people. To achieve this high-level goal we have divided the problem into a number of more concrete research questions that we will address in this dissertation.

RQ1 How can the introduction of different levels of collaboration improve the user experience in collaborative virtual environments?

Collaboration in real life can be more independent or, oppositely, cohesive, requiring several people to act simultaneously. These two levels of collaboration are often referred to as loosely-coupled and closely-coupled collaboration (Roberts et al., 2003). An example of loosely-coupled collaboration can be a scenario where several people have to decorate an apartment together, but every person is responsible for a separate room. In such a way they all work together towards a shared goal, ‘decorated apartment’, but contribute individually to this overall goal. In this situation, it is often possible to achieve the final goal without involving other people, but there are definite advantages resulting from the collaboration (i.e. quicker accomplishment). In the case of closely-coupled collaboration, actions of one user immediately impact the performance of others. A typical example of closely-coupled collaboration is moving heavy objects together, where two or more people are involved in carrying the object and have to coordinate their moving speed and/or height of lifting.

Being very common in real life, these two levels of collaboration have received different amount of attention in virtual environments. Most existing collaborative virtual environments utilize different forms of loosely-coupled collaboration. For example, users can freely navigate within the environment, communicate and perform different activities individually. Having a more complicated nature, closely-coupled collaboration is limitedly used in CVEs. However, this type of shared work can add more realism to the virtual collaboration, being more familiar to users from ‘real’ daily activities.

To investigate the potential of closely-coupled collaboration in virtual environments, we compare two types of shared work in a formal experiment. The description and results of the experiment are presented in Chapter 3, where the benefits and drawbacks
of each level of collaboration are identified. Based on the comparison, we determine what contributes to the user experience when users collaborate in a loose or close manner. As the goals of collaboration may differ across application types (performance vs. preference), we analyze which type of shared work is more efficient or preferred among the users.

**RQ2 How do the different technologies, used by people working together in a virtual environment, influence their experience?**

It is often the case that several people have to work together within a same environment, while accessing it using completely different technologies. The variety of these technologies and resources available to everyone nowadays leads to the question of how to combine them efficiently into heterogeneous setups. For example, the use of different interaction devices can facilitate an efficient allocation of activities between collaborators based on their abilities.

On the other hand, differences in user abilities due to this heterogeneity may lead to an unbalanced performance. This may cause decreased efficiency and, as a result, negatively affect the user experience and the outcome of the group work. For example, some collaborators may use a standard desktop computer while their partners are immersed in the environment through a CAVE technology. In such situations, the restrictions caused by using a small non-immersive display may lead to a lower contribution of the desktop user. This, in turn, can reduce a person's motivation to collaborate further leading to a decreased outcome of shared work. At the same time, it simply might not be possible to provide every user with his/her most preferred means of interaction (e.g. specific input or output device). The possible negative effect of combining different technologies in one setup, is particularly important in situations where the priority lies in motivating people to continue using collaborative applications (e.g. video games).

These considerations bring us to the investigation that is presented in Chapter 4. Here, we study the effect of heterogeneity of different input devices on the outcome of the collaboration. We have chosen this category of interaction devices since the ability to interact with a virtual environment contributes to the feeling of being present and leads to an efficient performance. We want to see whether or not a combination of different input devices negatively impacts the outcome of the collaboration by comparing this setting with a homogeneous setup, where the same input devices are involved.
1.2 Towards Realistic Interaction in Collaborative Virtual Environments:
Problem Statement and Research Questions

RQ3 How does the support for communication between people working together in a virtual environment influence their experience?

Collaborative work is often supported by communication, both in real and virtual environments. It requires the negotiation not only of task related content, but also of task structure in terms of roles and activities and task/sub-task allocations. As will be shown further in Chapter 4, a lot of researchers have studied the role of communication and its influence on the collaborative performance. Different forms of communication (e.g. verbal, non-verbal) are being widely applied in the more recent collaborative virtual environments, resulting in numerous investigations on their influence on group work.

At the same time, there might be conditions when communication is not desirable or not even possible. In this case, there is a need to know how the collaboration in virtual environments is affected by the lack of communication. The role of communication on the outcome of shared work is addressed in Chapter 4. With the help of a user experiment, we study the impact of communication on user performance. More specifically, we investigate how the presence and absence of communication influences the efficiency of users and the perceived level of collaboration when performing a highly-interactive task.

RQ4 How to accommodate the user diversity in a virtual environment in order to enhance the outcome of the group performance?

When a team of people get together to accomplish a certain task, their levels of experience, backgrounds or performance abilities may vary greatly. For instance, a great variation in performance of each user when performing tasks in a collaborative virtual environment may cause a gap in their collaboration and eventually decrease the outcome of shared work. To accommodate the user diversity in CVEs, providing adaptation can be considered as a prospective solution to minimize the gap between user performances.

Adaptation performed separately for each user does not necessarily lead to an adaptive collaborative environment. In fact, it is important to take into account the characteristics and needs of all people involved in a collaborative task. To determine the adaptation, we suggest to model a group’s behaviour based on users’ individual performances and preferences. Chapter 5 presents several approaches (and their validation based on the formal experiment) to provide adaptation according to the context of users based on the goal of collaboration. As a result of the adaptation, every collaborator obtains a specific role (e.g. certain task), which is defined based on the modeling of group behaviour.
After addressing these questions regarding collaboration in virtual environments in general, we aim to investigate what contributes to the collaborative user experience in a specific domain – video games. We choose this type of multi-user virtual environments as the one that widely utilizes collaboration between users. Therefore, integration of different forms of collaborative activities that provide realistic and engaging gameplay is considered beneficial for the video games.

RQ5 To what extent are findings from RQ1, regarding levels of collaboration, applicable in a specific domain, namely multiplayer games?

After a general discussion regarding introducing different levels of collaboration (RQ1) in virtual environments and the ways collaboration in these environments can be enhanced (RQ2, RQ3 and RQ4), we intend to investigate the integration of collaboration (and especially closely-coupled collaboration) in environments which are developed for multiplayer games.

Analyzing existing games, we have observed that closely-coupled collaboration is lim- itedly used, being mainly applied in games for co-located play. At the same time, the few existing games that do incorporate close collaboration between players became highly popular among gamers. This popularity provides some indications regarding the potential of closely-coupled collaboration, that has not yet been fully investigated.

Chapter 6 presents an experiment, where games for remote play, based on loosely-coupled and closely-coupled collaboration, are compared. We define several ways players can interact with each other that are based on cooperative game design patterns and studied them separately for two levels of collaboration. By comparing patterns that represent loosely- and closely-coupled collaboration we reveal several design lessons regarding the integration of these two levels of collaboration in games. This discussion is continued in Chapter 7, where the question of integration of different levels of collaboration is addressed for a specific game type – casual games.

RQ6 How does network quality affect multiplayer video games based on closely-coupled collaboration?

While loosely-coupled collaboration has already been used in a substantial amount of games, games based on closely-coupled collaboration are still relatively new on the market. One of the possible reasons for that lies in the challenges to design such collaboration caused by a more complex nature of closely-coupled collaboration. For instance, closely-coupled collaboration requires almost constant coordination and synchronization of the users’ activities. Therefore, we want to investigate one of these
1.2 Towards Realistic Interaction in Collaborative Virtual Environments: Problem Statement and Research Questions

challenges, namely network quality, that in our opinion is among the most important (from perspective of interaction) when it comes to providing an enhanced player experience in closely-coupled collaborative games.

Collaborative virtual environments involve a group of people working together that can be present in different locations. In this case all collaborators are connected over the Internet. However, applications deployed on the Internet are often affected by network quality. Among other network impairments, presence of delay, jitter and packet loss affect interaction in collaborative virtual environments the most. Therefore, it is important to investigate the influence of these parameters on user performance and satisfaction, to be able to define the level of user acceptability for these impairments. One of the key issues here is the variety of this acceptability level based on the type of application. For example, the requirements for systems that do not involve direct interaction between participants may be lower than in applications in which participants are in constant interaction.

Our research on the quality of network in multiplayer games is presented in Chapters 8 and 9. In Chapter 8 we discuss the impact of delay and jitter in games that involve a lot of closely-coupled collaboration. One might imagine that these kinds of games are more sensitive to network quality, as they require very intricate and synchronized actions between several players. Therefore, the presence of the network impairments may decrease the player satisfaction in playing the game and have a negative impact on his/her choice to play the same game in the future.

Chapter 9 presents a study on the influence of packet loss on the interaction in collaborative virtual environments. Besides the impact on user actions in multi-user environments, packet loss is distinguished as one of the main error types encountered in multimedia communication. Realizing the importance of communication during collaboration (RQ3), we aim to investigate to what extent packet loss affects user experience in games. For our research, we choose a serious game for rehabilitation, as an example of an application where communication is not only occasionally needed to accomplish the task but is continuous and does not necessarily relate only to the performed actions.

RQ7 How can co-located collaboration be enhanced in multiplayer games?

Up till now we have been discussing a number of ways to improve remote collaboration between players in multiplayer games. Due to its nature, a co-located setup is often considered by default ‘more collaborative’ when compared to a remote one, as people can see and perceive each other’s activities naturally. This often results in neglecting the necessity to investigate how the collaborative experience of users can be enhanced
in such co-located virtual environments. Therefore, at the end of this dissertation we want to focus on investigating the possible solutions to provide an even better collaborative experience in virtual environments, using the example of a multiplayer video game. In particular, we look into different forms of game help systems as a prospective solution to increase the level of collaboration between players in a co-located setup.

Multiplayer games present their rules to the players in multiple ways. We envisage that the utilization of certain forms of help representation may serve as an additional source to increase the amount of collaboration between players within the game. We check this assumption in Chapter 10, where we compare several types of game help in a collaborative setting. As an example of game we select a collaborative game played on a tabletop. This particular technology is used as the one that encourages group interaction around an interactive setup in a way that other computer workstations do not, providing a very high level of collaboration among its users.

1.3 Research Approach

In our research, we attempt to determine what factors contribute to the satisfactory user experience in collaborative virtual environments in general, and also in multiplayer games. In the form of research questions, we propose several solutions to increase the level of collaboration between players, that we believe will lead to a more enjoyable and realistic shared work and play. Answering these questions enables us to provide some indications regarding the ways on how to achieve more natural collaboration in virtual environments that is familiar to users from real life collaboration. We consider our findings as the first step towards more general conclusions in the area of collaborative user experience and natural collaboration in virtual environments.

In the applications considered in our research, users are directly involved in interaction. Therefore, it is nearly impossible to make conclusions regarding the proposed solutions before the actual testing takes place by users themselves. As a consequence, we involved experimental investigations (Lazar et al., 2010) to study the influence of various factors on the collaborative user experience. This research method allows us to define causal relations between the factors under investigation. To answer the research questions presented in Section 1.2, a number of formal experiments have been conducted to analyze user experience under controlled conditions. In the experiments, we determine what contributes to the efficiency of group performance and the level of collaboration between players. Furthermore, as we also consider virtual environments designed for the specific purpose of entertainment, we analyze what
characteristics are important to provide users with an enjoyable and fun experience. For every experiment, where we need to control a certain factor or to expose users to a specific condition, custom developed environments and games are involved. However, if a study focuses on more general investigation of user behaviour and performance, we use existing (commercial) applications.

In order to know whether or not a certain factor has an important impact on user experience it has to be evaluated. However, evaluation of interaction in CVEs is not always easy due to the absence of an unified approach to do it. One of the reasons for this complexity is the diversity of applications based on collaborative virtual environments, facilitating different types of shared work. Several frameworks have been suggested (Steed and Tromp, 1998; Goebbels et al., 2003), defining general evaluation goals as the degree and ways in which the CVE allows users to feel present and aware of each other within the virtual world. The specific evaluation goal, however, remains always application dependent.

To evaluate interaction in virtual environments in the context of this dissertation, we adopt the approach of Heldal et al. (2005). Most methods used to evaluate group performance in a virtual environment are quantitative and qualitative. Quantitative methods are based on performance measures (objective measurements) and responses to different questions (subjective measurements), using techniques such as Likert and rating scales. The results obtained with these methods can provide valuable insights, but may be sometimes limited (e.g. evaluation scale does not have enough answer options to represent the user state, or the user is not sure what answer option actually corresponds to his/her state). A second set of methods is qualitative, using, for example, observations of how people collaborate, and analyzing their responses to open-ended questions. These methods allow us to examine the same phenomena from different angles. Performing qualitative analysis is considered to be useful to confirm and explain the findings obtained from the quantitative evaluation. Both these methods are used for most of the experiments presented in this dissertation.

1.4 Dissertation Overview

This dissertation consists of two main parts. The first part investigates the ways the collaboration in general virtual environments can be enhanced. Subsequently, the second part discusses how we can integrate the general knowledge of factors that contribute to the collaboration between users that are obtained in the first part, into a specific domain. In particular, we will look into collaboration in multiplayer video
games, that have become tremendously popular, one of the reasons being the availability of collaboration with other players.

In the first chapter of Part I, Chapter 2, we introduce general terminology regarding collaborative virtual environments and discuss the most typical examples of such environments that exist and are widely used nowadays. In this chapter, we also present a historical overview of collaborative virtual environments from early till modern applications in order to track the evolution of interaction that occur in these environments. In Chapter 3, we analyze and compare two levels of collaboration, loosely-coupled and closely-coupled, that occurs in a virtual environment in order to determine the benefits and drawbacks of each level (RQ1). This is followed by an experiment where we investigate the role of setup and communication in collaborative virtual environments in Chapter 4 (RQ2 and RQ3). Chapter 5 concludes Part I of this dissertation, where we discuss the ways to accommodate the diversity of people involved into a virtual collaboration (RQ4).

Having discussed ways to improve collaboration in virtual environments in general, Part II follows an investigation of the integration of realistic and enhanced collaboration in virtual environments with a more specific purpose (RQ5). In particular, we choose the domain of video games, as the example of applications widely utilizing the concept of collaborative play. First, similarly to the general Part I, we discuss different levels of collaboration that occur in games in Chapter 6. More specifically we focus on integration of closely-coupled collaboration in games as this type of shared activities remains still very limitedly used in games. This discussion is continued in Chapter 7, where we address the question of integration of two levels of collaboration in casual games. Due to its nature, closely-coupled collaboration leads to certain challenges that have to be taken into account when designing collaborative games. One of these challenges, namely the network quality, is studied in Chapters 8 and 9 (RQ6). In particularly, we discuss the influence of network delay, jitter and packet loss on applications supporting closely-coupled collaboration and rich communication. In the last chapter of Part II, Chapter 10, we investigate how the collaborative gaming experience can be enhanced in a co-located setting based on the example of a tabletop game (RQ7).

As a concluding chapter of this dissertation, Chapter 11 is dedicated to present the conclusions and future research directions of this dissertation.
Part I

Collaboration in Virtual Environments
Chapter 2

Collaboration in Virtual Environments: an Overview

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2.1 Introduction

Collaboration is an essential part of our everyday life. We work together with others to achieve common goals or be more efficient, we share our knowledge and expertise or collaborate even just for fun (Figure 2.1a). Not unsurprisingly we demand more and more hi-tech means of communication. For instance, companies start to team up globally dispersed people to perform shared activities within a virtual environment in order to prevent excessive traveling (Figure 2.1b). Situations where very complex tasks have to be performed by a group of people are not only a fact in real life, but are also becoming more common in virtual environments. The additional value of interaction through a shared virtual environment can be seen by the growing popular-
Collaboration in virtual environments is more complex when compared to other types of collaborative work. In a collaborative virtual environment, a group of users performs highly interactive tasks with the use of three-dimensional (3D) user interfaces. It is more complex compared to real life situations due to the amount of different 3D interaction techniques and interactive tasks that may not always be intuitive for users. Moreover, the usage of special 3D input devices can cause extra difficulties for the users. Most computer applications have traditionally used text-based input (keyboard) and 1 or 2 degrees of freedom (DOF) devices (e.g. mouse, joystick). 3D input devices provide more DOF to navigate and manipulate in virtual environments, which is not always straightforward and easy to learn for novice users. Additionally, globally dispersed users are often exposed to the network impairments typical for the Internet that may hinder communication and collaboration. Obviously, there is a need to investigate ways to overcome these complexities, and thus, enhance the efficiency of group work in a virtual environment.

This chapter provides an overview of collaborative virtual environments and highlights some challenges that arise when designing such environments. We start with relevant terminology and a historical overview related to collaborative virtual environments. Leaving the nuances of the systems’ architecture out of scope in this overview, we focus on the way in which interaction is supported between users. Afterwards ongoing research in the field is briefly discussed to outline the main challenges when
implementing highly interactive collaborative virtual environments. These challenges are studied more thoroughly in the next chapters.

2.2 What is a Collaborative Virtual Environment?

One of the most commonly used definitions of a collaborative virtual environment (CVE) is given by Churchill et al. (2001). They define a collaborative virtual environment as a computer-based, distributed, virtual space or set of places. In such places, people can meet and interact with others, with agents or with virtual objects. Collaborative virtual environments (CVEs) might vary in their representational richness from 3D graphical spaces, 2.5D and 2D environments, to text-based environments. Access to CVEs is by no means limited to desktop devices, but might well include mobile or wearable devices, public kiosks, etc.

Collaborative virtual environments have been referred to by many different names over the years (Singhal and Zyda, 1999). In particular, the terms networked (NVE), distributed (DVE) or shared virtual environments (SVE) will be used interchangeably throughout this dissertation.

Collaborative virtual environments are inhabited with numerous users, represented in some form of embodiment or avatar (Churchill and Snowdon, 1998). When present in an environment, users can freely navigate through the space encountering each other and interact with the environment or with other users. Such interaction often consists of communication, information exchange and modifying the environment either individually or simultaneously with other users (Ruddle et al., 2002). Due to its complex nature, supporting the latter type of interaction has been identified as one of the main challenges among researchers in the domain of collaborative virtual environments.

Churchill et al. (2001) and Singhal and Zyda (1999) consider a collaborative virtual environment as a space for real-time distributed collaboration, where users are dispersed over several physical locations. Although the focus of our research aligns with their definition, we realize its limitations. Analysis of numerous works in the area, allows us to extend these definitions by also considering non-real-time and co-located forms of shared work, where users are present at the same location. Additionally, in our work we will primarily consider 3D collaborative virtual environments, where users perform highly interactive tasks. These imply an immediate reaction of the system to the action of a user that may also have an impact on other users within the same environment (e.g. manipulation of a virtual object).

Numerous applications exist nowadays that are built on top of CVE technology and allow multiple users to perform different group activities. Based on their purpose,
Collaboration in Virtual Environments: an Overview

Figure 2.2: Examples of applications based on CVEs.

these applications can be categorized in several groups. Virtual interactive communities (Figure 2.2a) encourage interaction between geographically dispersed users with the main purpose of socializing and communicating with the help of different tools (e.g. message boards, chat rooms, social networking sites, or virtual worlds). Similarly, massive multiplayer online games (Figure 2.2b) allow users to interact with each other but here this interaction happens through certain game activities. The main purpose of these applications is entertainment which is achieved by playing a game together. The last type, applications for collaborative work (Figure 2.2c), include virtual environments that are designed for a more serious purpose. Examples of such applications can be telepresence systems that facilitate virtual meetings, or multi-user CAD applications. These and other examples of applications based on CVEs are discussed later in this chapter.
2.3 Evolution of Interaction in Collaborative Virtual Environments

Smooth and realistic collaboration between several people within a virtual environment has been one of the primary goals among researchers and developers since the first networked applications. The early networked multi-user environments were developed under military programs, and required expensive hardware making them unavailable for a large user community. However, the evolution and use of collaborative virtual environments have coincided with the advances in software and hardware technologies. These technology advancements have provided academia, business, and government with new opportunities, that enable the creation of less expensive and more enhanced forms of virtual environments. Figure 2.3 represents an overview of the existing collaborative virtual environments from the perspective of the supported forms of interaction and the amount of concurrently present users.

![Figure 2.3: An overview of different types of interaction supported in the existing collaborative virtual environments.](image)

2.3.1 Until the End of the 1990s

One of the earliest collaborative virtual environments can be traced back to the beginning of the 1980s. Then, the first successful large-scale real-time networked virtual environment SIMNET (Figure 2.3) was implemented by DARPA (Defense Advanced
Research Projects Agency) (Calvin et al., 1993). SIMNET is a network of simulators for military purposes, that supports several types of training (tanks, aviation, etc.) (Figure 2.4). The idea of SIMNET lies in the creation of a virtual battlefield arena that facilitates early phases of training at a cost far below the expense of operating real vehicles or conducting real exercises. The range of SIMNET applications goes from training tank drivers with a console that models the interior, controls, and external views provided in a real tank to tactical planning sessions for battlefield commanders.

The interaction in SIMNET was limited to information exchange between different objects. Two types of objects were present in the environment: static (e.g. terrain) and dynamic (e.g. participants, vehicles) objects. Objects could interact with each other through a series of events that allowed keeping the environment updated with these changes. Events in SIMNET are messages to the network indicating a change in the world or the state of an object. An example event that would be transmitted as a message might be that the tank is turning right or has fired its gun. Although not being able to interact directly with other people present in the environment, SIMNET users could perceive them and see individual changes made by them.

Being initially implemented over local area network, SIMNET was extended with the Distributed Interactive Simulation (DIS) protocol that provided the possibility for wide-area simulation exercises. The purpose in establishing DIS was to allow participation in the DIS virtual environments by any type of player on any type of machine from geographically dispersed sites.

Another CVE, initially developed for military purpose, was NPSNET (Figure 2.3), developed by the Naval Postgraduate School (Macedonia et al., 1995; Capps et al., 2000). It is a networked VE system designed for training (Figure 2.5) and simulation with the
goal of supporting large numbers of participants. Several versions of NPSNET were developed. While the earlier versions of NPSNET were designed for local networks, the later versions supported interoperation with SIMNET and were compliant with the DIS protocol. These versions were used for numerous studies on interaction in multi-user large scale environments, being deployed (and extended) in over a hundred military and civilian laboratories. Similar to SIMNET, the focus of this application was to support numerous simultaneous users, while interaction between them remained limited. NPSNET was capable of simulating articulated humans, seagoing vessels and ground and air vehicles. However, besides the information exchange between these objects (e.g. position), NPSNET also allowed adding new entities to the scene including user-defined models which was not possible in earlier CVE systems.

Although networked virtual environments are still widely used in the military (Stackpole, 2008), at a certain moment the army was no longer the sole owner and developer of this technology. In the early 1990s interest in multi-user virtual environments shifted from a purely military purpose to research among academia. One of the early academic architectures for implementing multi-user interactive virtual environments, called DIVE (Distributed Interactive Virtual Environment) (Figure 2.3), was developed in 1993 at the Swedish Institute of Computer Science (Hagsand, 1996; Frécon and Stenius, 1998). The importance of this environment lies in the first attempt to support more detailed interaction between the participants and the environment. DIVE enabled multiple users to navigate in a 3D space, see and interact with other users and objects. The interaction between users and objects typically consisted of creating, modifying and deleting objects. Interaction between participants happened in the form of communication with the help of text or audio. DIVE applications included
virtual battlefields, virtual meetings, real-world robot control and multi-modal interaction (Figure 2.6a).

BrickNet (Figure 2.3) is an example of a virtual environment toolkit developed at the Institute of System Science in Singapore (Singh et al., 1995), that provides support for graphical, behavioural, and network modeling of virtual worlds. It is primarily aimed at collaborative design environments, where a complete design task is distributed over multiple client workstations. Each site is responsible for its part of the design and for sharing that information with other collaborators. Except design applications, it was intended to be used for collaborative learning environments, entertainment, groupware systems and network-based graphical environments. BrickNet provides dynamic object sharing that allows users to determine which objects are private and which are shared during collaboration.

The Model, Architecture and System for Spatial Interaction in Virtual Environments (MASSIVE) (Figure 2.3) is a multi-user virtual environment for collaboration developed in 1995 at the University of Nottingham, UK (Greenhalgh and Benford, 1995). Massive was designed as an experimental networked CVE for teleconferencing (Figure 2.6b). This system targeted large scale environments, however in reality it was only used for the relatively low number of about 10 simultaneous users. MASSIVE was the first CVE based on the concepts of awareness, which defined the relevance between objects in space. The aura-concept was developed here, that represents a distance to which interaction with other objects is possible. Interaction takes place only when the auras of two objects intersect. In such a way it allowed to define objects that were important for a certain user at each moment in time. In particular, a user could only see the objects present in his/her vicinity. The focus of interaction in this system
was on supporting different forms of communication. When compared to the earlier architectures, MASSIVE provided more enhanced communication. It allowed users to communicate using combinations of audio, graphics, and text media over local and wide area networks.

Another toolkit for creating a multi-user virtual environment was developed by researchers at Mitsubishi Electric Research Laboratory in 1995 and got the name SPLINE (Scalable Platform for Large Interactive Networked Environments) (Waters et al., 1996). The platform provided a convenient architecture for implementing multi-user large-scale (up to several thousands) interactive environments, that was based on a shared world model (Figure 2.3). The SPLINE world model was an object-oriented database that specified all objects, their location and properties. The world model contained information about everything in the virtual world: where things are, what they look like, what sounds they make, etc. Each user had a copy of the world on his/her computer, which was updated through message exchanges which contained the current state of the changed world model. This principle has been adopted from SIMNET, as opposed to sending incremental updates, used in some other applications (Matijasevic, 1997). SPLINE made it easy to build virtual worlds where multiple people interact with each other in a 3D visual and audio environment. In particular, it has been used to develop Diamond park (Figure 2.7a), a virtual environment that combines visual, audio, and physical interaction. It is possible for multiple geographically separated users to speak with each other and participate in joint activities, e.g. biking. In particular, whole-body physical interaction is provided by means of modified recumbent exercise bicycles with variable pedal resistance. Visitors on exercise bicycles are represented in the park as animated bicyclists like those in Figure 2.7b.

Two systems for group collaboration have been implemented at the University of Illinois by Leigh and Johnson (1996); Leigh et al. (1997). CALVIN (Collaborative Ar-
Collaboration in Virtual Environments: an Overview

architectural Layout Via Immersive Navigation) is a prototype interface for VR architectural design and collaborative visualization which emphasizes multiple perspectives (Figure 2.3). In particular, a user can observe the world from an egocentric (inside-out) view, as if standing inside the environment. In this system, developers tried to address the problem of co-presence which was quite actual at the time (Figure 2.8a). This was achieved by using CAVE technology to immerse the participants in a virtual world. Based on CALVIN, multi-user educational (Roussos et al., 1997) (Figure 2.8b) and scientific visualization environments were created. For example, CALVIN allowed collaborating users to edit an architectural design by picking up objects, moving, rotating and scaling them. Another project, CAVERN (the CAVE Research Network), is a continuation and generalization of the work that has been done earlier in CALVIN. CAVERN was another multi-user virtual environment that utilized CAVE technology and high-performance computing resources all interconnected by high-speed networks. Similar to other VE applications developed at this time, CAVERN aimed to support collaboration in design, training and scientific visualization. Using CAVE technology, these architectures allowed more realistic interaction between users mainly by means of immersion.

Table 2.1 summarizes the collaborative virtual environments presented in this section.

2.3.2 Collaborative Virtual Environments in the 21st Century

The systems presented in the previous section were, first of all, focused on supporting large amounts of users (several hundreds), that co-exist in the same world and perceive the changes done by others. Although these applications allowed different forms of communication, interaction between users remained quite limited. In most
2.3 Evolution of Interaction in Collaborative Virtual Environments

Table 2.1: The overview of the supported interaction in the earlier collaborative virtual environments.

<table>
<thead>
<tr>
<th>Name</th>
<th>Purpose</th>
<th>Supported interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMNET</td>
<td>Military</td>
<td>- information exchange between the virtual objects</td>
</tr>
<tr>
<td>NPSNET</td>
<td>Military</td>
<td>- information exchange between the virtual objects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- ability to add new entities</td>
</tr>
<tr>
<td>DIVE</td>
<td>Academic</td>
<td>- interaction with objects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- interaction between people in form of text and audio</td>
</tr>
<tr>
<td>BrickNet</td>
<td>Academic</td>
<td>- object sharing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- distribution of design tasks over clients</td>
</tr>
<tr>
<td>MASSIVE</td>
<td>Academic</td>
<td>- concept of awareness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- enhanced communication in form of combination of audio, graphics and text</td>
</tr>
<tr>
<td>SPINE</td>
<td>Research</td>
<td>- visual, audio and physical interaction</td>
</tr>
<tr>
<td>CALVIN</td>
<td>Academic</td>
<td>- supported immersion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- detailed interaction with objects</td>
</tr>
<tr>
<td>CAVERN</td>
<td>Academic</td>
<td>- supported immersion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- detailed interaction with objects</td>
</tr>
</tbody>
</table>

cases, these systems allowed creation, deletion, individual modification of the objects and perception of other inhabitants in a shared virtual world. From an interactivity perspective, those systems differed greatly from real life collaboration. Support of more natural forms of interaction where one person is often dependent upon his/her collaborators was not so common for these applications. However, from the second half of 1990s this situation started to change drastically.

The evolution of computer technology has resulted in a rapidly growing interest among numerous research organizations and companies, making collaboration in virtual environments affordable for a wider public. The creation of multi-user environments was no longer a privilege of military organizations or big institutions. Numerous small and medium labs started active research in the domain of collaborative virtual environments. This growing popularity has resulted in a first international CVE conference that took place in 1996 in the United Kingdom. We believe that this event was sort of a milestone that defined the future of collaboration design and development in virtual environments. The success of the conference was followed by publishing
Collaboration in Virtual Environments: an Overview

A number of collaborative virtual environments have been created for research purposes (Steed et al., 1999; Schroeder et al., 2001; Slater and Steed, 2002; Heldal et al., 2005; Steed et al., 2005). Compared to earlier CVEs presented in section 2.3.1, the main focus shifted from the scalability of the architectures to their usability and user experience during collaborative interaction (Figure 2.3). In particular, one of the primary goals at that time (and to some extent it remains up till now) was realism of interaction in CVEs. The systems were often designed in such a way that they motivate users to collaborate in a natural way with each other in order to complete a task successfully. For example, in the earlier CVEs interaction between users was mainly in a form of communication. However, it was required for all players to communicate a lot in order to accomplish the task (Figure 2.9a). Later collaborative environments involved more detailed task performance besides high level of communication. For example, Figure 2.9b shows two users trying to accomplish a Rubik’s cube puzzle, which requires a lot of object manipulation.

More advanced work with respect to interaction in networked virtual environments has been done between 2000 and 2005 by several labs (Ruddle et al., 2002; Roberts et al., 2003, 2005). In the systems described above (Steed et al., 1999; Schroeder et al., 2001; Slater and Steed, 2002; Heldal et al., 2005; Steed et al., 2005), users were sequentially interacting with the same object. In environments developed by Ruddle et al. (2002); Roberts et al. (2003, 2005) (Figure 2.3) concurrent interaction, that often occurs in real life, has been addressed (Figure 2.10a). They define closely-coupled collaboration as interaction where actions of one user immediately impact the performance of others. This work resulted in a series of studies that focused on different
2.3 Evolution of Interaction in Collaborative Virtual Environments

(a) Constructing gazebo by Roberts et al. (2003).

(b) Collaborative peg-in-hole task by Ullah (2011).

Figure 2.10: Examples of virtual environments supporting closely-coupled interaction.

aspects of closely-coupled collaboration by different research groups. Although addressed in many studies, closely-coupled interaction remains a challenge that many researchers are trying to tackle (García et al., 2009; Wolff et al., 2007; Ullah, 2011) (Figure 2.10b).

Besides the ability to accommodate a large number of users, effective data sharing and coherent interaction of the users, many collaborative applications, appearing nowadays, also aim at supporting and emphasize the richness and the quality of the multimodal interfaces. Among others, applications in the domain of the Computer Aided Design (CAD) have utilized the benefits of the CVE technology enabling numerous designers to work together while being remotely located. Although collaborative CAD applications have been known for a long time (Bidarra et al., 2001; Li et al., 2005; Li and Qiu, 2006), with the wide use of the Internet in the late 90’s and the increasing interest in virtual environments, many research and industrial organizations have directed their efforts towards collaborative 3D CAD systems and the integration of CAD with multi-user virtual environments. Having a lot in common with more general collaborative virtual environments, we will briefly discuss the existing collaborative CAD systems that allow product design and development in a 3D virtual environment, while supporting synchronous interaction between remote experts.

A collaborative CAD system extends an existing single-location CAD system to a multi-location CAD application so that two or more geographically dispersed users can work together on 3D CAD geometry co-editing and do CAD-related tasks dynamically and collaboratively (Tay and Roy, 2003). A number of research works and commercial systems have appeared to provide solutions for collaborative and distributed product design and development. The first design systems based on virtual environ-
ments started to appear at the end of the 1990’s. These applications combine advanced CAD software with virtual reality technology to produce an environment that allows geographically dispersed engineers to assemble a series of components (Jayaram et al., 1999) or concurrently build 3D models (Arangarasan and Gadh, 2000; Tay and Roy, 2003). The problems of concurrency and synchronization in a collaborative modeling context have been addressed by Bidarra et al. (2001). Later research has proposed several solutions to improve virtual collaboration during the assembling and modeling tasks by providing different levels of details depending on individual roles and collaboration requirements (Chu et al., 2006) and by integrating different software platforms used by remote engineers (Xu et al., 2006). Barbieri et al. (2008) have developed a software interface for data exchange between CAD and virtual environments for assembly and cabling.

The utilization of virtual environments and virtual worlds for product design remains common in many modern systems for product design. Work presented by Rosenman et al. (2007) describes a 3D virtual world environment that provides real-time multi-user collaboration for designers in different locations. This world provides a more complete collaborative environment by integrating multiple views on the designed objects (e.g. building) from the perspective of different disciplines (Figure 2.11).

Work by Merrick et al. (2011) investigates the innovative use of emerging multi-user virtual world technologies for supporting collaborative co-creativity in design. The authors describe the different aspects of virtual worlds that make them useful as

Figure 2.11: The 3D collaborative virtual environment for design by Rosenman et al. (2007).
2.3 Evolution of Interaction in Collaborative Virtual Environments

Platforms for modeling new artifacts. By analyzing the design tools within existing commercial virtual worlds, the authors demonstrate the advantages offered by these applications: support for in-world, open-ended modeling and multidisciplinary collaborative design.

Besides the research activities, the appearance of many commercial multiplayer games and virtual worlds has contributed to the popularity of collaboration in virtual environments (Figure 2.3). One of the first virtual communities (started the development in 1998, launched in October 2003) that received a lot of attention was There with over one million members (in 2009). It is a 3D online virtual world, which serves as "an online getaway where you can hang out with your friends and meet new ones" (Makena Technologies, 2003). Through a customizable avatar, players can communicate and interact with other inhabitants of the virtual world (e.g. doing activities together) (Figure 2.12a). Seeing the success of virtual worlds as a mean of interaction, another company Linden Lab launched in 2003 their virtual world called Second Life (Linden Labs, 2003). Here users interact with each other in the form of customizable avatars, which were more advanced than in earlier virtual worlds (e.g. CVEs for research purposes). For instance, users cannot only change the look of the avatar but also express emotions and make gestures typical of real-life communication. Residents of the virtual world can navigate through it, meet other residents, socialize, participate in individual and group activities (Figure 2.12b), and create and trade virtual property and services with one another. The game reached its top popularity in 2005 – 2010, when major politician and show-business personalities made virtual appearances, concerts and public speeches on Second Life.

The first multiplayer games like Doom (Figure 2.13a) and Quake have been actively played since the mid 1990s. These were first-player shooter games that allow inter-

Figure 2.12: Examples of interaction in virtual communities.
Collaboration in Virtual Environments: an Overview

Figure 2.13: Examples of multiplayer first-person shooter games.

(a) Doom.  
(b) Halo.

action within small groups of participants present solely on the local area networks. Having a rather competitive than collaborative nature, these games however support a high level of interactivity between players. For example, in these games it is important to be updated on the changing location of enemies, weapons or if an enemy is trying to kill you while you are shooting back. However, in the last years it became natural for this game genre to involve more collaborative elements into the gameplay. For example, games like Halo (Figure 2.13b) and the Battlefield series allow cooperation between team members while competing with other players.

The availability of high speed Internet marked the next milestone in the evolution of collaborative interaction in 3D virtual environments, namely the rise of massive multiplayer online role-playing games (MMORPGs) in the early 2000s. This type of games brought interaction and collaboration in a virtual environment at the foreground, allowing people all over the world to compete or collaborate together. One of the early popular MMORPGs was Everquest (Sony, 1999), a fantasy 3D world launched in 1999 by Sony. In 2007 Blizzard entertainment launched their game World of Warcraft (Blizzard Entertainment, 2004) that became the most played MMORPG with more than 10 million subscribers as of December 2011. MMORPGs allow different forms of interaction between players, which may have contributed to their popularity. Having individual roles, players often have to work together to accomplish the game’s objectives and coordinate different joint activities (Figure 2.14a). The team’s success depends on the ability to define and retain a coherent group identity and establish shared social incentives rather than individual incentives for participation. The potential of massive multiplayer games to unite large amount of players and the high interactivity of first-person shooters have resulted in several successful applications, with PlanetSide (Sony, 2003) (Figure 2.14b) and MAG (Sony, 2010) being among the most popular examples.
2.3 Evolution of Interaction in Collaborative Virtual Environments

(a) Collaborative interaction in World of Warcraft.
(b) PlanetSide – massive first-person shooter.

Figure 2.14: Examples of massive multiplayer games.

(a) Mario Bros. for Nintendo Wii.
(b) LittleBigPlanet for PlayStation3.

Figure 2.15: Examples of collaborative multiplayer games for consoles.

The last group of games, worth mentioning with regard to group interaction and collaboration, are console games. Nowadays, almost everyone has a PlayStation, Xbox or Nintendo Wii. Games for these consoles do not target high numbers of participants, but still provide for a truly collaborative experience while playing together with your friends and family. An increased number of games produced for these consoles shift from general interaction between players (e.g. communication and individual contribution) towards collaboration to guarantee success. In fact, in these games, collaboration is not an optional feature but a must in order to complete the game (Figure 2.15).

Collaborative virtual environments have been extensively studied. Even so, the interest among academia and within all kinds of industries keeps on growing resulting in the creation of numerous applications based on CVEs for the military, education, business, entertainment, health and other areas.
2.4 Making Interaction in Collaborative Virtual Environments Successful: Main Challenges

To achieve a successful and efficient collaboration in virtual environments, VE designers and developers have to meet many requirements and overcome numerous challenges. A collaborative virtual environment is not just a graphical representation of a virtual world, but so much more. It combines features such as multiple users with their preferences, various levels of experience and performance; different devices and technologies; communication in multiple forms; quality of the network connecting distributed users; etc. Although we thoroughly study these challenges throughout the dissertation, in this section we will shortly discuss some of them to provide an overall reference framework for these challenges.

In real life, people can interact in a number of ways: be more independent from other collaborators or, oppositely, almost constantly synchronize their activities. While the former type of interaction is often supported in virtual environments, the latter type remains relatively limited due to its complicated nature. Furthermore, a collaborative virtual environment has to support a smooth transition between these types of collaboration, as well as between individual and cooperative activities (Churchill and Snowdon, 1998). However, when a team of people get together to accomplish a certain task, their levels of experience, backgrounds or performance abilities may vary greatly, making this transition more complex. Providing adaptation according to user characteristics and needs is a prospective solution to enhance group interaction, allowing less experienced users, or those who experience more difficulties interacting with an environment, to contribute equally with the rest of the team.

Not only differences among users is an important factor that affects collaboration. It is often the case, that several people have to work together within the same environment, while accessing it using completely different technologies. A difference in the given conditions may negatively affect the outcome of collaboration or user satisfaction from the interaction. However, it can be just impossible to provide every user with his/her most preferred means of interaction.

Churchill and Snowdon (1998) have defined the main features of collaborative work in virtual environments, communication being one of them. A lot of researchers have studied the role of communication and its influence on the collaborative performance (Biocca and Levy, 1995; Otto and Roberts, 2003; Galimberti et al., 2001). At the same time, there might be situations when communication in virtual environment is not possible. In this case, it is important to know to what extent the lack of communication negatively affects group performance.
2.5 Conclusion

Finally, collaborative virtual environments often involve people that are geographically dispersed and connected over the Internet. In this case, the interaction can be affected by degrading network quality. One of the open questions here is to define levels of acceptability of the network impairments by users, that depend on the type of collaborative application. For example, the requirements for systems that do not involve direct interaction between participants may be lower than in applications in which participants are in constant interaction.

2.5 Conclusion

In this chapter, we provided an overview of interaction in collaborative virtual environments. We first introduced what collaborative virtual environments are and discussed the main types of applications built on top of CVE technology. Afterwards, we provided a historical overview of collaborative virtual environments, showing the evolution of interaction within environments from the first military applications till modern sophisticated examples of virtual communities and multiplayer games.

In order to come up with a good user experience in CVEs, designers and developers of virtual environments have to overcome a lot of challenges. We summarized and briefly discussed the most crucial factors that contribute to the successful usage of collaborative virtual environments. These are studied more thoroughly in the next chapters. We will start with a discussion on different interaction types between users in CVEs, which is followed by a detailed analysis of the presented challenges. In particular, we address questions of the effective combination of different technologies to interact with the environment, role of communication and the ways on how to accommodate the variability of users involved in collaboration.
Interaction between people through computer-mediated virtual environments has become a common practice in the last decade. A proof of this is the incredible popularity of virtual communities like Second Life (Linden Labs, 2003) or There (Makena Technologies, 2003) and Massive Multiplayer Online Role Playing Games (Blizzard Entertainment, 2004; Electronic Arts, 2004), which have millions of active users. Their success is not only determined by advanced three-dimensional graphics and immersion, but also by providing interaction and communication between players.
Supporting natural and realistic collaboration in virtual environments is a very complex task, as a group of people may interact in a number of ways. Due to this complexity, interaction in multi-user applications is reduced to merely communication or individual contribution to the overall goal. Although common in real life, collaboration where people are directly depending on each other is very limited in virtual environments. With our research, we aim to address this problem by investigating what are the benefits and drawbacks of different levels of collaboration in virtual environments.

In this chapter, we will discuss what levels of collaboration exist in current multi-user applications. After presenting an existing classification of group work in collaborative virtual environments, we describe an experiment where different levels of collaboration are compared. Here user performance and preference are analyzed to determine the benefits and drawbacks of each type.

### 3.2 Classification of Collaboration in CVEs

Users may interact in a number of ways, while working in a shared virtual environment. Several works attempt to classify the interaction in collaborative virtual environments based on multiple criteria.

Ellis et al. (1991) classify group interaction based upon notions of space and time. According to the authors, users can collaborate in a face-to-face setting or be dispersed over many locations. Moreover, collaboration can happen in real time, or oppositely in an asynchronous non-real-time manner. These time and space considerations suggest four categories of shared working represented by a 2x2 matrix (Figure 3.1).

![Group collaboration matrix (Ellis et al., 1991).](image)

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1Throughout our research, we define collaboration as interaction between two or more people through a virtual environment and its objects in order to achieve a common goal. Therefore, the terms ‘collaboration’ and ‘interaction’ are used interchangeably.
3.2 Classification of Collaboration in CVEs

Focusing primarily on real-time collaboration, Broll (1995) categorizes group work based on the distribution of virtual objects among users. While being present in the same environment, users can manipulate objects either consequently or concurrently, which Broll accordingly defines as collaborative and cooperative work (Figure 3.2).

Similarly to Broll, Ruddle et al. (2002) classify collaboration according to the level of coupling between collaborators and define three levels of shared work in virtual environments. The first level defines collaboration as an ability to communicate and perceive the shared environment (Figure 3.3). This type is widely supported in virtual communities (e.g. Second Life (Linden Labs, 2003)) and most early multi-user environments (e.g. MASSIVE (Greenhalgh and Benford, 1995), DIVE (Frécon and Steenius, 1998)). The second level extends this ability, allowing individual modification of the environment (Figure 3.4). This type of interaction is typical for design applications (city landscape application ARTHUR (Moeslund et al., 2003)) and games (Little Big Planet (Sony, 2008), World of Warcraft (Blizzard Entertainment, 2004)), where users can individually create, modify or delete the content of the scene. The third one is defined by simultaneous impact of multiple users on the same objects or parts of the environment (e.g. shared object manipulation) (Figure 3.5). Though mostly related to real life, this type of user interaction is less utilized in virtual environments. Being mainly limited to research (García et al., 2008), we observe an inceptive interest in the third level of collaboration in some applications. One of the most prominent examples are recent video games, such as Little Big Planet and Battlefield (Electronic Arts, 2004). In such games, players often encounter shared challenges or have to manipulate the same objects simultaneously. Although very limitedly used in current CVE applications, we assume the third type of collaboration can increase user engagement and add more realism to the performance in a virtual environment. The last type of collaboration is often referred to as closely-coupled, while the first two types represent loose coupling between players.
36 Levels of Collaboration in Collaborative Virtual Environments

Figure 3.3: Examples of CVEs supporting the first level of collaboration according to Ruddle et al. (2002).

Figure 3.4: Examples of CVEs supporting the second level of collaboration according to Ruddle et al. (2002).

Figure 3.5: Examples of CVEs supporting the third level of collaboration according to Ruddle et al. (2002).
3.3 Research on Loosely-coupled and Closely-coupled Collaboration

There is a substantial amount of work investigating different aspects of loosely- and closely-coupled collaboration within small groups. The major part of research in this area focuses on the implementation of collaborative interaction techniques (Bowman et al., 2008), such as shared object manipulation or giving the correct perspective views over the environment. For example, Pinho et al. (2002, 2008); Margery et al. (1999) present frameworks that support development of cooperative manipulation techniques. In (Pinho et al., 2002, 2008), the authors combine simultaneous user actions, based on the separation of degrees of freedom between two users (e.g. one user rotates the object, while the second user moves it). A set of rules, developed by the authors, define how to combine individual interaction techniques in order to allow multiple users to manipulate the same object at the same time. Another cooperative manipulation technique called “SkeweR”, that allows two users to move the same virtual object simultaneously in a virtual environment, is presented by Duval et al. (2006). Here, each user manipulates an object by one crushing point and the final movement of the object is based on a combination of the two translation movements of the users.

While interacting on the same object(s), it is important that all collaborators share the same view on the objects they are working with, or have a certain level of awareness within the virtual environment. Provenzano et al. (2007) investigate how to provide remote viewpoint awareness in a 3D collaborative desktop application in which multiple shared objects can be independently positioned and manipulated. Ullah et al. (2009) show the importance of visual feedback and investigate the effect of different visual aids when closely collaborating in the virtual environment.

Also, several studies focus on perceptive aspects of loosely- and closely-coupled collaboration, namely presence and co-presence within shared virtual environments (Steed et al., 1999; Schroeder et al., 2001; Heldal et al., 2005; Garcia et al., 2007; Wolff et al., 2007). These studies investigate factors that contribute to effective collaboration and people’s behaviour in distributed virtual environments while performing different activities. The work of Schroeder et al. (2001) examines the effect of different immersive technologies on interaction during closely-coupled tasks. Similar research is performed by Roberts et al. (2003) and Wolff et al. (2007), which focuses on concurrent interaction with shared objects by users of a variety of display system configurations. In both studies collaboration is measured in terms of team performance and user perception.
The increasing popularity of closely-coupled collaboration in gaming, triggers the interest to fully assess its potential for other types of applications. Furthermore, possible advantages over loosely-coupled collaboration, based on individual performance, have to be investigated as well. Analysis of the existing research related to loosely- and closely-coupled collaboration, presented here, reveals that most initiatives focus either on one or another level. One of the open research questions here is their effective combination in order to achieve a better group performance. However, before being able to answer this question, it is important to compare these two levels of collaboration in order to determine their drawbacks and benefits in relation to each other. With the help of user experiment described in the next section, we compare loosely- and closely-coupled collaboration in virtual environments.

### 3.4 Experiment: Comparison of Levels of Collaboration

In order to analyze different levels of collaboration in a 3D virtual environment we performed a study, where two levels of group work were compared. In particular, we focused on the second and third levels of collaboration defined by Ruddlet et al. (2002), which are referred as loosely-coupled and closely-coupled collaboration respectively during our discussion. An experiment was conducted where groups of participants had to complete two tasks with different levels of collaboration. Firstly, they performed individually to achieve a shared goal, and secondly, they completed a task involving simultaneous actions of multiple users to achieve a shared goal. The aim of this study is to define advantages and disadvantages of each condition. A simple 3D game involving numerous object manipulations was the selected interactive task. The purpose of this experiment was to determine the factors that have a positive impact on interaction in a shared virtual environment, separately for each level of collaboration. Due to the entertaining nature of the task, we also determined the condition most preferable for users enhancing their experience.

We believe that simultaneous activities, although not always easy and straightforward to perform, will provide a more convincing shared experience of working together. Additionally, as we investigate these two levels of collaboration during a game-like task, we expect that close coupling increases enjoyment of users’ interaction. Therefore it will be more preferable for most participants based on several criteria (i.e. performance, naturalness, etc.) and provide more enjoyable interaction among partners when compared to loose coupling. Another expectation is that differences in levels of user experience with single- and multi-user 3D environments will not influence user preference and enjoyment.
3.4 Experiment: Comparison of Levels of Collaboration

3.4.1 Participants

Thirty unpaid volunteers (five females and twenty-five males) participated in the experiment. The average age of participants was 27 years, ranging from 20 to 37. Twenty-five participants had a computer science background with different experience levels regarding working in 3D single-user and multi-user virtual environments, mainly limited to computer games. Five participants had a social science background with no or very limited experience, solely linked to computer games. Most participants had no experience working with the input devices involved or have only used them previously in other user tests. All participants were right handed and used their dominant hand to operate the devices.

3.4.2 Apparatus

For the experiment 3 laptops with 15.4” screens were connected over a LAN. Two laptops were HP Compaq 8510p (Intel Core 2 Duo T8100, 2.1 GHz, 3 GB with ATI Mobile Radeon HD2600 graphic adapter). The third laptop was a Dell Latitude D830 (Intel Core 2 Duo T7100, 1.8GHz, 2GB with NVIDIA Quadro NVS 140M). Two SpaceMouses (Figure 3.6a), one SpaceExplorer (Figure 3.6b) and three keyboards were used for input. Participants were sitting in the same room facing each other, so they were not able to see their partners’ screen as shown in Figure 3.7.

(a) SpaceMouse.  (b) SpaceExplorer.

Figure 3.6: Devices used in the experiment.

3.4.3 Design

During the experiment, a within-subject design was used. The independent variable was the form of interaction with two conditions: loosely- or closely-coupled. All
participants, in groups of three, had to complete two sessions, each corresponding to one of the conditions. The order of the conditions was counterbalanced (Table 3.1). The dependent variable was task completion time for every session. Additionally, the number of mistakes when selecting the correct sum of numbers, was calculated. As subjective measurements are important in this type of user studies, they were obtained through a post-experiment questionnaire based on (Witmer and Singer, 1998; Steed et al., 1999) (see Figures B.1 and B.2 in Appendix B).

Table 3.1: Session order.

<table>
<thead>
<tr>
<th>Session</th>
<th>Groups 1-5</th>
<th>Groups 6-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Session 1</td>
<td>Loosely-coupled collaboration</td>
<td>Closely-coupled collaboration</td>
</tr>
<tr>
<td>Session 2</td>
<td>Closely-coupled collaboration</td>
<td>Loosely-coupled collaboration</td>
</tr>
</tbody>
</table>

3.4.4 Procedure

Ten groups of 3 people were sequentially asked to perform a game-like task in a 3D virtual environment. The goal of the task was to collect 20 digits in the environment together with two partners. The odd number of participants was chosen in order to keep the interaction more dynamic, as it did not allow the group to split into two smaller subgroups with an even number of players (which, in turn, would allow sub-
3.4 Experiment: Comparison of Levels of Collaboration

groups to perform the complete task). The game was represented as an environment that consist of two virtual houses containing 20 cubes (Figure 3.8a). Part of this environment is shown in Figure 3.8b. Half of these cubes had a digit on one of its sides. In order to complete the game, participants were asked to calculate a sum of all digits, and then to select the correct number (corresponding to the calculated sum) out of four options, presented as a four-item menu. To search for the digits within the environment, participants had to select and manipulate objects. The players were represented by cones of different colors in the virtual environment.

Participants were allowed to practice for 15 minutes with the device in order to get used to the environment and the way objects had to be manipulated, before actually

![Image](image1.png)

(a) Virtual houses where users, represented by color cones, search for the objects.

![Image](image2.png)

(b) Objects inside virtual houses that users have to manipulate.

**Figure 3.8:** The virtual environment used in the experiment comparing loosely- and closely-coupled collaboration.
starting the experiment. Once the training was completed, two sessions were performed: loosely-coupled collaboration and closely-coupled collaboration. For every session a different environment was created with the same level of complexity. In the loosely-coupled session every object could be moved or rotated by a single person. In the closely-coupled session there were two types of objects: those that could be manipulated by one user and those that required joint manipulation by two users. If an object of the second type was selected, a help message was generated to inform other participants within the same virtual house in the virtual environment that there is a person requiring a partner’s help. However, the message did not indicate who triggered the call for help and where that person was located. Participants had to discuss about this event to discover the feasibility to help each other. If none of the co-players was in the same virtual house, the person who initially selected such an object got another message, indicating that his/her partners are not in the same area.

To indicate successful object selection, visual feedback was used. An object highlighted in red indicated it was already selected but in order to manipulate it two people were required. An object highlighted in green indicated that it had been selected and could be manipulated. To select, manipulate and deselect an object the SpaceMouse or the SpaceExplorer was used. When it was necessary to move or rotate an object jointly with a partner, participants had to perform a simultaneous movement in the same direction using their devices. Arrow keys on the keyboard were used to navigate within the environment. Additionally, participants could switch to a top view for an overview of the whole environment.

During the experiment participants were allowed to communicate. Due to the co-located setup participants were able to talk to each other without using any communication technology (e.g. Skype). Apart from voice communication they had a text messenger running on their laptops which was used to share already found digits to the partners. Once all 20 digits were found, one of the group members calculated their sum and selected the answer from the four-item menu (Figure 3.8b). If a correct option was selected other items disappeared, if not the participant had to select another option. The amount of mistakes was captured. Participants were supervised in order to avoid guessing the correct answer from the menu.

Participants were asked to complete an individual questionnaire regarding their experience after each session (see Figure B.1 in Appendix B). Moreover, after two sessions a group questionnaire that involved a discussion of three collaborators was completed (see Figure B.2 in Appendix B). In all questionnaires participants had to evaluate their performance and preference for every condition on a 10-point likert scale. Questions were grouped into several categories: enjoyment, level of working together, perfor-
mance and communication activity. It took approximately one hour for each group to complete the whole experiment.

3.4.5 Hypotheses

With our experiment we wanted to compare two levels of collaboration: loosely- and closely-coupled. To define the advantages of one level over the other, the following hypotheses were suggested:

H1: task completion time is longer when closely-coupled collaborating without negative influence on the user experience;

H2: user enjoyment, performance activity and level of collaboration are higher when closely-coupled collaborating;

H3: amount and importance of communication are higher when closely-coupled collaborating;

H4: the differences in levels of user expertise does not influence user enjoyment and level of collaboration.

3.5 Results

The focus of our study is to compare two levels of shared work: loosely-coupled collaboration and closely-coupled collaboration. Firstly, we present these levels separately by defining factors with positive or negative influence on each. Secondly, we compare loose and close coupling to determine the most preferable and enjoyable one of these settings. Here we compare individual and group responses to investigate whether there is an influence of a particular individual or individuals on the overall group experience and if there is any significant difference between individual and group performance. Thirdly, we present the analysis that shows the influence of the users’ experience on their performance and enjoyment. Finally, we analyze user behaviour based on observations, and also their answers to open-ended questions.

3.5.1 Analysis of Loosely- and Closely-coupled Collaboration Separately

As mentioned earlier, users were asked to complete a questionnaire about their experience in two sessions: one with loosely-coupled collaboration and the other one with
closely-coupled collaboration. Here we present the analysis of the two sessions separately based on the users’ responses. The data is analyzed using Pearson’s correlation test. Table 3.2 summarizes the factors, defined based on the subjective evaluation, affecting different sides of user experience in each session.

**Table 3.2: Factors affecting user experience in loosely- and closely-coupled collaboration.**

<table>
<thead>
<tr>
<th>Level of collaboration</th>
<th>Enjoyment</th>
<th>Level of working together</th>
<th>Performance and communication activity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loosely-coupled collaboration</strong></td>
<td>- ease of object manipulation</td>
<td>- communication activity</td>
<td>- no communication required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- naturalness of joint work</td>
<td></td>
</tr>
<tr>
<td><strong>Closely-coupled collaboration</strong></td>
<td>- performance activity</td>
<td>- performance activity</td>
<td>- communication activity (coordination)</td>
</tr>
<tr>
<td></td>
<td>- level of working together</td>
<td>- communication activity</td>
<td>- convenience with a 3D device</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- awareness</td>
</tr>
</tbody>
</table>

**Loosely-coupled collaboration**

**Enjoyment** We found a positive correlation between *enjoyment* and *ease of object manipulation* \( (R^2 = 0.36, p = 0.049) \). People enjoyed performance significantly more when it was easy for them to manipulate a virtual object using a given device. When people experienced difficulties with the manipulation or navigation within the virtual environment they enjoyed the game less. At the same time, no correlation between *performance* or *communication activity* and *enjoyment* was found. Observations have shown that although the participants were not always able to participate as actively as their partners, they still enjoy the shared experience.

**Level of working together** During the loosely-coupled collaborative session, participants’ performance was mainly concurrent, as they did not have to work together on shared objects. Their collaboration was limited to the achievement of a common goal. That is why there was no correlation between *level of working together* and *activity*. At the same time most participants indicated communication as the only “collaborative tool”, which increased the feeling that they were not isolated but working together with others \( (R^2 = 0.62, p = 0.05) \). This also significantly influenced the naturalness of joint work \( (R^2 = 0.6, p < 0.05) \).
3.5 Results

Performance and communication activity We expected that *convenience with the devices* would greatly influence the level of activity when performing a task (as an activity here we consider actions within the virtual environment which were required in order to complete the task, in particular object manipulation). Although observations have shown that participants worked more actively when they felt comfortable using the suggested 3D input device, no correlation was found between these two factors. Another conclusion obtained from this session was that, during such concurrent performance, participants did not require much communication. They were aware of the situation around them and did not need information regarding the rest of the environment.

Closely-coupled collaboration

Enjoyment In the closely-coupled collaborative session, part of the objects in the virtual environment required joint manipulation by two participants simultaneously. In order to move the virtual block, participants had to coordinate their movements. The complexity of manipulation increased because participants were not always sharing the same view and could be located from different sides of the same block. We expected that this difficulty would significantly decrease overall users’ enjoyment. However, against our expectations, we found no correlation, indicating still a high level of enjoyment.

Users indicated that they had to be more active in this session in order to complete the game. It was always necessary either to help someone or to ask partners for help. This fact resulted in influence of the *activity* during the task performance on users’ *enjoyment* in a positive way ($R^2 = 0.53, p = 0.002$). We also asked participants to evaluate their perception of working together with other participants. Analysis has shown a strong correlation ($R^2 = 0.48, p = 0.006$) between *enjoyment* and *level of working together*.

Level of working together The *level of working together* was influenced by active *communication* and *performance*, which were absolutely necessary in order to complete the task. Analysis has shown that participants indicated a higher level of proximity when they performed ($R^2 = 0.58, p = 0.001$) and communicated ($R^2 = 0.69, p < 0.05$) more. Moreover, these two characteristics supported the *naturalness* of interaction.

Performance and communication activity In order to manipulate objects participants had to coordinate their movements all the time. Such coordination required lots of *communication* ($R^2 = 0.51, p = 0.004$), as well as *convenience with a 3D device* ($R^2 = 0.47, p = 0.008$) in order to move objects together with your partner.
Another important finding was the influence of awareness \( (R^2 = 0.53, p = 0.003) \) during a cooperative task. It was absolutely necessary for the participants to know who could help them or who required help at a certain moment, especially when they were located in different regions of the virtual environment.

### 3.5.2 Comparison of Loosely- and Closely-coupled Collaboration

The main goal of the conducted experiment was to compare two levels of shared work: loosely- and closely-coupled collaboration. We wanted to determine (based on the hypotheses suggested earlier) which one is preferred by users and can be more beneficial when integrating highly-interactive tasks in collaborative virtual environments. For this purpose, we analyzed the data using paired-samples t-tests.

#### Task Completion Time

The analysis has shown that it took significantly longer for participants to complete the task during the closely-coupled collaboration \( (t(9) = -3.867, p = 0.004) \), confirming. Figure 3.9 shows the task completion time for every group in both conditions.

![Figure 3.9: Task completion time for loosely- and closely-coupled collaboration.](image)

As a long task completion time may cause boredom and fatigue, it is important to investigate the effect of the length of the task on the overall enjoyment of users. We analyzed both types of joint work in order to search for any correlation with the time. We found a significant negative correlation \( (R^2 = -0.687, p = 0.028) \) between enjoyment and total time for loosely-coupled collaboration. This indicates that the enjoyment of users decreases with the increase of task completion time. For the closely-coupled collaboration no correlation was found between task completion time and
3.5 Results

Enjoyment, indicating that people enjoy interaction even if more time was required to complete the task. This confirms hypothesis H1. The obtained result has an important impact for integrating closely-coupled tasks in a virtual environment, where it is important to engage users for a longer period of time (for example, in games). Though, it is still necessary to investigate the influence of time on users’ experience for continuous long-term performance.

Additionally, we found that there is no influence of user expertise on completion time. From observations we discovered that closely-coupled collaboration took longer because it was often necessary to wait for the partner in order to perform the joint activity. It also took some time to find the location of a person who needed help in the virtual environment. Taking into account these findings we can conclude that completion time can be considered as a task-dependent variable, but users still enjoy longer interaction when they are closely coupled with their partners.

Enjoyment and Performance

Participants had to rate two types of shared work from different perspectives. First, we collected responses of individuals regarding their work under both conditions. Afterwards, the same questions were directed towards the whole group to collect the group’s opinion, based on a discussion between the three partners. All questions were grouped into several categories which were analyzed separately. There were also questions that were only asked either individually or to the whole group.

In Table 3.3 all statistics are given in order to compare the loosely- and closely-coupled collaboration, based on the individual and group responses. They are grouped similarly to the categories of the questionnaire given to participants. Empty cells indicate certain questions that were only asked to the group or to individuals. As we can see, participants enjoyed the closely-coupled task significantly more, either individually or as a group. At the same time the activity during the performance was rated differently. Individually, participants performed almost equally active as no difference was found across the conditions. However, as a group they performed significantly more active during the closely-coupled collaboration. During loosely-coupled collaboration participants indicated their individual activity ($M = 7.43, SD = 1.3$) higher comparing to group one ($M = 5.9, SD = 1.66$). They explained that they “were not really working as a team but mainly in a parallel manner”. Some users compared their partners to the non-player characters, which co-exist but do not interfere with you a lot. Both individual and group activity were rated similarly during the closely-coupled session. Manipulation of objects during the closely-coupled collaboration required more effort and cohesive work from participants, and was indicated to be significantly harder
Table 3.3: Comparison of loosely-coupled and closely-coupled collaboration based on individual and group responses.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Group responses</th>
<th>Individual responses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Activity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enjoyment</td>
<td>$t(9) = 2.449$</td>
<td>$t(29) = -2.421$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.037$</td>
<td>$p = 0.022$</td>
</tr>
<tr>
<td></td>
<td>$M_{lc} = 6.7$, $SD_{lc} = 1.25$</td>
<td>$M_{lc} = 6.37$, $SD_{lc} = 1.5$</td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 7.5$, $SD_{cc} = 0.85$</td>
<td>$M_{cc} = 7.23$, $SD_{cc} = 1.52$</td>
</tr>
<tr>
<td>Activity of task performance</td>
<td>$t(9) = -3.250$</td>
<td>$t(29) = -0.711$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.01$</td>
<td>$p &gt; 0.05$</td>
</tr>
<tr>
<td></td>
<td>$M_{lc} = 5.9$, $SD_{lc} = 1.66$</td>
<td>$M_{lc} = 7.43$, $SD_{lc} = 1.3$</td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 7.7$, $SD_{cc} = 1.06$</td>
<td>$M_{cc} = 7.63$, $SD_{cc} = 1.3$</td>
</tr>
<tr>
<td>Object manipulation</td>
<td>$t(29) = 2.079$</td>
<td>$M_{cc} = 7.1$, $SD_{cc} = 1.9$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.047$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 6.3$, $SD_{cc} = 1.37$</td>
<td></td>
</tr>
<tr>
<td><strong>Working with others</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of working together</td>
<td>$t(9) = -2.535$</td>
<td>$t(29) = 7.623$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.032$</td>
<td>$p = 0.000$</td>
</tr>
<tr>
<td></td>
<td>$M_{lc} = 5.3$, $SD_{lc} = 1.89$</td>
<td>$M_{lc} = 5.33$, $SD_{lc} = 2.12$</td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 7.6$, $SD_{cc} = 1.35$</td>
<td>$M_{cc} = 8.07$, $SD_{cc} = 1.23$</td>
</tr>
<tr>
<td>Naturalness of working together</td>
<td>$t(29) = -3.713$</td>
<td>$M_{cc} = 6.44$, $SD_{cc} = 1.38$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.01$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 7.37$, $SD_{cc} = 1.45$</td>
<td></td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication activity</td>
<td>$t(9) = -1.686$</td>
<td>$t(29) = -5.835$</td>
</tr>
<tr>
<td></td>
<td>$p &gt; 0.05$</td>
<td>$p = 0.000$</td>
</tr>
<tr>
<td></td>
<td>$M_{lc} = 1.9$, $SD_{lc} = 1.1$</td>
<td>$M_{lc} = 5.77$, $SD_{lc} = 1.87$</td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 3.1$, $SD_{cc} = 1.79$</td>
<td>$M_{cc} = 7.87$, $SD_{cc} = 1.079$</td>
</tr>
<tr>
<td>Easiness of communication</td>
<td>$t(9) = -9.380$</td>
<td>$M_{cc} = 5.1$, $SD_{cc} = 1.73$</td>
</tr>
<tr>
<td></td>
<td>$p = 0.05$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$M_{cc} = 8.33$, $SD_{cc} = 1.06$</td>
<td></td>
</tr>
</tbody>
</table>

*lc - loosely-coupled collaboration, cc - closely-coupled collaboration*
3.5 Results

than single-user object manipulation. But, as indicated before, such difficulty did not significantly influence the overall user enjoyment during the closely-coupled session.

Another question that was asked, both individually and to the group, related to users’ level of working together with others, rather than on their own. Both responses showed another advantage of closely-coupled collaboration – players perceived a group acting to be on a higher level than in loosely-coupled session. Furthermore, participants also indicated the close coupling condition as a more natural way of working together as a team. We also found that there was no significant difference across the two conditions regarding the level of awareness that participants perceived ($t(29) = -1.925, p > 0.05$), indicating that they were equally aware of the situation in the environment during their activity. These findings confirm our hypothesis $H2$, showing that user enjoyment, performance and level of collaboration while performing closely-coupled tasks are significantly higher when compared to loose coupling.

The activity of communication and the level of its importance was also analyzed. As mentioned before, closely-coupled collaboration required much more communication and coordination from participants. Statistical analysis has shown that individuals communicated significantly more during the closely-coupled sessions. Participants also indicated that communication was more important in this case, confirming hypothesis $H3$. They said that the loosely-coupled session “did not require much communication, and the task itself can be actually completed without communication”, while for the closely-coupled session “it would be almost impossible to complete the task if the communication is prohibited”. Furthermore, we found that there was no difference across two conditions in the level of difficulty of communication and coordination. This finding allows us to make another conclusion in favor of closely-coupled tasks, indicating that the amount of communication does not imply its level of difficulty.

3.5.3 Influence of User Expertise on Shared Work

We asked participants to define their level of expertise in 3D single-user ($M = 5.2, SD = 2.93$) and multi-user ($M = 3.67, SD = 2.43$) virtual environments. Although most participants did not have much experience in shared virtual activities they still enjoy playing the game under both conditions. Moreover, we found no correlation between expertise level and enjoyment. This indicates that both experienced and less experienced users can equally enjoy activities with others in multi-user virtual environments.

Test groups were randomly formed, so that certain groups contained only inexperienced or only experienced users, or were mixed. That is why we additionally com-
pared group enjoyment and average experience within each group. We found no significant influence of the experience on the group enjoyment. In spite of such heterogeneity, user interaction during both sessions was enjoyable for every participant. Additionally, we found no correlation between expertise and level of working together, which proves the fact that despite lack of experience users got an equally high perception level of working together with their collaborators for both conditions. These findings prove our last hypothesis H4.

3.5.4 User Behaviour

Previous sections already partially covered our analysis of users’ behaviour. Further analysis of user observations and answers to the open-ended questions (given both individually and in groups) reveals interesting information regarding the user experience during the experiment. This section presents the collected and analyzed qualitative information, that confirms and explains our findings obtained from the statistical analysis.

Preferences The analysis showed that participants preferred the closely-coupled session significantly more than the loosely-coupled, rating their enjoyment higher. Observing people playing the two games allows us to draw a conclusion what actually caused such enjoyment.

Loosely-coupled collaboration was considered less interesting and less fun compared to the closely-coupled session because of the reduced interaction. Participants performed more individually, rather than as a group to complete the task. Some players said they did not feel part of a group, but rather co-existed with others. Only one group preferred the loosely-coupled session because they completed the task quicker, not having to wait for assistance.

Closely-coupled collaboration involved more activity in order to complete the game, resulting in a high level of interaction with other participants. Although it was often necessary to wait for a helper, participants still were excited to perform joint activities. Moreover, frustration caused by different views for remote participants on the same objects, did not influence the enjoyment. Almost all players experienced more fun when playing the game based on close coupling between them, as it really gave the feeling of teamwork. People pointed out that “being fun” is more crucial than “being difficult” when playing computer games.

Performance Most participants were quite active during both sessions of the game. Users who experienced some difficulties with object manipulation or device usage, were obviously not always as active as their partners. However, this did not influence
3.5 Results

the overall group performance significantly. *Loosely-coupled sessions* were found more active from the perspective of individual performance. Players did not have to wait and, thus, needed less time to complete the task. On the other hand, players indicated that it would be possible to complete this game on their own without being part of a team. We may assume that activities based on loose coupling between users can be more efficient for those tasks where completion time should be minimized.

For *closely-coupled sessions*, it was necessary to stand by and wait for help. This was indicated as the main drawback of this type of collaboration. At the same time, you cannot complete the game individually and it gives a feeling of being part of the group. Participants indicated that adding more people to the game could improve their efficiency. They explained that having a bigger team would allow to decrease the task completion time as it would be easier to find a partner who is available to help and at the same time involve more interaction with several people simultaneously.

Although the analysis has shown no significant influence of expertise on the performance, for several groups an interesting observation was made during the closely-coupled sessions. If one of the players had more experience than the other two, or felt more convenient with the 3D device, he preferred to work on his own, and let two less experienced users jointly manipulate shared objects. In such a way more balanced performance within the group was achieved resulting in greater enjoyment of the team work.

**Voice communication** By analyzing quantity and content of communication during loosely-coupled and closely-coupled collaboration, we wanted to determine when it was necessary to talk with the partners, and what kind of communication was used while working under different conditions.

First of all, we noticed that participants who had difficulties with the actual performance (e.g. object manipulation) used communication to compensate their lack of activity to complete the task. They communicated actively during strategy discussion and during the task itself. With *loosely-coupled collaboration*, communication was mainly used for strategy discussion at the beginning, to do a bit of joking or to keep each other aware of what the other participants were doing. Players also discussed sometimes, how many objects were still missing, or where the objects were that still had to be checked. Communication was indicated as the only instrument of collaboration, as players performed individually rather than as a team. We also observed that a few pairs did not even discuss their strategy, which resulted in a longer task completion time. They concluded that it was not necessary to communicate, because they were able to see if there is anyone around, otherwise it was not really important what others were doing at the same moment.
During the closely-coupled collaboration, all pairs admitted the necessity of communication. Players not only talked about their strategy or their role as a group member, but also coordinated their movements actively. They indicated that the help message they saw, when someone picked up an object which had to be manipulated jointly, did not really help if you cannot communicate about the object description and location. For this condition the communication was almost continuous, due to someone needing help. Vocal conversation was also used as an awareness mechanism in the same way as for loosely-coupled collaboration. People communicated regarding their positions and actions in the virtual environment, thus making their performance smoother.

It is obviously preferable to include voice communication when working together with others. It contributes by making interaction more fluent and realistic. The main purpose of communication during loosely-coupled collaboration is division of work between group members, which can also be replaced with a text chat. At the same time, closely-coupled collaboration required communication mainly for real-time coordination, which would be difficult to complete having only text chat.

### 3.6 Conclusion

In this chapter we have presented an analysis of loosely- and closely-coupled collaboration in 3D virtual environments. Although these levels of collaboration have been studied previously, the contribution of our work lies in their comparison based on user performance and preferences and also in determining the benefits and drawbacks of each level.

Results of the user experiment showed that users really enjoyed closely-coupled collaboration while working together. In this particular task they indicated close coupling as more realistic and engaging as it allowed them really to work as a team. The main advantage was that users not only had a joint goal, that could be achieved concurrently, but they really had to perform activities together in order to reach the final aim. Further analysis also showed that there was no influence of users’ level of expertise on their enjoyment enabling non-experienced participants to enjoy the task not less than more experienced partners. With the game-like task as a case study, this experiment provides indications for shared activities in CVEs but further research is necessary to generalize the conclusions to other CVEs. We can assume that similar closely-coupled activities where users can truly work together in a shared environment will be beneficial in different types of applications (in particular, computer games). We do not reject loose coupling between users as it was also found to be successful (Seif El-Nasr et al., 2010). Moreover, combining the two types of joint work within the
3.6 Conclusion

same application has potential. In particular, some multiplayer games provide more
dynamic interaction based on combination of two levels of collaboration, allowing
their users to switch activities from one type to another.

In the next chapter, we would like to focus on specific factors influencing collabora-
tion in shared virtual environments. In particular, we will investigate how the group
performance is affected by the setup. Furthermore, the importance of communication
during collaboration is analyzed.
Levels of Collaboration in Collaborative Virtual Environments
Chapter 4

Influence of the Setup and Communication on Collaboration in Virtual Environments

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4.1 Introduction

As collaborative virtual environments are becoming more and more popular for both entertainment and professional activities, it is important to know which factors influence the collaboration between participants. The variety of computer technologies and resources nowadays provides a wide range of possibilities for the developers of virtual worlds. Different platforms, a variety of input and output devices and the latest technologies allow the creation of powerful applications with a high degree of realism and the possibility to interact. The potential of these resources leads to the question
Influence of the Setup and Communication on Collaboration in Virtual Environments

of their effective combination into heterogeneous setups, in such a way that the tasks between participants can be divided according to their abilities. Among other resources, the focus of our research lies on the combination of different input devices. This choice has been made since the ability to interact with a virtual environment contributes to the feeling of being present and leads to an efficient performance.

In the previous chapter we have compared two types of interaction in a virtual environment, namely loosely-coupled and closely-coupled collaboration. During the experiment we have enabled participants to interact with each other in a homogeneous setup, i.e. using similar input devices (SpaceMouse and SpaceExplorer). We have found loosely-coupled interaction to be less preferable by the participants as they indicated a lower level of collaboration, often acting independently from each other. Whereas other chapters of this dissertation will focus on closely-coupled collaboration, in this chapter we will look into possibilities to improve loosely-coupled collaboration. In particular, we envisage integrating different interaction devices in this condition may lead to a tighter bounding between collaborators. However, this assumption has to be checked in order to see whether introducing different types of devices will have any negative affect on the collaboration.

Another important factor that has received a lot of attention among researchers is the role of communication when collaborating in a virtual environment (Palmer, 1995; Biocca and Levy, 1995). Several studies have shown the importance of communication to increase the degree of presence (feeling of being within virtual environment) and co-presence (feeling to be present with other participants) within the environment (Otto and Roberts, 2003; Roberts et al., 2005; Galimberti et al., 2001). The results of the experiment described in the previous chapter have shown that communication contributes to the level of collaboration between users. However, its influence on the efficiency of collaboration remains an open question, that has not been widely addressed.

This chapter presents an investigation of several aspects of the collaboration between two people carrying out the same highly interactive task. After an overview of the existing research about the effect of setups and communication on collaboration in virtual environments, we present a user experiment. Based on the experiment we study the effect of heterogeneous interaction – collaboration based on unequal conditions between participants (in our case different input devices). The main question that rises here is whether the heterogeneity improves the efficiency or, in contrast, makes people uncomfortable because of their unequal contribution. Secondly, we investigate the influence of communication on collaboration efficiency.
4.2 Influence of Setup on Collaboration

Although virtual reality and collaborative virtual environments have been widely covered in literature, highly interactive collaboration has received less attention. Most of present collaborative environments support a high level of visualization when aiming for high immersion and presence. Although these applications are collaborative, the interaction is reduced to voice communication, individual contribution or common navigation.

In the last ten years there is a growing interest in the research community in detailed task performance, where actions of one collaborator impact other participants. In most cases collaborators have equal performance abilities. Examples of such collaborative applications are presented by Basdogan et al. (2000), Alhalabi and Horiguchi (2001) and Duval et al. (2006). These applications mainly support collaboration between 2 users, where both of them use the same device to perform the same actions. In particular, in (Basdogan et al., 2000; Alhalabi and Horiguchi, 2001) the authors investigate interaction in a collaborative virtual environment, where users interact using the two same haptic devices. In the study presented by Duval et al. (2006) a collaborative interaction technique called Skewer is tested in a homogeneous setup involving 3D tracker devices.

Another example of interaction, that is homogeneous with respect to the I/O devices is presented by Pinho et al. (2002, 2008). Both users wear a head-mounted display and hold a 3D tracker device. However, the actions performed by each user are different. The authors combine simultaneous user actions, based on the separation of degrees of freedom between two users. Actions are divided between the participants so only by cooperating they are able to complete the task (Figure 4.1).

Performance, leadership and intuitiveness have been identified as key issues in virtual environments (Heldal et al., 2005). Some of the previous studies also examine such topics as presence and co-presence while collaborating (Steed et al., 1999; Schroeder et al., 2001; Steed et al., 2005). It has been shown that some of these factors depend on the type of virtual environment and the tasks to be performed, others on computational resources and input or output devices. For example, experiments presented in (Steed et al., 1999; Schroeder et al., 2001) compare user performance based on different levels of immersion (e.g. using head-mounted display, immersive projection display and desktop computer). Here, the authors have proven that the person who has the highest degree of feeling to "be present" in the virtual environment is singled out as the leader.

Applicability of heterogeneous setups of input devices in 3D virtual environments has received less attention when compared to other domains (e.g. ubiquitous com-
Influence of the Setup and Communication on Collaboration in Virtual Environments

Figure 4.1: Combination of users’ actions during collaborative object manipulation (Pinho et al., 2008).

puting (Tandler, 2001; Kim et al., 2010), e-learning (Giemza et al., 2012)). However, some studies have successfully made initial attempts to evaluate how the combination of different input devices affects the outcome of group work. In particular, a heterogeneous setup involving different input devices is presented by McLaughlin et al. (2003). In this work, the authors investigate the performance and co-presence of users when collaborating in a heterogeneous haptic shared environment using Phantom and CyberGrasp haptic devices. A combination of different technologies, including desktop computers, mobile devices and sophisticated visualization environments like Cave, is discussed in (Skarbez and Whitton, 2009). Here the primary focus lies in technological aspects of such combination to define how people would work together in an environment of heterogeneous resources, using different mobile devices for data input. However, the influence of such heterogeneity on user performance and also its utilization for 3D virtual environments are not investigated in this work.

The aforementioned studies indicated the necessity for closer analysis of the relationship between the performance and different I/O devices. The experiments presented in (Schroeder et al., 2001; Steed et al., 2005, 1999) involve a heterogeneous setup where heterogeneity appeared in different immersion possibilities of the output devices. The participants’ performance has been greatly influenced by different output devices. This result asks for a more thorough investigation of heterogeneous interaction in which everyone can perform some specific task. Studying such interaction is important in a context of increasing productivity and also when a task cannot be completed by one person. In this way, it is possible to optimize the task(s) between participants where everyone performs his/her specific role to achieve a higher productivity.
4.3 Influence of Communication on Collaboration

Another area where such asymmetric systems are important is when participants have different restrictions on their activities (similar to Pinho et al. (2008)), leading to the impossibility for one person to perform the task alone. Only by collaborating with the partner they can achieve a positive result.

We would like to contribute to the research in this area by investigating the impact of combination of input devices on the user performance in collaborative virtual environment. We have chosen the heterogeneity in input devices, as it directly affects the ability to interact with the environment. This, in turn, contributes to the feeling of realism and being present within the environment, as well as the efficiency of performance.

4.3 Influence of Communication on Collaboration

Several researchers have identified multi-user virtual environments as a communication technology or medium (Riva, 1999; Biocca and Levy, 1995). It can be considered as "the leading edge of a general evolution of present communication interfaces like television, computer and telephone" (Riva, 1999). The advantage of new evolutionary technology above its predecessors lies in a full immersion of the human into a communication experience (Biocca and Levy, 1995).

Communication is one of the key components of any team activity. Most existing collaborative virtual environments offer their users a wide range of communication forms. Users can easily communicate with the help of text, voice and/or video chats. Moreover, some virtual worlds allow also for non-verbal communication, which is so natural in real life. For example, some virtual communities (e.g. Second Life (Linden Labs, 2003)) and games (e.g. Little Big Planet (Sony, 2008)) support a variety of gestures and facial expressions that avatars can have (Figure 4.2). Non-verbal communication has received a lot of attention among researchers as a solution towards more natural communication in networked collaborative virtual environments (Guye-Vuillème et al., 1999; Manninen and Kujanpää, 2002; Pandzic et al., 1996).

A number of studies investigating communication in virtual environments aim to analyze role, content and structure of communication (Galimberti et al., 2001; Friedman et al., 2009; Lee et al., 2009; Schmeil, 2009). Studies performed by Friedman et al. (2009) aim to analyze the discussion flow happening in a virtual environment. By performing a conversational analysis, the authors compare the dynamics and content of group discussions in desktop virtual environments to the one in a face-to-face situation. The results have shown that virtual-world discussions are found to include shorter sentences on average, have a smaller number of themes discussed, discuss a
smaller number of themes in depth, and require a longer time for discussion threads to form. This results in a lower amount of on-topic information exchanged by the participants in the virtual-world discussions than in the physical world. Schmeil (2009) studies how participants share information and make decisions with team members in a 3D virtual environment vs. a simple text chat. The findings obtained during the study show that being virtually embodied in a configurable 3D collaborative environment improves the collaboration, making the meetings in a virtual environment more structured. However, participants indicated also advantages of text chats, such as higher satisfaction of the meeting, less communication difficulties and distraction.

A similar study is performed by Lee et al. (2009). Here, the authors compare communication in both face-to-face and distributed settings while collaborating on a design task. Oppositely to the findings obtained by Friedman et al. (2009) mentioned earlier, where the purpose of interaction was purely discussion, Lee et al. (2009) show more preference towards virtual collaboration, that is found more efficient and engaging among the team members. Example of conversational analysis in virtual environments, where group of users had to collaborate together in order to accomplish a certain task, is performed by Galimberti et al. (Galimberti et al., 2001). As during cooperative activities the key content of communication is the interpretation of the situations in which collaborators are involved, the authors try to find the most effective way of clarifying the meaning of content. To do so, a conversational analysis of the interaction has been performed in order to structure information exchanged during collaboration. Based on the findings, the conversations clearly show an intention to collaborate to achieve the mutual goal. This intention is sustained by specific strategies in which collaborators exchange information and maintain contact with each other.

However, the impact of verbal communication on the highly interactive tasks (e.g. shared object manipulation) in 3D collaborative virtual environments has not been
studied so extensively (Wolff et al., 2007; Roberts et al., 2005; Otto and Roberts, 2003). In (Otto and Roberts, 2003) the authors investigate how the primary forms of human communication in the real world map to those in the virtual world. They discuss how each form of communication relates to the feeling of co-presence while collaborating in a closely-coupled setting. Otto and Roberts (2003) compare verbal vs. non-verbal communication when using different display configurations (similar to the studies performed by (Steed et al., 1999; Schroeder et al., 2001)). They observed a higher importance of verbal communication for less immersed user (e.g. using desktop computer). At the same time, a higher level of immersion (that can be achieved by using different immersive projection technologies) leads to a greater use of both verbal and non-verbal communication. This results in more interaction and higher contribution of a "more immersed" team member. Similar work is presented (Roberts et al., 2005), where different forms of communication are analyzed to achieve efficient collaboration when manipulating shared objects. Besides verbal and non-verbal communication, they define communication through objects in a virtual environment and the environment itself.

Such a high interest in role of communication in multi-user virtual environments shows its undoubtful importance for collaboration. However, the studies discussed in this section have always focused on the different aspects and forms of communication while not touching the impact of absence of communication. Moreover, the possible negative influence due to the ability to talk remains an open question. To address these two questions, and also to investigate the effect of heterogeneous setup discussed earlier in Section 4.2, we have conducted a user experiment which is presented in the following section.

### 4.4 Experiment: Influence of Setup and Communication on Collaboration

While single-user interaction has been studied at great lengths (Mine, 1995; Bowman et al., 2005), enabling detailed interaction using a heterogeneous set of input devices is not trivial. The studies discussed earlier indicated the necessity for a closer analysis of the relationship between the performance and different I/O devices, as well as influence of communication on the outcome of collaboration. To perform this analysis, we have conducted a user experiment aiming to compare homogeneous and heterogeneous setups, and also to investigate the benefits and drawbacks of voice communication during collaboration between two people carrying out the same highly interactive task in a 3D environment. As an example of a collaborative task, we have chosen a
Influence of the Setup and Communication on Collaboration in Virtual Environments

Figure 4.3: An example of 3D puzzle-solving task and its subtasks.

puzzle-solving task (Figure 4.3a), as it not only requires manipulation with the virtual environment, but also can be divided into different sets of subtasks (e.g. translation (Figure 4.3b) and rotation (Figure 4.3c)). This allows us to investigate whether people use different strategies depending on their ability to communicate and the combination of the devices used.

One of our goals is to investigate the effect of a homogeneous setup (where both participants are using the same kind of device) versus a heterogeneous setup (where two different devices are used). In particular, a SpaceMouse (Figure 4.4a) and a Phantom device (Figure 4.4b) were chosen. Besides the availability of these devices in our HCI lab, this choice is based on the fact that both devices have a completely different way of use. The Phantom device has an absolute mapping of its position and orientation.

Figure 4.4: Devices used in the experiment.
to the 3D cursor, while the SpaceMouse is a relative device. Furthermore, since the Phantom device is a haptic device, it allows the participants to feel the different puzzle pieces in the virtual environment. For example, haptic feedback is responsible for not letting user to push through the objects while feeling the resistance of the blocks.

### 4.4.1 Participants

Six female and twenty-six male unpaid volunteers, ranging in age between 23 and 39 (average 27 years) participated in the experiment. They were randomly divided into 16 pairs. All test persons had a computer science background. All but one participant were right-handed and used their dominant hand to operate the devices. Most participants had no experience working with the input devices involved. The others only had experience from participating in other user tests, where the same devices were involved.

### 4.4.2 Apparatus

For the experiment, two desktop computers were connected over a LAN. For output two 19” monitors were used. As mentioned earlier, a SpaceMouse and a Phantom device were used for input. Participants were sitting in the same room quite close to each other but they were not able to see the partner’s screen, as can be seen in Figure 4.5.

![Experimental setup](image)

**Figure 4.5:** Experimental setup.
Table 4.1: The experiment sessions.

<table>
<thead>
<tr>
<th>Session number</th>
<th>Participant 1</th>
<th>Participant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Homogeneous Setup</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 1</td>
<td>SpaceMouse</td>
<td>SpaceMouse</td>
</tr>
<tr>
<td>Session 2</td>
<td>Phantom</td>
<td>Phantom</td>
</tr>
<tr>
<td><strong>Heterogeneous Setup</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Session 3</td>
<td>SpaceMouse</td>
<td>Phantom</td>
</tr>
<tr>
<td>Session 4</td>
<td>Phantom</td>
<td>SpaceMouse</td>
</tr>
</tbody>
</table>

4.4.3 Design

The independent variables were the type of the setup and presence of communication, each with two conditions: homogeneous vs. heterogeneous setup, presence vs. absence of communication. A between-subject design was used for the presence or absence of voice communication, while a within-subject design was used for type of the setup. All participants had to use both input devices one after another. The order of the devices was counterbalanced using a Latin square design. This resulted in four puzzling sessions that had to be solved by each pair (Table 4.1): two using homogeneous interaction and two with heterogeneous interaction. The dependent variables were the time to solve the puzzle for each group and the amount of correctly placed blocks for each participant. However, as the subjective feeling of the participants is also an important measure in this kind of collaborative applications, the participants had to complete a questionnaire regarding their collaborative experience, contribution and about which user took the lead in solving the puzzle (see Figure B.3 in Appendix B).

4.4.4 Procedure

Pairs of participants were asked to complete a 3D puzzle-solving task, which consisted of collecting 12 pieces. These puzzle pieces were representing a picture, where one was already placed (see Figure 4.6) in order to act as visual guide. Each session presented a new puzzle to the participants. The puzzles were assigned to all pairs in the same order and had the same level of complexity. To assist with the task, the participants got a printed picture of each puzzle that guided the assembling process. Puzzle pieces were represented as cubes, with the picture only on one face, dispersed in the 3D environment. Some picture faces of the blocks were turned away from the participants so it was necessary to rotate the blocks in order to see them. Start and
4.4 Experiment: Influence of Setup and Communication on Collaboration

Finish buttons had to be clicked when they were ready to perform the task and as soon as the task had been completed. For selecting and manipulating the puzzle pieces within the 3D environment, the virtual hand technique (Bowman et al., 2005) was chosen. Users were represented by cones in the virtual environment, each assigned a different color. The environment was developed on top of the VRment framework and using the NiMMiT notation (De Boeck et al., 2007, 2008), extended with networking capabilities.

In order to investigate the influence of communication, half of the pairs were instructed to talk with each other, while the other half had to stay silent while puzzling. As not all participants speak the same native language, all communication was held in English.

Figure 4.6: Puzzle task used in the experiment.

In the beginning of the experiment, participants were allowed to practice with both devices for about 10 minutes. Once the training was completed, the four puzzle-solving sessions were performed. After each session, the participants had to fill in a questionnaire, based on (Steed et al., 1999), regarding their experience. The questionnaire consisted of three sections: regarding the leadership of the participant and his/her partner, regarding the perceived level of collaboration, and regarding the contributions to the task (see Figure B.3 in Appendix B). Participants had to evaluate their own and their partners’ activity on a 10 points likert scale. It took approximately one hour for each pair to complete the entire experiment.
4.4.5 Hypotheses

The goal of our experiment was to investigate the influence of the setup and communication on user experience when collaborating in virtual environments. Although in our analysis different characteristics of group work are evaluated, the following hypotheses highlight the most important expectations from the conducted study:

H1: the task completion time does not differ across homogeneous and heterogeneous setups;

H2: combination of different devices into a heterogeneous setup does not affect the efficiency of collaboration (in terms of completion time);

H3: combination of different devices into a heterogeneous setup contributes to the player perceived level of collaboration;

H4: the task completion time will be lower when users are allowed to communicate;

H5: presence of communication affects the efficiency of collaboration (in terms of completion time);

H6: presence of communication contributes to the player perceived level of collaboration.

4.5 Results

The goal of our experiment is twofold. Firstly, we investigate the performance and behaviour of the participants under unequal abilities (homogeneous vs. heterogeneous setup) when using different input devices. Secondly, we analyze how presence of communication affects collaboration.

4.5.1 Influence of Setup

Based on the performed experiment we wanted to investigate the potential of unequal interaction between collaborators within the same environment. This diversity in our case lies in the heterogeneity of input devices used when performing a 3D interactive task collaboratively. In our experiment, there were no limitations to the actions that both partners could perform. One of the main goals we wanted to achieve was to see the possibilities and drawbacks of creating heterogeneous collaborative environments
where everyone can perform specific tasks to achieve a common aim. Although we did not perform such a separation in the experiment, it will be shown later in this chapter, that participants divided their roles by themselves when allowed to communicate.

To achieve our goal, we compared the outcome of group collaboration when people perform the same tasks using various input devices, to the one where the same participants had equal equipment. These steps, in our opinion, can help in building effective heterogeneous collaborative environments where everyone can have his own role and be responsible for certain tasks based on his abilities, computational resources and I/O devices.

Analyzing the heterogeneous and homogeneous setups, based on a linear mixed model, we found no significant difference for the performance time (confirming hypothesis H1), but there is a main effect of convenience with the device, $F(1, 57) = 4.050$, $p = 0.049$ for participant #1 and $F (1, 57) = 23.224$, $p < 0.001$ for participant #2. There was no significant interaction effect between the two devices, confirming hypothesis H2. This result provides us with the ability to design collaborative environments where the use of certain devices does not limit other device types that could be involved.

Using a generalized linear model analysis of the effect of different conditions on the total amount of blocks placed correctly, we found a main effect of one of the device types ($\chi^2 (1) = 3.869$, $p = 0.049$). However, no interaction effect of device combination (whether the setup is homogeneous or heterogeneous) can be found. This indicates that a pair placed significantly more blocks if at least one of the devices was comfortable to use.

Although we will discuss the influence of communication on collaboration in detail in the next section, we will shortly discuss certain results about the relationship between setups used and communication. As will be shown later, communication is a factor that influences the feeling of collaboration in a positive way. Therefore, the change from a homogeneous device combination to a heterogeneous one does not bring any significant result (Figure 4.7a). However, when no communication is present, there is a tendency to improve the feeling of collaboration and increase the efficiency in the heterogeneous setup (Figure 4.7b). This partially confirms hypothesis H3, for the case where no communication is present.

According to the total time to perform the task, we can see that the heterogeneous setup reduces the time to complete compared to SpaceMouse – SpaceMouse case (Table 4.2). It takes, however, longer than the Phantom – Phantom case. This can be explained due to the reported inconvenience of the use of a SpaceMouse. In the heterogeneous case, the persons who were not able to perform as well, relied on their
Influence of the Setup and Communication on Collaboration in Virtual Environments

(a) Communication case.

(b) Non-communication case.

Figure 4.7: Effect of the homogeneous (HM) and heterogeneous (HT) setups on the collaboration.

Table 4.2: Total time for different setups (sec).

<table>
<thead>
<tr>
<th>Setup</th>
<th>Communication</th>
<th>No communication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M&lt;sup&gt;*&lt;/sup&gt;</td>
<td>SD&lt;sup&gt;*&lt;/sup&gt;</td>
</tr>
<tr>
<td>SpaceMouse – SpaceMouse</td>
<td>266.68</td>
<td>84.74</td>
</tr>
<tr>
<td>SpaceMouse – Phantom</td>
<td>235.64</td>
<td>133.75</td>
</tr>
<tr>
<td>Phantom – SpaceMouse</td>
<td>145.34</td>
<td>39.28</td>
</tr>
</tbody>
</table>

<sup>*</sup> M – average, SD – standard deviation

partner to achieve a better result. On the other hand, these tests showed that a homogeneous setup provides a more balanced performance between the participants.

Figure 4.8 shows the dependence between the contribution to the task solving and the type of the device used (for participant #1) when communication is allowed (Figure 4.8a) and when not (Figure 4.8b). Because the SpaceMouse was considered by most participants as a more complicated device to use, the SpaceMouse homogeneous case has a rather changing character of the trend (jumping from min extreme to max several times). This means that the contribution to the task solving is higher in each case when the convenience with the device is higher. The homogeneous case with the Phantoms shows that the contribution is quite high and remains almost the same during the whole experiment. In the heterogeneous case, the participant using the Phantom has a higher share in the task solving than compared with the same
device in the homogeneous case. The heterogeneous case SpaceMouse – Phantom shows that the participant using the SpaceMouse had the impression of having contributed less in solving the task. The maximum peaks correspond mainly to the cases where the participant with the SpaceMouse gave different suggestions, but was not always the one who did a lot during the task. In the non-communication case (Figure 4.8b) a more balanced performance is observed. Similarly to the other condition, in non-communication sessions we observe a wider spread in a SpaceMouse – Phantom setup.

It is also important to investigate the correlation between the device usage and the contribution to the block placing (Figure 4.9). Figure 4.9a shows this correlation for the cases, where communication was present. As can be seen from the graph for the homogeneous case, most of the values remain within a certain range and have little data spread. For the heterogeneous sessions more extreme values can be observed,
especially in the case when the participant was using the SpaceMouse. But also it is necessary to keep in mind that during the communication case the “placing cubes” variable might not always represent the actual course of things, as some pairs divided the work: one partner would orientate all puzzle pieces, while the other would place them in the puzzle. The graph of non-communication case shows a more balanced trend with less extreme values (Figure 4.9b). There is also not much data spread for the homogeneous case which was caused by a more balanced collaboration.

### 4.5.2 Influence of Communication

In order to assess the users’ performance, we analyzed how the ability to talk influenced the total time to perform the task. Against our expectations the task was completed quicker in all 4 sessions for the pairs who were not allowed to talk (rejecting
Table 4.3: Total time (sec).

<table>
<thead>
<tr>
<th>Setup</th>
<th>Communication</th>
<th>No communication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Homogeneous setup</td>
<td>206.01</td>
<td>89.43</td>
</tr>
<tr>
<td>Heterogeneous setup</td>
<td>235.64</td>
<td>133.75</td>
</tr>
</tbody>
</table>

* M – average, SD – standard deviation

hypothesis H4). In Table 4.3 the performance results of homogeneous and heterogeneous setups are compared.

Total time on task was analyzed using a linear mixed model. We found a significant main effect of communication on total time ($F(1,58) = 4.768, p = 0.03$), confirming hypothesis H5. This indicates that people spent significantly more time on a task when they were able to talk to the partner. This occurred regardless of the devices used, as no interaction effect was found between the setup and communication.

One of the characteristics that test persons had to evaluate was the convenience with a certain device. Results have shown that this indicator was not based only on the device itself but also on the conditions that were presented to the participants. Figure 4.10 shows that using the same device setup under different conditions changed the feeling of the participants. In particular, when they were allowed to talk, the mean value of “convenience” was higher. This can be explained by the fact that when people were allowed to communicate they were able to ask the other person for help (for example, if it was difficult to rotate a puzzle piece) so they really did not feel themselves being aside from the performance.

The generalized linear model analysis has shown that for the non-communication case there is a significant main effect of the convenience with device on the total amount of blocks placed by a participant ($\chi^2(1) = 5.671, p = 0.017$). This indicates that people placed significantly more blocks correctly when they were convenient with the device although they were not able to speak. For the case where communication was allowed, there is a main effect of the device convenience on the total time ($F(1,27) = 11.094, p = 0.003$).

When building a collaborative environment it is important to take into account factors that help to increase the feeling of collaboration. The results of the experiment show that the ability to communicate in a CVE increases the feeling of collaboration (see Table 4.4), confirming hypothesis H6. The feeling of working together with the partner was higher independent of the setup. The way in which this level of collaboration depends on each setup was considered in the previous section.
Influence of the Setup and Communication on Collaboration in Virtual Environments

Figure 4.10: Convenience with the device, for heterogeneous (HT) and homogeneous (HM) setups in communication (C) and non-communication (NC) cases.

Table 4.4: Feeling of collaboration.

<table>
<thead>
<tr>
<th></th>
<th>Communication</th>
<th>No communication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Feeling of collaboration</td>
<td>7.19</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Table 4.4: Feeling of collaboration.

<table>
<thead>
<tr>
<th></th>
<th>Communication</th>
<th>No communication</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Feeling of collaboration</td>
<td>7.19</td>
<td>1.36</td>
</tr>
</tbody>
</table>

For the sessions with communication, the linear mixed model analysis shows a main effect of the partner’s contribution to the task solving on the “feeling of collaboration” \( (F(7,11) = 4.327, p = 0.015) \). We found that the contribution to the placing of the cubes is not significant for this case. The partner’s convenience with the device has a main effect on collaboration \( (F(9,20) = 2.445, p = 0.046) \), which indicates that people felt to collaborate significantly more when their partners were comfortable with the devices. For the case where no conversation was allowed, the own contribution to the cube placing is significant for the feeling of collaboration \( (F(1, 27) = 13.099, p = 0.001) \).

Because communication is an essential part of collaboration, we checked how people evaluate their own contribution to the tasks, when they are allowed to communicate and when they are not. Figure 4.11 shows that in all sessions the mean values of
4.5 Results

Figure 4.11: Contribution to the task, when using a SpaceMouse (M) or a Phantom (P).

contribution to the task by the participants were higher when they had the chance to talk to each other and discuss the task.

Amongst others we wanted to determine in our research the factors that define leadership when collaborating. One of our initial expectations was that the person would be considered as a leader more when he/she performs more active and places more blocks to the correct position in both cases. But for the communication cases it turned out that people who were assessed as being talkative were seen as the leaders, rather than participants who performed more. All participants of the first 8 pairs were asked to indicate who did the most talking. Although among the given answers “None” and “Equal” were present, it became obvious that the person who was indicated (by him/herself and the collaborator) more frequent as the most talkative person, was also mentioned as a leader.

Participants were asked to estimate to what extent they considered themselves as a leader. Furthermore, we asked to evaluate the extent of the leadership of the partner. In our opinion it is interesting to compare how these evaluations differ from each other under different conditions. The following Table 4.5 presents this comparison analysis for communication and non-communication cases.

In the cases where communication was allowed, the persons who operated a SpaceMouse had the same idea about their leadership as their partners. In contrast, when the person was using a Phantom device, he/she tended to overrate own leadership value comparing to the one given by their partner. For the cases without communication, there is little difference between the self evaluation and the partner’s rating.

Checking the correlation between leadership (self and partner’s evaluation) and convenience with the device under the two conditions the following can be observed: for the communication case the leadership is defined mostly by the communication, while
Influence of the Setup and Communication on Collaboration in Virtual Environments

Table 4.5: Self and partner’s evaluation of leadership for communication case.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Self Evaluation</th>
<th>Partner’s Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M*</td>
<td>SD*</td>
</tr>
<tr>
<td>Communication case</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpaceMouse – SpaceMouse</td>
<td>5.50</td>
<td>2.07</td>
</tr>
<tr>
<td>SpaceMouse – Phantom</td>
<td>4.38</td>
<td>2.39</td>
</tr>
<tr>
<td>Phantom – SpaceMouse</td>
<td>6.50</td>
<td>1.20</td>
</tr>
<tr>
<td>Phantom – Phantom</td>
<td>5.75</td>
<td>0.71</td>
</tr>
<tr>
<td>Non-communication case</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SpaceMouse – SpaceMouse</td>
<td>5.38</td>
<td>0.92</td>
</tr>
<tr>
<td>SpaceMouse – Phantom</td>
<td>4.50</td>
<td>1.20</td>
</tr>
<tr>
<td>Phantom – SpaceMouse</td>
<td>5.00</td>
<td>0.76</td>
</tr>
<tr>
<td>Phantom – Phantom</td>
<td>5.13</td>
<td>0.64</td>
</tr>
</tbody>
</table>

* M – average, SD – standard deviation

for the non-communication cases, the comfort of device usage is more influential (see Table 4.6).

As can be seen from Table 4.6 the correlation between the device convenience and leadership is stronger for non-communication cases. For the communication cases, there is an input of the communication to the correlation.

Mixed model analysis has shown no main effect of the contribution characteristics (e.g. amount of blocks placed, share to the problem solving, etc.) on the leadership value for the communication case. Contrary to this, for non-communication cases, there is a significant main effect of blocks placed by the participant ($F_{1,24} = 5.064$, $p = 0.34$) and his contribution to the task solving ($F_{1,24} = 6.247$, $p = 0.020$) on the level of his perceived leadership.
4.6 Discussion

The results of our study have a number of implications for CVE applications. In this section we will discuss these results and also compare our findings to results of existing similar studies.

4.6.1 Influence of Setup

In our experiment, there were no limitations to the actions that both partners could perform. One of the main goals we wanted to achieve was to see the possibilities and drawbacks of creating heterogeneous collaborative environments where everyone can perform specific tasks to achieve a common aim. Although this division was not performed in this experiment, results have shown that in communication cases, participants divided their roles by themselves. This resulted in the fact that for communication sessions, the contribution to the cube placing was not a significant characteristic. This is a logical conclusion because during communication sessions, it happened that one participant was responsible for rotation only and did not perform much positioning.

During the analysis, we wanted to compare results obtained in our experiment with those collected in other studies investigating heterogeneity of the setups in collaborative virtual environments. In particular, we have compared our findings with the research of Schroeder et al. (2001), where the heterogeneity lied in different immersive systems. Understanding the possible difference between the influence of input (our study) and output devices (study by Schroeder et al. (2001)) on the outcome of collaboration in virtual environments, we believe that their comparison can reveal in a more efficient manner the ways these two types of devices can be combined in.

In their work, Schroeder et al. (2001) have shown that there was no significant effect of combination of different output devices on the level of collaboration. In the case of input devices, we have observed that the heterogeneous setup contributed to the perceived feeling of collaboration as players have indicated it higher than in the homogeneous setup (see Figure 4.7). Although the available activities of both participants were the same, they felt more comfortable when they could rely on their partner using a different device. Observations have shown that within heterogeneous setups the participant with the more comfortable device has been helping quite a lot independent of the presence of communication. On the other hand, these tests showed that a homogeneous setup provides a more balanced performance between the participants. This result can be used in two ways. The first conclusion that can be drawn here is that unequal interaction (in terms of I/O devices) can decrease the efficiency
Influence of the Setup and Communication on Collaboration in Virtual Environments

and contribution of one of the participants, and cause uncomfortable experience for these participants in a CVE. However, as in reality the device that is most suited for performing a task, is not always available, we can conclude that a heterogeneous setup still allows to work in an efficient manner. On the other hand, we can think of other types of tasks to be performed in a CVE, where participants have limited abilities and should perform different tasks to achieve the common goal.

Analysis has shown that the choice of one device does not influence the efficiency of the other device as there is no interaction effect of the two devices used. That gives us a possibility to build setups where devices can be combined as desired. This fact is important for developing heterogeneous setups in such a way that one should not worry that one of the devices limits the other one. The productivity of the interaction will not be significantly different in heterogeneous setup to the one in homogeneous. However, the difference between devices in our case caused less enjoyable cooperation. Furthermore, no interaction effect of the heterogeneous combination on the amount of correctly placed blocks exists. Though there is a significant main effect of one of the devices, which indicates that a participant placed significantly more blocks if at least one of the devices was comfortable to use.

As the next step, we compared the task completion time with the one obtained by Schroeder et al. (2001). In their study, the authors experienced that in a heterogeneous setup (immersive screen vs. desktop) the task took longer than when working with two immersive screens setup. Similar results has been obtained in our work. Against our expectations, the heterogeneous setup was not the quickest. This result suggests the need to find more appropriate tasks that can optimize the completion time for each kind of setup.

Finally, we compared the contribution to the task in our experiment with the one in (Schroeder et al., 2001). In both tests, in a heterogeneous setup, participants with a ‘worse’ device (less comfortable SpaceMouse or non-immersive desktop screen) indicated their contribution as being smaller. A comparison of the contribution value between heterogeneous and homogeneous setup showed the difference of the contribution for the same device. This difference is based on the fact whether the opponent’s device was less comfortable (e.g. contribution of Phantom user is higher when he evaluated the sessions compared with the SpaceMouse). Analysis of such situations has shown that users with less comfortable devices did not enjoy the collaboration. They were not always able to follow their partners. This is the main negative effect of unequal collaboration. Such consequences should orient the developers of collaborative environments towards more balanced cooperation. But this fact does not mean that it is necessary to avoid heterogeneity. The development of appropriate tasks, where the
diversity of abilities can be beneficial for all the participants and involve everyone at the same level of cooperation, is one of the possible solutions.

4.6.2 Influence of Communication

The analysis performed in Section 4.5.2 brings us to several important results of our study. First of all, communication has played an important role for a feeling of collaboration. The feeling of working together with a partner was higher regardless the setup. Even the device convenience was evaluated better in the communication cases. This can be explained by the fact that when people were allowed to communicate they were able to ask the other person for help (for example, if it was difficult to rotate a puzzle piece) so they really did not feel themselves being aside from the performance.

The main drawback of the communication, that was found, was the increase of the time to perform the task. For all sessions participants spent more time solving the puzzle when they were allowed to talk. According to the observations, the conversations of pairs contained a short strategy discussion at the beginning, and afterwards they were mostly sharing their emotions and comments.

We therefore come to the following conclusion. When it is important to achieve a better feeling of “working together” then communication plays an essential role. But when it is crucial to perform the task quicker and divide it between the participants, the ability to communicate can decrease the productivity and efficiency of the collaboration. The presence of communication had also a positive effect on the evaluation of the contribution to the task solving. In (Otto and Roberts, 2003) it was found that the verbal communication is significantly more important than non-verbal. As we aimed to study the effect of voice communication on the group performance, we did not support non-verbal communication, but just compared the interaction when speech was present and when it was not. Our experiment has shown that the contribution was higher in all sessions for the pairs that were allowed to talk. This fact also leads to an increase of collaborative effect between the participants who were allowed to speak.

Amongst others we wanted to determine in our research the factors that define leadership when collaborating. The studies by Slater et al. (2000); Steed et al. (1999) investigated leadership as one of the aspects of collaboration within virtual environments. The authors have demonstrated a correlation between the leadership and the immersion possibilities of the output device, showing that the users perceived the more immersed participant as a leader. In our case, we expected that the person would be considered as a leader more when he/she performs more active and places more blocks to the correct position in both cases. But for the communication cases this hypothesis cannot be completely proven or declined because in most of the cases of
collaboration with communication, people defined their roles themselves. Usually one participant placed only a few puzzle pieces but rotated them for the other participant to position them correctly. Further analysis have shown that the level of “being a leader” was in all sessions higher for the person who was indicated as more talkative. There were no main effects of contribution characteristics found on the leadership for the communication case. For speechless collaboration, players defined a leader as the one who placed most of the blocks correctly and contributed more to the task solving. Our analysis led to the conclusion that when people are not able to communicate with each other, they take the lead when they feel comfortable to operate within the environment and this can be achieved by using suitable devices.

4.7 Conclusion

In this chapter, we have presented our findings from a case study investigating the effect of the input device combination and the influence of voice communication. The contribution of our work is twofold. First, we compare not only performance between different device types (relative and absolute) within a homogeneous setup, but we also show the heterogeneous performance when everyone is using a different device. Secondly, we contribute to the research on role of communication in CVEs by studying its impact on the collaboration efficiency.

The user experiment revealed several important lessons regarding the implementation of collaborative virtual environments. First of all, we have found that the combination of different devices does not significantly influence the collaboration. This fact is important because it is not necessary to impose a certain device and in such a way to limit possible combinations. The heterogeneous setup additionally contributes to the feeling of collaboration perceived by the participants. Besides the heterogeneity, communication contributes towards the perceived level of collaboration. It also allows the participants to explicitly divide their work. At the same time, the ability to communicate during the experiment results in a longer task execution.

To increase the efficiency of heterogeneous collaboration, we can think of other activities to be performed in the VE where every participant can supplement each other’s performance. In particular, assigning each player with a certain task according to the device he/she is operating is a prospective solution. Although it might not be realistic for every type of CVE, some environments can benefit from such assignment (e.g. in games it can create a tighter bounding between players). As we observed during the experiment, participants divided tasks among themselves when communication was present. However, when communication was not supported it was not possible to per-
4.7 Conclusion

form such division. Therefore, we believe that in this condition, providing adaptation of tasks according to the user performance with a specific device in a heterogeneous setup may lead to an improved group collaboration. In the next chapter we will discuss how to perform such adaptation.
Influence of the Setup and Communication on Collaboration in Virtual Environments
Chapter 5

Adaptation in Collaborative Virtual Environments

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5.1 Introduction

Collaborative interaction in virtual environments has its own challenges compared to other types of collaborative work. A collaborative virtual environment involves a group of users performing highly interactive tasks with the use of three-dimensional (3D) user interfaces, while trying to make collaboration efficient. Interacting in such 3D environments is not always easy for every user. It is more complex compared to real life situations due to the amount of different 3D interaction techniques and interactive tasks that may not always be intuitive for users. Moreover, usage of special
3D input devices with a high degree of freedom (e.g. 3D SpaceMouse) to navigate and manipulate in 3D environments, can cause extra difficulties for the users. This may hinder user interaction and in the end also influence the group collaboration. Therefore, providing adaptation according to the context of users (e.g. performance, preference, etc.) is considered beneficial (Hariandja, 2011) to improve their interaction in virtual environments, not only individually but also as a group collaboratively.

In the previous chapter, we have investigated the user interaction while performing a collaborative task in a 3D environment. The comparative analysis has shown, that although the combination of different devices did not significantly influence the collaboration, a heterogeneous setup did not reduce the time to complete the task as was expected. Therefore, we envisage assigning each player a certain task according to the device he/she is operating as a possible solution to increase the efficiency of heterogeneous collaboration. During the previous study, we have observed that users often explicitly divided their tasks, but this division was done only when communication was present. For no communication cases, it was not possible to perform such division. Therefore, we believe that by adapting these tasks and devices according to users’ context we can further enhance the result of group interaction.

In this chapter we present our effort to apply adaptation according to user performance and preference as a prospective solution to enhance group interaction in collaborative virtual environments. After a short discussion of the existing research addressing adaptation in CVEs, we will present our attempt to integrate adaptation while collaborating on a highly interactive task. As the adaptation may take place differently according to the goal of collaboration, several approaches are considered. After an elaborated discussion of the suggested approaches, we describe an experiment conducted to validate them.

5.2 Use of Context for Adaptation

*Adaptation* refers to the changes or modifications performed in order to suit new conditions or needs (Collins English Dictionary, 2012). In computer science, the term adaptation relates to a process, in which an interactive system adapts its behaviour to individual users based on information acquired about its users and its environment. It becomes more and more common for the developers to integrate various adaptation techniques in order to react to changing conditions, which determine the context of use.

Over the past few years, a considerable amount of research has been done in context-aware computing. Dey (Dey, 2001) described the general definition of context, which
is likely the most popularly used in every HCI field: “Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between the user and the application, including the user and the application themselves.” In this chapter we will use the term adaptation to describe any changes made to the application according to user context. As the user context we consider any information that can be used to characterize a user and is relevant to the usage of the application by this user (Dey, 2001).

The use of user context for making decisions about adaptation for a variety of user interfaces has raised significant interest in the research community (Bouchelligua et al., 2012; Höpken et al., 2008; Blumendorf et al., 2009). For example, different multimodal user interfaces provide the means to support the user in various situations and to adapt the interaction to the user’s actions and preferences. In ubiquitous computing the context of use, which is defined by the triplet ‘user, platform, environment’, is continuously and dynamically changing (Bouchelligua et al., 2012). This results in numerous challenges for engineering user interfaces that are compliant to their context of use. Also, many web applications utilize personalization and adaptation based on the user history and preferences (Höpken et al., 2008).

In the past years the interest in context-based adaptation in virtual environments has started to grow significantly among the research community. Studies of (Vanacken et al., 2008b; Octavia et al., 2010) have investigated an approach for detecting and switching context for contextual interaction in single-user virtual environments and integrating adaptation in virtual environments. In those works context was defined by the available input and output devices, and also external parameters such as the experience level of the user, whether or not there are collaborative partners in the environment, or even the pose of the user (sitting or standing). Using a context-aware design process, Hariandja has incorporated adaptation in virtual environments (Hariandja, 2011). The author experimented with providing adaptation to users based on their individual context, such as switching between interaction techniques (based on personal preference) and adapting the interaction technique itself (based on motor ability). When performing a certain task in virtual environments, users may prefer one technique to another depending on the environment condition or view of the virtual world. Thus, given users’ preference as context, we can enable users to switch between interaction techniques as a form of adaptation. Different motor abilities may affect user performance in virtual environments, for example a user who has hand tremor may perform an interaction technique less accurately than healthy users. Therefore, the interaction technique can be adapted by adjusting its parameters (e.g. viscosity) accordingly to comply with the user’s specific characteristics (e.g. hand tremor).
Among numerous application domains that are based on the virtual environment technology, adaptation has been widely applied in the context of video games and simulations. Due to the significant number of research initiatives in this area, we discuss them separately in the following section.

5.3 Adaptation in Games

The number of video games on the market constantly grows. So does the number of players, whose characteristics, needs and preferences are getting more and more diverse. Therefore, to ensure a longer playing time of each introduced game, producers need to take into account the differences among potential players and create conditions that motivate the widest possible range of users to keep playing. This triggers a need for tailoring games to individual playing experiences, making them adaptive and personalized to the characteristics of each player. In particular, this can be achieved by the modeling of the player experience that has been identified as one of the key components to achieve a high level of player satisfaction (Yannakakis, 2012). Player model incorporates any relevant information, such as playing style and current emotional and cognitive state, which are used for steering the adaptive components of a game (e.g. adaptation of task, character, game mechanics, sound, difficulty, etc.) (Bakkes et al., 2012).

Player modeling and adaptive technologies facilitate an improved player-centered game design by providing a more appropriate level of challenge, a smoother learning curve, and enhance the game-play experience for individual players regardless of gender, age, and experience (Cowley et al., 2008). Charles et al. (2005) define three game elements, through which a game may be adapted: (1) a player’s character; (2) non-player characters in the game and (3) the game environment or game state. A substantial amount of research has attempted to incorporate the adaptation of these elements in games such as the modification of difficulty levels (Hunicke, 2005), enemy’s behavior (Yannakakis and Hallam, 2007), or graphic elements of the game environment itself and object representation (Buttussi et al., 2007; Liapis et al., 2012).

A lot of work has been performed by introducing artificial intelligence (AI) that learns a player behaviour and adapts the behaviour of non-human characters to it (e.g. enemies or environment elements) (Laird and Lent, 2000). In (Yannakakis and Hallam, 2007), the authors suggest an AI approach to adapt the behaviour of interactive opponents and in such a way achieve a more appealing and entertaining play in predator/prey type of games. In this particular game type, the authors provide adaptation based on an analysis of (1) level of challenge experienced by user, (2) opponents’
5.3 Adaptation in Games

behaviour and (3) spatial diversity. While the first criterion defines whether or not a game is too easy or too hard for the player, the second and the third criteria give the player an impression of intelligent opponents (changing behaviour in the gaming environment).

Besides the aforementioned research initiatives in the area of adaptation, there are numerous examples of adaptive commercial games available on the market. For example, video game "Left 4 Dead" (Turtle Rock Studios, 2008) uses an AI technology that generates a different experience for the players each time the game is played. In particular by monitoring their performance, the game AI decides how many enemies attack the player and in such a way determine the pace of the game. Similarly, the enemy characters in "Halo" (Bungie, 2011) and "The Darkness 2" (Digital Extremes, 2008) are driven by AI, that is able to detect the surrounding world (including the actions of a human player) and to act according to it, making the game less predictable.

In order to apply adaptation it can often be required to perform numerous trials to learn a player’s behaviour. An alternative approach is presented by Bakkes et al. (2008), where domain knowledge is gathered automatically by the game AI, and is immediately utilized to evoke effective behaviour. In the ‘rapidly adaptive game AI’ approach, each game character feeds the game AI with data on its current situation, and the observed results of its actions. The game AI adapts by processing the observed results, and generates actions in response to the character’s current situation. Similar approach is used in "Madden NFL 09" (Electronic Arts, 2008), incorporating an adaptive difficulty engine to tailor the game to the playing style in a football game. Another sports game "MLB 07: The Show" (SCEA, 2007) provides baseball players with an adaptive pitching intelligence, that adjusts the game according to the player’s individual strengths and weaknesses.

Charles et al. (2005) suggest a general framework for adaptive games based on the modeling of players. The framework suggests an online adaptive game system that changes according to a player’s behaviour in run time. As players may progress differently during the gameplay, this approach also allows to update the player model according to the player achievements during the game. A similar approach is proposed by Houlette (2004): a game maintains the profile of each player that captures the skills, weaknesses, preferences, and other characteristics of that player. This profile is being updated by the game as the player interacts with it in run time. The game AI accesses this player model in order to determine how to adapt the game behaviour to the particular player. Adaptation based on the similar principles is integrated in the game "Resident Evil 5" (Capcom, 2009). In this game, a certain number is assigned to every player, that represents the level of his/her performance (number of deaths,
attacks, etc.). The adaptation of enemy behaviour takes place based on this number, that can evolve over time according to the player in-game progress.

An approach based on dynamic scripting is proposed by Spronck et al. (2006) that deals with online adaptation of an opponent AI, suitable for implementation in complex computer games such as role-playing games. Dynamic scripting is based on the automatic online generation of AI scripts for computer game opponents by means of an adaptive rule database. To further improve the dynamic-scripting technique, the authors suggest an enhancement that allows the scaling of the difficulty level of the game AI to the human player’s skill level. Alternatively to the scripting of the opponents behaviour, Lujan et al. (2008) focus on the use of an Accuracy-based Learning Classifier System as the learning mechanism for generating in a virtual simulation environment, based on the example of a real time strategy game. The Learning Classifier System receives information of the game state, which is compared to the set of rules that define the behaviour of the AI system within the game.

A rule-based approach to adjust different game parameters in order to achieve a higher entertainment value is presented by Yannakakis and Hallam (2009). In their research, the authors aim to optimize player satisfaction in augmented-reality games by mapping individual player characteristics to reported entertainment preferences of augmented-reality game players (based on the existing literature). An adaptive mechanism then adjusts controllable game parameters in real-time in order to improve the level of player satisfaction.

Adaptation has been widely used in the commercial games to adjust the difficulty level, so that the game is not too easy or too hard for the player. For example, in ”Max Payne” (Remedy Entertainment, 2001) the difficulty level is altered by increasing the numbers of enemies or the difficulty of killing them. This is done by analyzing player’s statistics that is used to make an in-game decision regarding how difficult the game should be for the player. The ”Mario Kart” (Nintendo, 2011) series employ adaptation that assists less experienced drivers during the racing game.

In the research presented by Liapis et al. (2012), the authors introduce a generic two-step adaptation framework for the generation of personalized content within games with regard to a user’s visual preference. The approach is based on a two-step adaptation procedure where the evaluation function that characterizes the content is adjusted to match the preferred visual aesthetics of users and the content itself is optimized based on the personalized evaluation function. An example of the adaptation of the environment is presented by Buttussi et al. (2007). Here the authors propose a fitness game system which adapts game graphics and gameplay to the user’s movements and physiological parameters. The adaptation takes place according to the user’s personal information, such as age, gender, current heart rate and movements, as well as infor-
information collected during previous game sessions and aims to adjust the required intensity of physical exercises through context-aware and user-adaptive dynamic adaptations of graphics and gameplay.

Several researchers study the adaptation in games based on the player emotional state (Gil-leade and Dix, 2004; Tijs et al., 2009). In these games a player experience is optimized by continuous adaptation of the game mechanics to the player’s emotional state, measured in terms of emotion-data (e.g. level of excitement or frustration).

5.4 Adaptation in Collaborative Virtual Environments

Numerous works in the field of CSCW and mobile applications have tried to provide adaptation based on context to improve group collaboration (Kirsch-Pinheiro et al., 2005; Yamin et al., 2002). However, adaptive interaction has received less attention in collaborative virtual environments. Interacting in virtual environments is mostly associated with complex interaction where multiple users have to perform complicated tasks with highly interactive 3D user interfaces. Different user characteristics influence user interaction in virtual environments and lead to performance deviation among users. Adaptive user interfaces can be considered as one way to accommodate these individual differences and enhance users’ performance (Benyon, 1993; Mourlas and Germanakos, 2009). Integrating adaptation into virtual environments, by providing adaptive user interfaces according to users and other contexts, is considered as a key to comply with user’s differences and enhance user interaction.

Becoming more and more popular, collaborative virtual environments cause an additional complexity due to the diversity of users that may be working together. Abilities, skills and preferences of every single user may greatly vary causing unbalanced performance and worsen the outcome of collaboration. It is especially important in the case of highly interactive activities. Only a few studies (Schroeder et al., 2001; Steed et al., 1999) have investigated people collaborating to perform interactive tasks in virtual environments. For example, in (Steed et al., 1999) all participants had to complete different subtasks in order to achieve the task goal. The authors have investigated the variation of performance based on the available output devices. In our opinion it is interesting to see if the adaptation of the tasks based on the devices would increase the performance.

Another example of highly interactive collaboration can be found in (Schroeder et al., 2001), which investigated collaboration of two participants on a Rubik’s cube task. They compared performance between a physical setup and an immersive virtual one, which showed to be almost the same. The users have provided a higher evaluation of
these two setups comparing to the desktop one. It also showed that the participant using the desktop contributed less to the task and did not enjoy the collaboration. Based on this, it may be interesting to improve collaboration by adjusting the performance of the desktop user and providing him with a more appropriate task. For example, a user can be assigned with a task that does not require immersion in a virtual environment and that is more suitable to be accomplished using two-dimensional devices (e.g. mouse). In such a way it is possible to increase the contribution of this particular user towards the group collaboration. This possible extension of their work can be seen as one example where adaptation based on the devices and performance can benefit the collaboration of several people.

A phenomenon related to recent CVEs is their rapidly increased popularity and ability to unite thousands of people all over the world (e.g. MMORPG and virtual communities). The main aim for developers now is to support interaction of these users, which can be achieved for example by providing different services based on their context (Bergsträsser et al., 2007). Another approach to provide enhanced collaboration is a context-aware communication support for remote gamers (Singh and Acharya, 2004), which can improve a gaming experience by integrating voice interaction between users based on game context. In (Gerbaud et al., 2009) a collaborative virtual environment for training is presented, where different elements (virtual world, virtual humans’ behaviour, scenario, etc.) can be adapted to a specific training situation. To our knowledge, there are only very few works which describe how collaborative virtual environments can benefit from adaptation based on users’ context. In particular, Ibáñez and Delgado-Mata (2011); Delgado-Mata and Ibáñez (2011) suggest an adaptation in two-player competitive games such as tennis and air hockey, that allows both players enjoying the game in spite of their different levels. More specifically, if a player is playing too badly (the game is too difficult for him), the game gets easier for him so he does not get frustrated. If a player is playing too well (the game is too easy for him), the game gets more difficult for him so he does not get bored. Adaptation happens according to the context of user performance (i.e. amount of hits done by each player). With our work we would like to extend the existing research on the applicability of user context for adaptation in multi-user virtual environments (this research has been carried out together with dr. Johanna Renny Octavia Hariandja (Hariandja, 2011)). Adaptation may play an important role in elevating user performance in such a dynamically changing virtual world. Therefore, we think that through context-based adaptation users can achieve more enjoyable interaction within the virtual world.

The aim of collaborative virtual environments should be to achieve group goals, not individual goals of each user involved in the collaboration. Group interaction and performance may be enhanced by integrating adaptation into collaborative virtual envi-
5.5 Group Behaviour Modeling

In order to enhance group performance (which is defined based on the collaborative task, e.g. shortest completion time, highest score, etc.) in a collaborative virtual environment we propose the adaptation of user roles while performing a highly interactive task. As the user role, we consider any task that can be performed by a user or combination of task and other factors (e.g. task performance using specific device, or under other specific condition). To determine the adaptation, we suggest to model a group’s behaviour based on users’ individual performances and preferences. The purpose of this modeling approach is to come up with the best prediction of role combination. Here, adaptation is performed by assigning users’ roles (i.e. deciding which roles are appropriate for the users) which leads to an improved group interaction. Taking individual characteristics of each user as an incoming parameter, the group behaviour model provides at the end information about the most suitable role for each participant of the collaboration (Figure 5.1).

Based on the goal of collaboration, several approaches to model group behaviour can be defined to maximize a certain aspect of shared experience. In particular, in some cases it is more important to perform the collaborative task efficiently in terms of minimal loss of resources (e.g. time). In other collaborative applications, e.g. multiplayer
games, the priority is in a higher level of user satisfaction or more balanced performance. In our study, we have considered four different approaches to model group behaviour in collaborative virtual environments: minimum total time, exclusion of worst performance, minimum performance gap and maximum preference. Although these approaches are not limited to any amount of collaborators, we describe each approach for pairs of users, where every user is assigned with a complementary (mutually excluding) role.

**Minimum total time**: this approach aims to find the best role combination that provides the shortest total completion time. The completion time is calculated using a two-stage approach. First, we estimate the time necessary for every user separately to perform each role. Second, for all possible role combinations, we estimate the total time necessary for two users to accomplish a task collaboratively, and select the one that corresponds to the quickest performance.

**Exclusion of worst individual performance**: this approach aims to find the best combination that excludes the worst individual performance of a certain user. To model group behaviour based on this approach, we considered the performance difference between users within the pair for every role. By performance difference we imply the time difference between two users needed to perform the same role. By doing so, it is possible to determine the role which takes the longest for one participant comparing to his/her partner. For the combination with the maximum difference, the worst role is given to the user with the lower time, while his/her collaborator automatically obtains the complementary role.
5.6 Experiment

Minimum performance gap; this approach aims to find the best combination that guarantees the most equal performance among two participants. Here, we first calculate the difference between task completion times for all possible role combinations. Afterwards, the combination with the minimal time difference is chosen as the one that gives the most balanced performance.

Maximum preference; this approach aims to find the best combination that assigns the most preferred role to the user. For every possible combination, the total subjective preference rating given by users is calculated. Based on the total ratings, the combination with the maximum value is determined as the best combination. Here, we first calculate the total subjective rating for all possible role combinations. Then, based on the total ratings, the combination with the maximum value is selected as the best combination.

For the best combination of users’ roles in each approach, the total completion time is estimated following a two-stage procedure. First, for every user, we calculated the time it took them to perform each role separately. Afterwards, for all combinations of roles, we calculate the total time to perform both roles collaboratively. The estimated total times are used to evaluate the efficiency of these four user modeling approaches.

In the next section, we present a user experiment that investigates two main goals of our research: the potential of role-based collaboration its applicability for adapting interaction in CVEs. First for every approach, we analyze whether or not the role-based interaction results in an improved group performance (by comparing this with the interaction where no roles are assigned). Afterwards, we focus on role-based adaptation that is provided to accommodate user differences in performance or preferences, and thus, enhance the results of collaboration.

5.6 Experiment

To investigate how the group performance can be enhanced by introducing role-based interaction and, furthermore, its usage for providing adaptation in collaborative virtual environments, an experiment was conducted. The experiment was designed based on the findings of the study presented in Chapter 4. It has been shown that users often explicitly divided their roles during collaboration based on their convenience with the device being used. But this division was only explicitly done when communication was allowed. For no communication cases, it was not possible to divide the roles explicitly. Therefore, we believe that this issue can be solved by automatic adaptation of users’ roles in collaborative virtual environments which is the primary focus of the current study.
Similarly to an experiment presented in Chapter 4, an interactive 3D puzzle solving task (Figure 5.2) was chosen for the experiment, which is considered to be highly collaborative. The adaptation is determined based on the context of use by assigning a specific role to a user. User roles can vary greatly based on the purpose of the application. In our case, we define a user role as the combination of action and device with the help of which this action is performed. Due to the nature of a 3D puzzle solving task, two types of actions were defined: translation and rotation. As no interaction effect of combining different devices has been found in the earlier study, SpaceMouse and Phantom were involved (Figure 5.3).

With our experiment, we aim for an improved group interaction by modeling group behaviour that suggests the adaptation of assigning users’ roles based on their individual performance and preference when executing a certain action (translation or rotation) using a certain device (SpaceMouse or Phantom). Therefore, four roles were defined, that were further complementary combined in order to model group behaviour:

1. Translation using SpaceMouse
2. Rotation using SpaceMouse
3. Translation using Phantom
4. Rotation using Phantom

During our study we consider two different situations of collaboration: the co-located and remote collaboration. The difference in these two conditions lies in availability of devices used by the collaborators. In the co-located setup users can easily switch
available devices, thus each of them can always use the most suitable device. In the other setup switching between the two devices is not an option any more because the other device is not locally present.

This study was performed in collaboration with another PhD student from our university dr. Johanna Renny Octavia Hariandja (PhD successfully defended on November 29th, 2011). As an extension of this experiment, a follow up study has been conducted where the adaptation of assigning users’ roles has been investigated for a real-life scenario. In particular, by applying one of the approaches suggested in Section 5.5 in an existing video game we have outlined some of the challenges that occur when employing role-based adaptation in games. In Appendix D, we present the manuscript of a journal paper that was very recently submitted based on the results of this additional study and our former I-Society proceedings contribution (Beznosyk et al., 2012a).

### 5.6.1 Participants

Ten randomly coupled pairs of unpaid volunteers (4 females and 16 males) participated in the experiment. Their average age was 28 years, varying from 23 to 34 years. Having a computer science background, most of the participants had little experience with a virtual environment and also with the devices involved. All participants were right-handed and used their dominant hand to operate the device during the experiment.
5.6.2 Apparatus

For the experiment, two input devices, a SpaceMouse and a Phantom, were available for each user. Two desktop computers with 19” monitors as displays were used in the experiment. During the experiment, participants were located in the same room and close to each other, however, they were seated in such a way that it was impossible to see each other’s screen. Due to the co-located setup being used, participants were allowed to naturally communicate without involvement of any additional equipment (e.g. microphone, headphones). Figure 5.4 illustrates the experiment apparatus and settings.

5.6.3 Design

For the experiment a within-subject design was adopted. For the free collaboration session, the independent variable was the device used (SpaceMouse, Phantom). For the role-dependent collaboration session, the independent variable was the combination of role and device (Rotation SpaceMouse, Translation SpaceMouse, Rotation Phantom, Translation Phantom). Task completion time was measured as the dependent variable. Subjective evaluation of each condition was obtained through a questionnaire (see Figure B.4 in Appendix B), asked after each session.
5.6 Experiment

(a) Virtual environments with puzzle blocks and users represented by cones.

(b) Visual feedback on puzzle block selection by users.

Figure 5.5: The puzzle solving task in the experiment.

5.6.4 Procedure

Similar to the experiment in Chapter 4, participants were asked to collaborate on a 3D puzzle solving task with the shared goal of assembling a complete picture. Each puzzle consists of 12 cubes dispersed in a virtual environment as shown in Figure 5.5. One cube was already placed and served as a visual cue. Part of the picture was presented on one of the cube’s sides. Users were represented by cones with different colors in the virtual environment (Figure 5.5a). With the help of the cone users could select and manipulate cubes. A visual feedback was provided to indicate which block was currently selected (Figure 5.5b).

This time, the experiment consisted of three parts: an individual session, a free collaboration session, and a role-dependent collaboration session. The first session aimed to gather the individual performance data of both participants. Every participant had to complete four separate puzzles individually, which included all possible combinations of roles and devices. Based on this data we further modeled group behaviour. During this session, for rotation, participants only had to make the picture on one cube’s side visible, while for translation, participants had to move all cubes to the designated position to make the picture complete.

The second and third sessions aimed to gather the data of users’ performance in pairs. The second part of the experiment consisted of two free collaboration sessions, where no role division was involved so both participants were able to rotate and translate. Participants had to collaborate together to solve the puzzle in a heterogeneous setup of devices, where one participant used the SpaceMouse and the other used the Phantom. The third session of the experiment contained four puzzles to be solved collaboratively in a heterogeneous setup, but with applying the division of roles to participants. In
this part, complementary roles were assigned (one participant could only translate, the other rotate). Table 5.1 presents the complete overview of the experiment sessions that resulted in ten different puzzles to be solved.

Table 5.1: The experiment sessions.

<table>
<thead>
<tr>
<th>Session</th>
<th>Participant 1</th>
<th>Participant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual session</td>
<td>Rotation SpaceMouse</td>
<td>Rotation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Translation SpaceMouse</td>
<td>Translation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Rotation Phantom</td>
<td>Rotation Phantom</td>
</tr>
<tr>
<td></td>
<td>Translation Phantom</td>
<td>Translation Phantom</td>
</tr>
<tr>
<td>Free collaboration session</td>
<td>Free SpaceMouse</td>
<td>Free Phantom</td>
</tr>
<tr>
<td></td>
<td>Free Phantom</td>
<td>Free SpaceMouse</td>
</tr>
<tr>
<td>Role-dependent</td>
<td>Translation Phantom</td>
<td>Rotation SpaceMouse</td>
</tr>
<tr>
<td>collaboration session</td>
<td>Rotation Phantom</td>
<td>Translation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Translation SpaceMouse</td>
<td>Rotation Phantom</td>
</tr>
<tr>
<td></td>
<td>Rotation SpaceMouse</td>
<td>Translation Phantom</td>
</tr>
</tbody>
</table>

Throughout the experiment, we measured task completion time of each puzzle. Subjective evaluation regarding users’ performance and preference was collected after each session by means of the questionnaire (see Figure B.4 in Appendix B). On average, each pair spent one hour to complete the whole experiment.

5.6.5 Hypotheses

To validate the presented approaches of modeling group behaviour for adaptation based assigning users’ roles\(^1\), the following hypotheses were formulated:

H1: the actual task completion time based on role-based collaboration will be lower than the task completion time during free collaboration;

H2: the estimated task completion time based on the modeling of group behaviour will be lower than the task completion time during free collaboration.

The first hypothesis shows whether or not the group performance (in terms of completion time) can be enhanced by introducing role-based interaction. By comparing

\(^{1}\)appropriateness of these approaches for providing adaptation in collaborative virtual environments has been validated and presented by Hariandja (2011)
it with collaboration where no roles are assigned, we expect the time, needed for each group to accomplish the task, based on the actual role-based performance not to exceed the time during free collaboration. The second hypothesis validates our approaches to model group behaviour for role-based adaptation by comparing modeled task completion time and time during free collaboration.

5.7 Results

Our study focuses on role-based collaboration as a promising solution to improve group performance. By conducting the user experiment, we aim to analyze whether or not introducing role-based interaction can improve the outcome of collaboration. Furthermore, we are interested in applying role-based adaptation in order to accommodate differences between participants involved in shared activities. In the experiment, we provided adaptation by assigning every user with a specific role, which was defined based on the modeling of group behaviour. Group behaviour was modeled based on the user’s individual performance and preference and gives information about the best combination of actions and devices for a particular group. Four approaches to model group behaviour based on the goal of collaboration were proposed in Section 5.5. The potential of each approach to improve the result of group interaction is now analyzed under two different conditions: co-located collaboration and remote collaboration. Co-located interaction, where all collaborators are present at the same location, allows them easily to exchange the devices to the most appropriate one. Oppositely to the co-located collaboration, during the remote collaboration users are not able to switch devices between each other. As every participant is limited to only have a certain device available, we will have the two best predicted combinations of actions and devices for every pair (e.g. one best combination determined when the first participant has the SpaceMouse, and another best combination determined when the first participant has the Phantom).

We will first analyze whether the actual role-based collaboration improves the outcome of group performance (hypothesis 1). Afterwards, based on individual performance we model group behaviour in order to validate our assumption that the role-based adaptation can be used in order to enhance the collaborative experience (hypothesis 2). Analysis of the four proposed approaches in co-located and remote setup is summarized in Table 5.2.
Table 5.2: Modeling group behaviour approaches for co-located and remote collaboration.

<table>
<thead>
<tr>
<th>Hypotheses</th>
<th>Co-located collaboration</th>
<th>Remote collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statistics</td>
<td>Hypothesis confirmed?</td>
</tr>
<tr>
<td></td>
<td>Minimum total time</td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>$t(9)=2.302$, $p=0.047$,</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{actual}}$ (M=213.9 s) $&lt; M_{\text{free}}$ (M=283.5 s)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>$t(9)=3.508$, $p=0.007$,</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{model}}$ (M=217.8 s) $&lt; M_{\text{free}}$ (M=283.5 s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exclusion of worst individual performance</td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>$t(9)=0.465$, $p=0.653$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{actual}}$ (M=237.5 s) $&lt; M_{\text{free}}$ (M=250.9 s)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>$t(9)=0.747$, $p=0.474$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{model}}$ (M=280.9 s) $&gt; M_{\text{free}}$ (M=250.9 s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum performance gap</td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>$t(9)=1.291$, $p=0.229$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{actual}}$ (M=225.8 s) $&lt; M_{\text{free}}$ (M=263.7 s)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>$t(9)=1.627$, $p=0.138$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{model}}$ (M=228.9 s) $&lt; M_{\text{free}}$ (M=263.7 s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum preference</td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>$t(9)=1.517$, $p=0.164$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{actual}}$ (M=219.3 s) $&lt; M_{\text{free}}$ (M=267.9 s)</td>
<td></td>
</tr>
<tr>
<td>H2</td>
<td>$t(9)=1.292$, $p=0.229$,</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{model}}$ (M=240.6 s) $&lt; M_{\text{free}}$ (M=267.9 s)</td>
<td></td>
</tr>
</tbody>
</table>
5.7 Results

5.7.1 Minimum total time

First we compared the actual and modeled task completion time to the time spent during the free collaboration in co-located setup. We observed that both average completion times were lower than the average time during the free collaboration session, where no roles were assigned. Participants spent significantly less time to complete the task when roles were introduced, what demonstrates the advantage of applying role-based collaboration. Moreover, as the average completion time based on the modeling approach was also significantly less than the free collaboration time, we conclude that minimum total time is an appropriate approach that effectively improves group performance.

Slightly different results were obtained by analyzing average time during actual and modeled role-based interaction and free collaboration in a remote setup. Similarly to the co-located setup, role-based collaboration has demonstrated its effectiveness as the participants spent significantly less time to complete the task than during free collaboration sessions. This demonstrates that assigning roles to users improves the group interaction and performance. Comparison of the time during free collaboration sessions and the modeled time showed no significant difference between them. Seeing that the average estimated completion time based on the modeling approach was lower, we can say that role division between participants results in a better group performance.

5.7.2 Exclusion of worst individual performance

For our second approach, we have found that the actual and the free collaboration time to complete a task do not differ significantly during co-located interaction. However, the average actual task completion time was found to be lower than the one of the free collaboration, showing that role-based collaboration can be appropriate and improve group performance. Comparing the modeled and the free time, we found that task completion time does not significantly differ across those situations. Additionally, the average estimated task completion times based on the model was higher than the one of the free collaboration. These findings show that our second approach is not effective for providing adaptation of assigning users’ roles as it shows no significant improvement in the group performance.

Comparing role-based performance time to the free collaboration in a remote setup, we can conclude that role involvement can give a lower completion time leading to an increase of performance, however, this difference was not significant. This result was obtained in both cases of role-based collaboration: actual time and modeled time.
5.7.3 Minimum performance gap

The analysis of the third approach in a co-located setting has shown that the average actual performance time when roles were assigned and the average estimated completion times based on the modeling, were lower than the free collaboration. However, these differences were not statistically significant. Seeing a decrease of task completion time, we can state that introducing roles to minimize the performance gap between users can be quite effective. It also demonstrates a decrease of task completion times after the adaptation is applied although this improvement is not statistically significant.

When analyzing this approach in a remote condition, the same results were obtained. Although on average role-based collaboration (both actual and modeled time) required less time than free collaboration, this difference was not significant.

5.7.4 Maximum preference

When analyzing the fourth approach for co-located collaboration, we found that the average time when roles were assigned (both actual and modeled time) were lower than the average time of free collaboration. But again these differences were not statistically significant. These findings are similar to the third approach, where the role-based interaction results in a better performance by decreasing task completion time. The completion time is also decreased after applying the adaptation, although not statistically significant. Thus, we can conclude that this approach can be effective to determine the adaptation of assigning users’ roles.

For remote condition, role division showed its efficacy in enhancing the group performance of collaborators through a significant decrease of completion time. Furthermore, we observed that by adapting user roles according to this approach resulted in a lower task completion time when compared with the free collaboration, though this difference was not significant. This finding confirms once again that the assignment of roles can greatly improve the total completion time comparing to the free collaboration.

5.8 Conclusion

Realizing the diversity of users collaborating together in a shared virtual environment and its possible impact on the group performance, we have explored how collaboration can be improved through adaptation based on user context. The contribution
of our work lies in the proposed adaptation of users’ roles while performing highly interactive tasks in a collaborative 3D virtual environment. This adaptation is determined based on users’ individual performance and preferences. As a result of such adaptation, every collaborator obtains the most suitable role, which in its turn, leads to better group interaction. Although we did not apply this approach at runtime, we expect it to be beneficial in particular application contexts.

An experiment has been described to examine how introducing role-based collaboration results in an improved group performance. The effective assignment of roles was ensured by modeling group behaviour. Based on the goal of collaboration we proposed four approaches to model group behaviour which are used further for applying adaptation of user roles. Although we did not provide the adapted roles to the users immediately, these approaches can be used to apply adaptation at runtime. Through a detailed analysis every approach was investigated under two different conditions: co-located and remote collaboration. Except for the Exclusion of worst performance approach, we have shown that adaptation according to the context of users (i.e. performed action and device used) leads to improved group collaboration (i.e. faster task completion time). The Minimum total time approach, that determines the roles resulting in a shortest performance time, is found to be the most effective approach in both situations.

This chapter concludes the first part of the dissertation dedicated to investigate how the collaboration in general virtual environments can be enhanced in order to achieve a realistic and efficient performance. The main goal of this part was to analyze and define those factors that contribute to an improved interaction between users. In the second part of this dissertation, we will continue with an investigation on collaboration in virtual environments for a specific purpose, namely video games. By doing so, we aim to define the factors contributing to the user experience when playing together.
Part II

Integration of Closely-coupled Collaboration in Multiplayer Games
Introduction

In the first part of this dissertation we have analyzed different types of interaction in a 3D virtual environment, namely loosely- and closely-coupled collaboration. Through a series of user experiments, it has been shown that closely-coupled collaboration does not always provide the most efficient performance (i.e. in terms of task completion time). However, introducing such type of collaboration in a 3D virtual environment did result in a higher satisfaction rate of users. In particular, they have indicated closely-coupled interaction as the one that leads to a higher enjoyment and increases the level of collaboration, evolving into real team work. At the same time loosely-coupled collaboration was perceived more like individual performance, despite the fact that users had to achieve a shared goal.

Seeing such a positive reaction towards closely-coupled interaction in 3D virtual environments brought us to the following thoughts. Entertainment is one of the application domains where it is important to provide users with a satisfactory experience and where efficiency is not always the most important factor of collaboration. Collaboration in games has been widely used since the growth of massive multiplayer online games (MMOGs) in the beginning of the 2000s. Since then, for many games it has evolved from merely an additional element to a core component of a game. Not only entertaining games have been utilizing collaboration. It has also actively been used in the domain of serious games, such as for (tele)rehabilitation and e-learning. In these situations, collaboration is adopted to motivate users to perform certain activities that are not purely entertaining, but still fun to do.

Although the amount of games (both in entertainment and serious gaming) that support collaboration is quite high, only a few of them utilize the principles of closely-coupled collaboration (Co-optimus, 2012). Most collaborative games utilize loosely-coupled interaction, where team work is supported but may not always be required. For example, in many MMOGs groups of people can defeat enemies by playing together. However, this being harder to achieve, it is often possible to complete such
Introduction

tasks by a lesser amount of players or even alone. Oppositely, in games with close coupling the game is designed in a way that collaboration between a certain amount of people is required to successfully complete the game. Some of such games have received a lot of attention among players worldwide (VideoGamer.com, 2010), not in the least due to the support of this truly teamplay experience. This popularity indicates that the potential of closely-coupled interaction in the game domain has not yet been completely revealed.

An increased popularity of games based on close coupling (e.g. Wii games) on the one hand and their limited number on the other hand, results in the necessity to thoroughly analyze both types of interaction in collaborative games. It remains an open question whether or not players would prefer one type of coupling over the other and what exactly contributes to this preference. Additionally, in case of closely-coupled interaction, it is obvious that this type introduces more challenges for designers when applied in games. We believe that this can be one of the reasons for the limited amount of games based on close coupling.

Therefore, in the second part of the dissertation, we address the question of applying different types of collaboration in games. Here, we first perform a comparative analysis of different ways of coupling between players. Afterwards, we discuss the challenges that occur when implementing closely-coupled collaboration in games. We determine the factors that have a significant effect on players. By doing so we aim to point the attention of game designers and developers to the most important issues with regards to collaboration in games in order to enhance player experience.
Chapter 6

Levels of Collaboration in Multiplayer Games

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6.1 Introduction

As part of this dissertation we intend to investigate the integration of collaboration (and especially closely-coupled collaboration) in multiplayer games. Closely-coupled collaboration has been identified as a more preferable way to perform a general virtual task. However, this does not immediately imply this preference among players within game applications. As has been mentioned in the introduction to this part of the dissertation, closely-coupled collaboration has been used in some multiplayer games, although the number remains relatively low. The popularity of these games triggers a necessity to investigate the potential of closely-coupled collaboration that can raise player experience to a higher level by allowing natural and unobtrusive teamplay.
In our previous work we have considered collaboration in a distributed virtual environment where users were able to communicate naturally. We have hinted at the importance of communication, especially during closely-coupled collaboration, as it involves a lot of coherent and synchronized work, that is hard to achieve without communication. However, in some types of games communication might be not supported, be very limited (e.g. text chat) or not desired by players. These conditions may directly or indirectly affect the player experience. The same level of collaboration could, therefore, result in a completely different player perception and influence his/her choice to continue playing the game in the future.

Taking these two considerations into account, we realize the necessity to fully investigate the potential of closely-coupled collaboration in the context of video games. In this chapter, we present a study that intends to determine how players perceive loose and close coupling when playing video games collaboratively. Furthermore, as loosely- and closely-coupled collaboration can be represented through different types of in-game activities, we wanted to determine those that provide a better player experience for each type of interaction. We defined several ways players can interact with each other that are based on cooperative game design patterns and studied them separately for loosely- and closely-coupled collaboration.

### 6.2 Cooperative Game Design Patterns

Integrating collaboration in some genres of multiplayer games has increased their popularity. Such games encourage players to team up and work together towards common goals whilst emphasizing group interest versus personal stakes. Many game designers and researchers are currently exploring different ways of integrating and evaluating cooperative activities within their games (Seif El-Nasr et al., 2010). In doing so, one of the open issues remains the discovery and analysis of cooperative patterns that could improve interaction between players in multiplayer games with a collaborative nature.

**Game patterns** are descriptions of recurring interaction, that depict how game components are used by players to affect various aspects of gameplay (Björk and Holopainen, 2004). In (Björk and Holopainen, 2004), the authors have identified a large amount of patterns by analyzing existing games, some of them being classified as cooperative patterns with different possibilities and incentives for players to achieve things together. In the last years, cooperation has evolved from an additional feature into a full-grown game component, motivating more and more players to participate in a
game. Although several works have attempted to address the question of cooperative game design patterns, it remains an open question in the research community.

In (Pape et al., 2003), the cooperative nature of interaction between players is classified by the order in which actions may be taken: turn-taking and simultaneous games. Zagal et al. (2006) explore cooperative patterns based on board games. Interaction patterns in massive multiplayer games (based on the example of Star Wars Galaxies) are investigated by Ducheneaut and Moore (2004), but the authors focus on the social aspect of interaction (verbal and non-verbal communication between players). Other studies (Battocchi et al., 2009; Goh et al., 2011) investigate cooperative game design as a motivational factor for special target groups (e.g. people with disabilities) and focus on such patterns as enforced collaboration, sequentially-dependent roles, etc.

More elaborated research in the area of cooperative design patterns is performed by Seif El-Nasr et al. (2010); Rocha and Mascarenhas (2008). Following the same approach presented in (Björk and Holopainen, 2004), Rocha and Mascarenhas (2008) define several cooperative design patterns by analyzing numerous commercial games, that support some form of collaboration between players. This list is considerably extended by Seif El-Nasr et al. (2010). Here, the authors not only introduce a more complete series of cooperative game patterns, but also describe a methodology to evaluate the cooperative nature of games. Using this methodology, they analyze which pattern triggers which event during the shared gameplay (e.g. laughing, strategy discussion, etc.).

The evaluation described in (Seif El-Nasr et al., 2010) was performed for several existing cooperative games that were played on a shared screen, and players could easily and naturally communicate with each other. Although we have shown that communication plays a very important role during collaboration (see Chapter 4), communication in multiplayer games (especially when played remotely) may not always be desired or supported. Therefore, we find it crucial to investigate how interaction between players can be improved based on introducing different cooperative patterns in order to compensate a possible negative effect due to a lack of communication.

### 6.3 Experiment: Comparison of Loosely-coupled and Closely-coupled Collaboration in Multiplayer Games

In our study we investigate loosely- and closely-coupled collaboration based on cooperative game patterns where gameplay occurs over a distance and players are not able
to communicate in any way. Based on the user experiment, we have performed a comparative analysis of several cooperative patterns, described in the following section. During the experiment players evaluated six custom-developed games, each based on one of the chosen cooperative patterns. All games shared a similar design (e.g. same appearance of the avatar and objects in the virtual world), and were only different in the way users interacted with each other, defined by the patterns. Although modern games usually apply a combination of patterns, in our study we look at separate patterns to define those best suitable for the given conditions. Using different criteria, each pattern was graded based on its influence on player experience, revealing the drawbacks and benefits of each. Furthermore, a comparative analysis is performed between the same patterns when they are evaluated in co-located and remote setups.

6.3.1 Selected cooperative patterns

For purposes of the experiment, a selection of cooperative patterns (from the list presented by Seif El-Nasr et al. (2010)) was made based on popularity and frequency of appearance in existing multiplayer games. Based on the coupling between players, we group the selected patterns either in loosely- or closely-coupled types of interaction. Here, we present a list of patterns used in our study. The first three patterns represent closely-coupled interaction, while the last three correspond to loose coupling.

The limited resources pattern is concerned with providing a limited number of resources and thus encourages players to share or exchange resources to achieve the same goal. One of the examples of this pattern is collecting items which are a shared resource (e.g. collecting stars in Mario games, balloons in Little Big Planet).

The complementary roles pattern implies that players have a different role to complement each other’s activities within the game. This type of collaboration occurs when two players have two different abilities and have to accomplish a certain task with each other’s help (e.g. one player drives vehicle while the other one shoots enemies in Battlefield 2145).

The pattern ‘interaction with the same object’ provides players with interactive objects that can be manipulated by several characters together. Some games force players to collaborate in such manner by adding “heavy” objects in the game (e.g. sharing a ball in Beautiful Katamari, lifting and throwing different objects together in Little Big Planet).
6.3 Experiment: Comparison of Loosely-coupled and Closely-coupled Collaboration in Multiplayer Games

The shared puzzles pattern is a general category for all cooperative design puzzles, where players encounter a shared challenge or obstacle (e.g. Resident Evil 5, collaborative games of "room escape" type\(^1\)).

The pattern ‘abilities that can be used on other players’ encourages cooperation between players by providing certain characteristics that can be only applied to a different player, without which the team cannot achieve the final goal (e.g. player with medical character can heal a soldier player in the role-playing game Team Fortress 2).

The shared goals pattern is used to force players to work together. In games based on this pattern, a group of players is given a goal that can be easier achieved in a group (e.g. quests in World of Warcraft, where a certain number of enemies has to be killed which is easier to perform in a group).

6.3.2 Participants

Thirty-six unpaid subjects (thirty-one males and five females) participated in the experiment. Their average age was 28 years old, ranging between 21 and 38. Most of them had a computer science background and were recruited among university staff and students. Based on self evaluation, the average player experience with multiplayer games was 3.42 on a scale from 1 (never played) to 5 (played a lot).

6.3.3 Apparatus

During the experiment two players were located in neighboring rooms separated by a hallway. Each player used a 15.4" laptop connected over a LAN. One of the laptops was a HP Compaq 8510p (Intel Core 2 Duo T8100, 2.1 GHz, 3 GB with ATI Mobile Radeon HD2600 graphic adapter) and the other was a Dell Latitude E6510 (Intel Core i3 M370, 2.4 GHz, 2 GB with NVIDIA NVS 3100M). A separate external keyboard was attached to each laptop for a more comfortable input. There was no communication possible between the two players. To avoid any chance of hearing each other, music was played in the background. In each room one observer was present and sat beside the participant (Figure 6.1).

\(^1\)this is a type of game which requires a player to escape from imprisonment by exploiting their surroundings and solving different puzzles
6.3.4 Design

During the experiment, a within-subject design was used. The independent variable was the game type with six conditions. All participants, in pairs, had to complete six sessions testing every game type. The order of the conditions was counterbalanced using a balanced Latin square design. The dependent variables were: task completion time, player score, total group score and amount of lives lost. A subjective evaluation of each game type was collected through a self-developed post-experiment questionnaire (see Figure C.1 in Appendix C).

6.3.5 Procedure

Eighteen pairs of participants consecutively played six different collaborative games, described in detail in the following section. During each game the player had to collaborate with his/her partner who was located in a different room. Players were coupled anonymously and, therefore, did not know who their partner was. Any form of communication (voice chat, text chat, pop-up messages, etc.) was avoided. Pop-up windows were used only in one game to support some basic level of awareness between the two players. Several days before the actual experiment, a pilot test was performed to check the playability of every game.

Before the experiment, participants read a brief introduction and conducted a five minute trial to familiarize themselves with the gaming environment and controls. In addition, written rules were given, in which both the goal and the way of interacting
6.3 Experiment: Comparison of Loosely-coupled and Closely-coupled Collaboration in Multiplayer Games

with the partner were explained. After each game, players were asked to evaluate the subjective perception of their experience (see Figure C.1 in Appendix C). In particular, they were asked to quantify the following aspects of collaboration:

- necessity to discuss the game (strategy, ask your partner for help, etc.);
- level of collaboration with the partner;
- amount of waiting for the other player during the game;
- level of awareness of the partner’s actions;
- negative impact on the efficiency caused by the absence of communication, the physical distance, the necessity to wait for the other player, the actions of the other player;
- negative impact on the enjoyment caused by the absence of communication, the physical distance, the necessity to wait for the other player, the actions of the other player.

For evaluation purposes, a visual analogue scale (VAS) (Crichton, 2001) was used. The participants marked on the 10 cm line the point that they felt represented their perception of the current state from not at all to very much. Additionally, the players ranked the six games based on their level of enjoyment. It took approximately 60 minutes for each pair to complete the actual experiment.

6.3.6 Games

Six custom games were created for the experiment, each adopting one of the selected cooperative game patterns (Table 6.1). Based on the coupling between players, we classified each game into one of two categories: closely- or loosely-coupled. If a game required a lot of waiting or if the actions of one player directly affected the other player, it was categorized as the first type. The games that did not require tight collaboration between players and, allowed more independent performance, were assigned to the second type. Although more difficult, in the case of loosely-coupled games, it was possible to complete them without the partner’s participation. However, in closely-coupled games, only by acting together players could complete them successfully. We will discuss the interaction design for the games, that explains the reasoning behind assigning each pattern to either closely- or loosely coupled further in this section.
For every game, a similar 3D virtual environment was developed, which consists of several islands (a rectangular area, on which all game elements are located). Players are represented by alien-like avatars used from Unity 3D tutorial\(^2\). To distinguish the two avatars in the virtual environment, one is colored in a light blue color, while the other avatar is brown. Players are able to navigate freely in the environment and are not forced to stay together. They have to collect different objects by running over them. Some of the objects are located on higher platforms not directly reachable by the players. Therefore, they have to use the jumping pads that help a player to jump higher to collect certain items. In order to get on a different island players need to jump across the abyss. If one of the players falls off the island the team loses one life. After the fall, the player reappears at one of the respawn points. A group score is calculated and analyzed to measure the successfulness of the game completion. The game continues until one of the following conditions is met: (1) players collect all required objects; (2) players loose all their lives; (3) the time runs out.

For closely-coupled \textbf{Game 1}, a \textit{limited resources} pattern is adopted (Figure 6.2a). Two players have to collect items, but are able to store a maximum of 10 items at the same time. Once both players reach the maximum amount of items, they can collect the following 10 objects. If one of the players collects 10 objects he/she has to wait for the other player and cannot pick up new items in the meantime.

In closely-coupled \textbf{Game 2}, a \textit{complementary} pattern is used, which implies that players have a different role to complement each others’ activities within the game (Figure 6.2b). During this game two roles are introduced. One player moves the jumping pad around the island while not being able to jump, and the other player uses it for jumping to reach objects located on higher platforms. There is only one jumping pad on each island. The roles are assigned randomly when players start the game.

Closely-coupled \textbf{Game 3} follows an \textit{interaction with the same object} pattern (Figure 6.2c). In this game players have to move the jumping pad simultaneously. As soon as one of the players selects the jumping pad to move, the other player receives a message on his/her screen that the pad is selected and he/she is needed to help moving it. However, it does not indicate the location where the player has to be in order to help his/her teammate. When selected by two players, the jumping pad can be moved when both players walk in the same direction. Both players can use it for jumping. Similar to game 2, there is only one jumping pad on each island.

Loosely-coupled \textbf{Game 4} utilizes a \textit{shared puzzles} pattern (Figure 6.3a). Here, the focus is to collect 10 special objects: each contains a heart with a letter on one side. Once all 10 special objects and therefore ten letters are found, players need to use them

\(^2\)available online at http://unity3d.com/support/resources/tutorials/3d-platform-game
to formulate a word containing all the letters, and put them in a designated window. The game succeeds when the word is entered correctly. Players do not see what words are entered by their partners while guessing. Once the correct solution is given by one player, the other one can also see it in his/her window.

*Abilities that can be used on other players* pattern is used in loosely-coupled Game 5 (Figure 6.3b). In this game, players have to collect two types of objects: hearts and weapons. Each one is assigned to one player. They can see only one type which is randomly assigned on starting the game. Every time a player collects his/her 10 items, he/she gets the ability to see the partner’s objects for about twenty seconds, and is able to collect them as well. The goal of the game is not only to collect enough objects as a team. Individual results of each player also need to exceed a certain amount of items of both types.

Loosely-coupled Game 6 utilizes a *shared goals* pattern (Figure 6.3c). The collaboration is reduced to a shared goal of collecting a certain amount of objects while acting independent from the partner.

### 6.3.7 Hypotheses

With our experiment we wanted to compare two levels of collaboration – loosely- and closely-coupled – based on the six cooperative game design patterns presented earlier. Although we understand that the games among each level might be evaluated differently due to the diverse ways of interacting between players, we wanted to see whether or not closely-coupled collaboration in games would be found more preferable among the participants (similar to the findings obtained in Chapter 3 for a more general task performance in a CVE). To define the advantages of one level over the other, the following hypotheses were suggested:\(^3\):

- **H1**: the group performance (in terms of number of collected objects) is lower in closely-coupled games without negative influence on player enjoyment;
- **H2**: the user enjoyment is higher when closely-coupled collaborating;
- **H3**: the lack of communication has a greater effect in closely-coupled games without negative influence on the player enjoyment;
- **H4**: the physical distance has a greater effect in closely-coupled games without negative influence on the player enjoyment;

\(^3\)In our analysis different characteristics of group work are evaluated. Presented hypotheses highlight the most important expectations from the conducted study.
Levels of Collaboration in Multiplayer Games

(a) Limited resources: two players have to collect items, but are able to store a maximum of 10 items at the same time.

(b) Complementary roles: one player moves the jumping pad around the island and the other player uses it for jumping.

(c) Interaction with the same object: players have to move the jumping pad simultaneously and both can use it for jumping.

Figure 6.2: Closely-coupled games used in the experiment.
6.3 Experiment: Comparison of Loosely-coupled and Closely-coupled Collaboration in Multiplayer Games

(a) Shared puzzles: players have to collect hearts with letters and then use these letters to formulate a word.

(b) Abilities that can be used on other players: players can get an ability to see their partner’s objects every time they collect 10 objects of own type.

(c) Shared goals: players have to collect objects together while acting independent from each other.

Figure 6.3: Loosely-coupled games used in the experiment.
<table>
<thead>
<tr>
<th>Design pattern</th>
<th>Closely- or loosely-coupled</th>
<th>Amount of islands</th>
<th>Amount of lives</th>
<th>Total amount of objects to pick up</th>
<th>Necessary object type</th>
<th>Time, min</th>
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<td>5</td>
<td>100</td>
<td>hearts</td>
<td>7</td>
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<td>Closely-coupled</td>
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<td>100</td>
<td>hearts</td>
<td>7</td>
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<tr>
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<td>Closely-coupled</td>
<td>4</td>
<td>5</td>
<td>100</td>
<td>hearts</td>
<td>7</td>
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<td>5</td>
<td>200</td>
<td>letters</td>
<td>5</td>
</tr>
<tr>
<td>Abilities that can be used on other players</td>
<td>Loosely-coupled</td>
<td>4</td>
<td>5</td>
<td>200</td>
<td>hearts, weapons</td>
<td>5</td>
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<tr>
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<td>Loosely-coupled</td>
<td>5</td>
<td>3</td>
<td>150</td>
<td>hearts</td>
<td>5</td>
</tr>
</tbody>
</table>
6.4 Results

H5: the level of collaboration is higher when closely-coupled collaborating.

6.4 Results

This section presents the results of our study. As mentioned earlier, the main goal of the experiment was to analyze to what extent patterns based on loosely- and closely-coupled interaction are appropriate for remote play without communication to define the more beneficial ones for collaborative games. We aimed to investigate which patterns, if any, were affected more than the others by the conditions they were played in. First, we present an overview of player performance and preference. Secondly, we report results that reflect an impact of the remote setup on player experience (absence of communication and physical distance). Finally, the patterns are compared from the perspective of collaboration between players. Here, we also investigate if any relation between player performance and his/her partner’s evaluation exists. Throughout this section, we name games by the corresponding number. For detailed information on each game we refer to Table 6.1.

6.4.1 Player Performance and Preference

Table 6.2 summarizes the results of player performance (game completion rate and mean player efficiency) and preference (enjoyment and player decision upon games’ suitability for the conditions they were played in).

Performance

For every game, players had to collect a certain amount of objects within a certain time limit in order to successfully complete it. In order to compare three closely-coupled games, they all had equal conditions: players had to pick up 75 objects within 7 minutes (Table 6.1). Conditions of loosely-coupled games varied because of the differences in game design for these patterns. Due to the different ways of interacting between players, some games were found to be more difficult to finish within a given period. Analysis of the game completion rate has revealed that the majority of players managed to finish only two games in time: the ones with the limited resources and shared goals patterns (Table 6.2). As can be seen, the difference between the average amount of actual collected objects and the required amount of objects for games 2 and 3 was higher than in the other games.
Due to our decision to design games with equal conditions, in most cases the games were not completed successfully but finished because of a lack of time. Under these conditions it was hardly possible to compare game completion time. Therefore, as an alternative measurement of performance, we calculated the efficiency of the players for every game. It was defined as the amount of objects collected by each player in one minute. Repeated measures ANOVA has shown a significant difference across six patterns ($F(2.73, 95.37) = 105.37, p < 0.01$). A Bonferroni post-hoc test has demonstrated a significantly lower efficiency in two of the closely-coupled games (games 2 and 3) than in any other game ($p < 0.01$). At the same time, no significant difference was found between the three loosely-coupled games, all of them sharing a high level of player efficiency.

### Preference

The participants were asked to rank the six games according to the level of their enjoyment. They were explicitly asked to judge each game based on the way in which players interact and not to take into account other gaming elements (e.g., design of the environment, look of the avatar, etc.). We have analyzed how many times each game appeared on the first, second, etc. and last places, in order to define the most preferred games. Game 3 has been found to be the most enjoyable, followed by games 2, 5, 4 and 1. Game 6 has been indicated as the least enjoyable due to the total independence of players while working towards a shared goal. In this game, the other player was often considered as a non-player character or even a competitor rather than a team.
6.4 Results

From Table 6.2 we observe that a low efficiency in closely-coupled games (games 2 and 3) did not decrease player enjoyment, confirming hypotheses H1 and H2.

Finally, we asked players to define if there were any game patterns that were not suitable for playing remotely without communication. Participants were free to indicate which game(s), to their opinion, they would prefer not to play under the same circumstances. It was also allowed to leave the question unanswered if they found them all suitable. Although we have observed that participants found games 3 and 4 to be the least suited (possible reasons for that will be shown further in this section), 28% of the players indicated all games to be suitable for a remote gameplay without communication.

6.4.2 Impact of the Remote setup on Player Experience

Once the level of player performance and enjoyment for each game was evaluated, we aimed to estimate to what extent they were affected by setup conditions (the absence of communication and physical distance).

Absence of Communication

First of all, we asked players to evaluate to what extent they felt a necessity to discuss the game. In the questionnaire, we suggested some topics that could improve gameplay, e.g. strategy discussion, asking for help, etc. Our findings (Figure 6.4a) tend to confirm the general expectation that loosely-coupled games require less communication. Most of them have been evaluated significantly lower by the participants than closely-coupled games. Repeated measures ANOVA has shown a significant difference between six games ($F(5,175) = 11.45, p < 0.01$). A Bonferroni post-hoc test has demonstrated that game 6 required significantly less communication ($p < 0.01$) than all other games (except game 5). It has been also discovered that games 2 and 3 required more discussion than game 5. At the same time, there was no difference between the closely-coupled games.

Observing these necessity ratings (indicating an eagerness to communicate within certain games), it is important to see how the lack of communication affects player enjoyment and efficiency. As can be seen from Figure 6.4b, for all games, players indicated the perceived negative impact of communication on their enjoyment as relatively low (on average for every game, it did not exceed 5 on the 0 to 10 scale). A repeated measures ANOVA has shown a significant difference across the games ($F(5,175) = 6.13, p < 0.01$), but a Bonferroni post-hoc test has indicated that this difference in
fact only existed between game 2 and games 5 and 6. *This confirms hypothesis H3, as in the most cases of closely-coupled games there was no negative effect on player enjoyment.*

Finally, we analyzed whether or not a lack of communication decreased player efficiency. Figure 6.4b shows that games 2 and 3 are most affected. Players indicated that they felt they could be more efficient if they were able to discuss the strategy. Repeated measures ANOVA \( F(5,175) = 14.82, p < 0.01 \) and a follow-up Bonferroni post-hoc test \( (p < 0.01) \) confirmed that this difference was significant. Moreover, we found that even among loosely-coupled games game 4 was rated significantly worse \( (p < 0.01) \). For this particular game, players found communication important as it would improve the efficiency of the word guessing assignment if they would be able to discuss the possible options with a partner.

**Figure 6.4: Impact of the absence of communication.**
6.4 Results

Physical Distance

Furthermore, we quantified the negative impact caused by the physical distance between players. For both enjoyment and efficiency, players indicated that the physical distance had a rather low negative effect (Figure 6.5). For its impact on player enjoyment, we did not find any significant difference between the six games ($F(3.33, 116.41) = 2.48, p > 0.05$), indicating that all games were equally enjoyable when played over distance and confirming hypothesis $H4$. When analyzing the influence on player efficiency, we found a significant difference ($F(3.71, 129.96) = 3.7, p < 0.01$). Further post-hoc testing showed that these difference existed only between games 3 and 6 ($p = 0.021$). No difference between games within the closely-coupled and loosely-coupled groups was found.

![Figure 6.5: Negative influence of physical distance on player enjoyment and efficiency.](image)

6.4.3 Impact of the Type of Collaboration on Player Experience

The final part of the analysis is focused on the collaborative aspects of each game. Every game was developed in such a way that it follows a certain cooperative design pattern. Although all patterns are assumed to support team work, the level of collaboration in every game may be perceived differently among players.

Level of Collaboration

When creating multiplayer games, in some cases game designers try to include tasks that require a high level of collaboration between players in order to enhance their gaming experience. Analyzing the six patterns presented in this paper, our findings confirmed hypothesis $H5$ showing that closely-coupled games tended to provide a
higher level of collaboration than loosely-coupled. All games (except game 5) were significantly more collaborative than game 6 ($F(3.47, 121.58) = 77.09, p < 0.01$), with games 2 and 3 showing the highest level of collaboration (Figure 6.6). Therefore, we can state that among both closely-coupled and loosely-coupled games, some patterns can be more efficient when it comes to providing a high level of collaboration between players.

Additionally, we wanted to check for which types of games a higher level of collaboration will result in a higher gaming enjoyment. We found a positive correlation between collaboration and level of player enjoyment for game 1 ($R = 0.39, p = 0.019$), game 2 ($R = 0.36, p = 0.031$) and game 4 ($R = 0.39, p = 0.018$). Although game 3 had one of the highest levels of collaboration, it did not show an increase in player enjoyment. One possible explanation for this is that the other factors (e.g. way of interacting between players during the game) influenced a player preference towards this game more than the level of collaboration.

**Waiting for Others**

One of the characteristics, typical for team work, is the amount of time players have to wait for each other before being able to continue. The waiting time is caused by a variety of reasons: player skills, occupation with different in-game tasks, etc. Therefore, we wanted to investigate how often it was necessary to wait for the partner in each game. As we did not allow communication between players, we expected closely-coupled games to introduce more waiting time. This assumption was confirmed by further analysis. We asked players to estimate the necessity to wait for each other in every game. Figure 6.7a represents the amount of waiting, expressed as a score collected from the questionnaire, between six test conditions. A significant difference between
them was found ($F(5,175) = 37.79$, $p < 0.01$). A post-hoc analysis has shown that during any of the closely-coupled games, players spent significantly more time waiting for their partners than during the loosely-coupled gaming sessions. We observed that this was mainly due to the amount of collaboration required in closely-coupled games, although a difference in the experience level of players could also increase waiting time. At the same time no difference within the group of both closely- and loosely-coupled games was found.

As waiting time is a factor that may lead to decreased player enjoyment and performance, we analyzed how their enjoyment and efficiency were affected. As can be seen from Figure 6.7b, in case of loosely-coupled collaboration players perceived a very low negative impact of the necessity to wait for their partners both on enjoyment and efficiency. In case of closely-coupled games, the perceived negative impact has been

![Figure 6.7](image-url)

(a) Necessity to wait for the partner.

(b) Negative influence of the necessity to wait for the partner on player enjoyment and efficiency.

**Figure 6.7:** Impact of the necessity to wait for others.
found higher, however, it still remained in a lower half of the evaluation scale. Nevertheless, results of repeated measures ANOVA followed by a post-hoc test showed a significant difference, indicating that player experience in closely-coupled games was more influenced by the necessity to wait \((F(3.09, 108.21) = 16.85, p < 0.01)\) for enjoyment and \(F(3.24, 113.44) = 26.43, p < 0.01\) for efficiency).

Based on the subjective measurements, the necessity to wait decreased player efficiency and enjoyment. However, we still wanted to see whether or not waiting time affected player experience objectively, based on actual performance. This is especially important in the case of closely-coupled games as they introduce lots of waiting into the play. Surprisingly, the additional waiting in closely-coupled games did not affect players’ efficiency, as no correlation was found. The same result was obtained for loosely-coupled games. Additionally, we analyzed whether or not the necessity to wait had any influence on player engagement (this data was collected as a part of the experiment presented in the next chapter). No correlation was found between these two parameters for both loosely-coupled and closely-coupled games, indicating that players found the gameplay engaging even if they had to wait for their partners.

Additionally, we checked if there was any negative impact of waiting on the level of collaboration. A significant negative correlation between collaboration and amount of waiting time for game 3 was found \((R = -0.33, p = 0.047)\), making it weaker among other closely-coupled games when it comes to providing a high level of collaboration, as this game required quite a lot of waiting between players (players may move away from each other but need to combine their efforts in order to move the jumping pad).

**Influence of the Partner’s Actions**

In multiplayer games, the actions of one player often directly or indirectly affect the gaming experience of others. Here, we present results regarding the extent of the influence of the partner’s action and behaviour on the player’s own performance and enjoyment. We expect that, when tightly collaborating, players notice other players’ actions more, and therefore, are more affected by them.

One of our initial assumptions was that partner performance greatly affects player enjoyment, especially in closely-coupled games where two players are almost always working together. Repeated measures ANOVA, however, rejected our assumption, indicating that the partner’s actions did not decrease player enjoyment in certain games more than the others \((F(3.60, 125.83) = 2.63, p > 0.05)\). Also, the values for any negative effect of the partner’s action on player enjoyment provided by participants remained very low (on average for every game, they did not exceed 3.5 on the 0 to 10 scale).
6.5 Comparison of Cooperative Game Design Patterns in Co-located and Remote Setups

At the same time, this was not the case when comparing the influence of partner’s actions on player efficiency. We found that closely-coupled games were affected more than loosely-coupled games ($F(3.77, 131.8) = 14.95, p < 0.01$). As before, we have also checked the correlation between this influence and player enjoyment. No game showed a relation, indicating all games to be enjoyable even when the player efficiency was affected by the actions of the partner.

Finally, we wanted to see if the actual player contribution had an influence on the evaluation of the partner. We estimated player contribution to be based on the amount of objects he/she and his/her partner collected (the total amount of objects collected by a team is considered as 100%). Here, we confronted the player evaluation with the objective contribution of the partner to see if any correlation between those two existed. Such correlation existed only for games 2 and 3. In case of game 2, we found that a higher partner’s contribution reduced the negative effect of lack of communication on player enjoyment ($R = -0.38, p = 0.021$). In case of game 3, both player enjoyment and performance were related to the partner’s contribution. The higher the contribution, the more it reduced a negative impact on player experience that existed due to the gaming conditions. In particular we found that a higher partner’s contribution reduced the negative impact caused by the inability to communicate. This was found for both player enjoyment ($R = -0.39, p = 0.018$) and effectiveness ($R = -0.35, p = 0.039$). Also, a higher contribution of the partner compensated the negative influence introduced by the physical distance between players ($R = -0.35, p = 0.039$).

6.5 Comparison of Cooperative Game Design Patterns in Co-located and Remote Setups

To our knowledge, cooperative game patterns have been previously analyzed only when the players were present on the same location, and could naturally communicate and see each other (Seif El-Nasr et al., 2010). When considering interaction over distance, especially when no communication is allowed, additional challenges are present when trying to maintain the same level of player experience. Therefore, games based on the same cooperative patterns can result in an entirely different experience when considered in a non-co-located setup. Understanding these differences may help game developers improve player interaction in collaborative multiplayer games, both for co-located and remote play.

In order to see how different patterns affect player experience under two different circumstances, we compared the results obtained from our study with the evaluation of patterns provided in (Seif El-Nasr et al., 2010). In their work, the authors have
<table>
<thead>
<tr>
<th>Cooperative Performance Metrics study by Seif El-Nasr et al. (2010)</th>
<th>Patterns that cause each metric</th>
<th>Post-experiment questionnaire (our study)</th>
<th>Patterns that cause higher evaluation</th>
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<td>Laughter and excitement</td>
<td>Shared goals</td>
<td>Player enjoyment</td>
<td>Complementary roles</td>
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<td>Shared puzzles ISO*</td>
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<td></td>
<td>Shared goals (the least)</td>
<td></td>
<td>Shared goals (the least)</td>
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</tbody>
</table>

* interaction with the same object
chosen four popular multiplayer collaborative games and defined a set of patterns that occur in each of them. Then, using some self-developed Cooperative Performance Metrics (CPM), they mapped CPM elements to the cooperative patterns that caused them. Although we have not applied CPM for evaluation during our experiment, we believe some of the questions in our post-experiment questionnaire can be matched to certain CPM components. Table 6.3 summarizes this comparative analysis. We had to eliminate game 1 from the comparison as this pattern was not evaluated in (Seif El-Nasr et al., 2010).

The first metric in (Seif El-Nasr et al., 2010) was ‘laughter and excitement’. The authors reported that shared goals (in our case, game 6), shared puzzles (Game 4) and complementary (game 2) patterns provided the highest values for this metric, while abilities on other players (game 5) and interaction with shared object (Game 3) caused less positive emotions. Although in our case we did not analyze laughter and excitement directly, we believe that it is comparable with the rating of games based on the player enjoyment. Oppositely to co-located play, in our case game 6 was found to be the least enjoyable, while games 2 and 3 had the highest preference. Based on our findings, we believe that such difference between remote and co-located setups is caused by the inability to talk. Some players even indicated that without communication, game 6 tended to be more competitive than collaborative, as one barely notices the other player, and tasks are performed individually. Therefore, we conclude that in the case of no communication, it is preferable to include closely-coupled interaction in games as it contributes to the players’ satisfaction, while in the case of loose coupling players tend to enjoy the game more only when they can communicate with each other.

The next CPM components were ‘worked out strategies’ and ‘helping events’. These two patterns are directly connected with the ability to communicate between players. If you can communicate, you can easily decide upon the strategy or ask your partner for help. Therefore, we associated these two criteria with the evaluation of the necessity to communicate. During the co-located condition the authors observed that patterns of shared puzzles (game 4) and goals (game 6) caused most of ‘worked out strategies’ and ‘helping events’. These are followed by complementary (game 2) and interaction with same object (game 3) patterns. In our case, the complementary and interaction with the same object patterns required the most communication between players. One of the reasons for that was the unwillingness of players to stay together in the gaming environment. As a consequence, once help was needed, players could not immediately locate their partner. Therefore, to compensate the negative effect caused by the lack of communication in closely-coupled games one might think of some tools helping to track the activities of other players within the game. By doing so, players can
easily find out whether or not someone is available to collaborate, even when it is not possible to communicate directly.

In their work, Seif El-Nasr et al. analyzed the ‘wait for each other’ events that were caused by each pattern. The analysis of complementary (game 2) and interaction with same object (game 3) patterns did not cause waiting events at all. It is quite natural when you are together to immediately communicate what you are going to do, and whether it involves the other player. At the same time they have ascertained that shared puzzles (game 4) and goals (game 6) patterns were resulting in the longest waiting time. In our case, due to their loosely-coupled nature, games 4 and 6 required the shortest waiting time in comparison with game 2 and 3. In this case, we believe that the negative impact of waiting can be overcome using the same approach presented earlier. By knowing the specific location and activities of other players at any given moment, one can adjust his/her actions in order to minimize the waiting time.

The final metric used in (Seif El-Nasr et al., 2010) was ‘got in each others’ way’, which is related to the influence of partner’s actions in our questionnaire. Similarly to their results we observed that shared goals pattern (game 6) had the least influence of partner’s actions, while the complementary pattern (game 2) was rated highest in both studies. The partner’s actions, especially if he/she is less experienced, can hinder the player’s satisfaction with a game. When players are able to talk, it is possible to avoid this negative impact by communicating their intentions, so every player can adjust his/her actions according to the experience and performance abilities of others. However, when there is no communication, it is required to consider new solutions in order to indicate players’ intentions without direct communication.

6.6 Conclusion

Given the advantages of closely-coupled collaboration for general CVEs (see Chapter 3), in this chapter we have compared loosely- and closely-coupled collaboration in a specific domain – multiplayer video games. The main contribution of our work lies in the first attempt to evaluate cooperative game patterns (that represent different forms of coupling) in a remote setup where no form of communication is supported. Moreover, understanding that games can be played under a variety of circumstances which may lead to a complete different perception of the same manner of collaboration, we performed the comparison of the same patterns used in remote and co-located setups. Similarly to Chapter 3, the results of the user experiment have shown a general preference towards close coupling. This type of collaboration has shown a lower efficiency, but that did not affect player enjoyment while performing the task. Although the
6.6 Conclusion

lack of communication had a certain negative impact on player enjoyment and performance, its absence was not crucial, making games with closely-coupled interaction playable without communication. This finding coincides with the appearance of some commercial games that – on purpose – do not include any communication between players (e.g. Journey (Sony, 2012)).

The evaluation of each pattern was based on a single game. Although we realize that the same game patterns can be integrated and designed in multiple ways, we believe that these results can be valid for further research in cooperative game design. In particular, the comparison of the patterns in a remote and a co-located setups revealed several interesting design lessons that can be further applied in order to build better cooperative games being played under different circumstances or certain limitations.

In the next chapter, we continue our discussion on the applicability of closely-coupled collaboration in multiplayer games for a specific game genre, which often has reduced or no communication when played remotely – casual games.
Levels of Collaboration in Multiplayer Games
7.1 Introduction

In the previous chapter, we have analyzed different types of loosely- and closely-coupled collaboration in games based on cooperative design patterns. In accordance with the task performance in general CVEs discussed in the first part of this dissertation, we have observed a user preference towards closely-coupled collaboration in games. However, in the case of video games, communication – which was found to have a great impact on collaboration in general – might not be always supported. Therefore, during the experiment presented in Section 6.3 we have eliminated any form of communication. The obtained results have shown that although the absence of communication has a certain negative impact on player experience when closely collaborating in games, these games remain playable and enjoyable by the players.
After a general analysis of different levels of coupling between players in games, we would like to focus on a specific game type where closely-coupled collaboration remains somewhat limited – casual games. Casual games, targeted at a mass audience of casual gamers, attract because of their gameplay simplicity, short play time and a minimum of required commitments to progress in a game (The Nielsen Company, 2009). Over the last decade, they have become one of the most popular game types played over the Internet. The additional popularity of casual games is caused by the rise of social networks (e.g. Facebook) and the availability of various game consoles (e.g. Wii) and mobile devices (e.g. smartphones, tablets) that allow multiplayer gaming experience among friends (Di Loreto et al., 2010; Kuittinen et al., 2007).

This particular game type has been chosen for our analysis because of the following reason. Many existing casual games allow collaborative gameplay. However, it is either asynchronous, where simultaneous play is not required or synchronous in a collocated setup, where players share the same screen and can naturally communicate and see each other. In most cases, games played over distance, which employ synchronous features, are limited to communication such as different forms of chats (Ricchetti, 2002) or based on loosely-coupled interaction (e.g. achieving a shared goal) without a direct players’ influence on each other. Closely-coupled collaboration, where one player’s actions are directly influenced by the other(s), remains limited in existing casual games. One of the possible reasons for that can be a necessity to actively communicate and coordinate actions when tightly collaborating. Casual games are characterized by short game sessions, opposite to other game genres, which take a substantial amount of time. Therefore, providing rich voice communication in casual games may not be needed or players might not want to be heard (e.g. playing during breaks at work).

In this chapter we present our work investigating the applicability of synchronous collaboration in remote casual games where no form of communication is supported between players. By analyzing different types of collaboration (based on cooperative game patterns), we aim to study the effect of closely-coupled collaboration on player experience in casual games through a comparison with loosely-coupled interaction. For this research we utilized the same cooperative games (and thus patterns), presented in Chapter 6, that are now evaluated with regards to their applicability for casual games.
The casual game industry is growing rapidly. The worldwide social network gaming market exceeded 5 billion dollars during 2011 and is expected to increase to 8 billion dollars by 2014 (Association, 2012). Nowadays, 200 million people play casual games online each month. The number of players for the most popular games, like Tetris, Zuma, Angry Birds, Bejeweled, etc. (Figure 7.1) is counted in the tens of millions.

![Angry Birds](image1.png) ![Bejeweled](image2.png)

(a) Angry Birds. (b) Bejeweled.

**Figure 7.1:** Examples of popular casual games.

The phenomenon of casual games in the gaming industry has resulted in an increased research interest (The Nielsen Company, 2009; Gao and Mandryk, 2011). Part of the research done in casual gaming is focused on gender and age preferences (Inkpen et al., 1995; Tausend, 2006). Another group of studies analyzes the difference between casual and hardcore players (The Nielsen Company, 2009). The appealing appearance of casual games is often studied as a motivational factor (Gao and Mandryk, 2011).

While some games work well as single-player experiences, other games offer an entirely different kind of enjoyment by letting players unite in shared gameplay. Players can compete, or play together in order to achieve a common goal (Li and Counts, 2007; Mueller and Gibbs, 2007). Many social networking sites have started offering opportunities to chat and play multiplayer casual games with other users. Studies on digital games have shown that social characteristics of play settings have a strong impact on players’ in-game experience (Gajadhar et al., 2010).

Multiplayer casual games can be played in two ways: asynchronously and synchronously. Games of the first type are played in sequence. Although asynchronous games already exist for many years, recently they have received a new wave of interest among researchers (Di Loreto and Gouaich, 2010). With the increased use of social games,
game producers started to utilize this type of play, allowing players to play a game in sequence and break whenever is needed to “accommodate real life necessities”. Asynchronous collaboration is widely used (in combination with synchronous) for games on social networks, FarmVille, CityVille and Mafia Wars are among the most played (Figure 7.2).

In the case of synchronous games, the game is played simultaneously by multiple players. When analyzing existing games, most games of this type are competitive or cooperative games for co-located play supporting natural communication (e.g. party games like Rock Band and Wii games, co-op iPad games\(^1\)) (Figure 7.3). Synchronous cooperative games for remote play are often limited to loosely-coupled interaction, when players co-exist and work towards shared goals without much influence on each other. To our knowledge, there are only few existing games that involve closely-coupled collaboration and that are played by distributed users without a necessity to communicate (e.g. Draw Something\(^2\)).

Being frequently used in multiplayer hardcore games like role-playing games (World of Warcraft\(^3\)) and real-time strategies (Age of Empires II\(^4\)), closely-coupled cooperation is not widely supported in casual games. As mentioned earlier, one of the possible reasons for that can be a necessity to communicate and coordinate actions between players. Casual games are usually played in short sessions, and, therefore, communication might not be necessary or desirable by players.

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\(^1\)http://www.pocketgamer.co.uk/r/iPad/Top+10+iPad+charts/feature.asp?c=22242

\(^2\)https://www.facebook.com/playdrawsomething

\(^3\)www.battle.net/wow

\(^4\)www.microsoft.com/games/age2
7.3 Experiment: Comparison of Loosely-coupled and Closely-coupled Collaboration in Casual Multiplayer Games

In order to analyze synchronous cooperation in remote casual games, an experiment was conducted. During the experiment pairs of participants had to evaluate six games, each based on one of the cooperative patterns. For the purpose of the experiment we have utilized the same games (and therefore cooperative game patterns) presented in Chapter 6. These games can considered as casual: they share some of the main characteristics typical for casual games (such as short and easy gameplay design), and other requirements will come up later in this chapter. The description of each game is presented in Section 6.3.6. An example of the environment with all gaming elements is shown in Figure 7.4. The following patterns have been selected from (Seif El-Nasr et al., 2010):

- Closely-coupled interaction:
  1. Limited resources
  2. Complementary roles
  3. Interaction with the same object

- Loosely-coupled interaction:
  4. Shared puzzles
  5. Abilities that can be used on other players
  6. Shared goals

Figure 7.3: Examples of popular synchronous collaborative casual games.
In our current work, we investigate whether closely-coupled interaction can be beneficial for casual game design by providing players with a better experience than loose coupling. The same experimental setup and procedure have been adopted as in Chapter 6 (therefore, they are not described here). In order to decide upon the suitability of the cooperation type in the context of casual games, each game was analyzed based on five criteria: excitement, engagement, challenge, understandability and replay value (further referred as replayability). The subjective evaluation of these five values was provided by the participants through an experiment questionnaire (see Figure C.2 in Appendix C).

7.3.1 Hypotheses

To analyze six cooperative games from the perspective of their applicability for casual gaming, and more specifically to investigate the potential of closely-coupled games, we compare them based on five different criteria. While some of these criteria are chosen based on the general requirements for computer games (excitement, engagement, challenge), the others represent those characteristics more specific for casual games (understandability and replayability). The following hypotheses are formulated with respect to the casual games criteria:

H1: each closely-coupled game provides a higher excitement than each of the loosely-coupled games evaluated in the experiment;
H2: each closely-coupled game provides a higher engagement than each of the loosely-coupled games evaluated in the experiment;

H3: each closely-coupled game provides more challenges than each of the loosely-coupled games evaluated in the experiment without any negative impact on player excitement;

H4: each closely-coupled game does not provide additional difficulty to understand the interaction between players in the game when compared to each of the loosely-coupled games evaluated in the experiment;

H5: each closely-coupled game provides a higher level of replayability than each of the loosely-coupled games evaluated in the experiment.

### 7.4 Results

This section presents the results of our study. Firstly, the analysis of the six games is reported based on five criteria: excitement, engagement, challenge, understandability and replayability. Secondly, we examine player experience based on the observations done during the experiment.

#### 7.4.1 Subjective Player Evaluation

During the experiment the six games were compared based on five criteria: excitement, engagement, challenge, understandability and replayability. Figure 7.5 represents the averages and standard deviations of each criterion for every game based on a subjective player evaluation.

Although the games evaluated in the experiment share a lot of similar features like the graphics and in-game tasks (e.g. navigation, jumping, collecting objects), the interaction between players has been designed differently. Therefore, we check the hypotheses, presented in the previous section, separately for each closely-coupled pattern. By doing so we identify the closely-coupled patterns that improve the casual gaming experience when compared with the loosely-coupled patterns. Table 7.1 summarizes the decision upon each hypothesis (accepted or rejected).

First of all, we analyzed player excitement in every game. From Figure 7.5 we observe that closely-coupled games support a higher level of excitement. Repeated measures ANOVA with a Greenhouse-Geisser correction has shown a significant difference between the six games ($F(3.72, 130.34) = 28.72, p < 0.01$). A Bonferroni post-hoc test
revealed that games 2 and 3 were found significantly more exciting ($p < 0.01$) than any of the loosely-coupled games. Although game 1 showed an increase of player excitement when compared to the loosely-coupled games, the difference was not significant.

We have also discovered that not all closely-coupled games used in the experiment were equally exciting, as a significant difference existed among them. In particular, game 1 was found to be significantly less exciting ($p < 0.01$) than the other two closely-coupled games. One of the possible explanations for this could be the different nature of the in-game activities. Games 2 and 3 were the only ones where players had to move the jumping pad, which was not necessary in the other games.

The second important characteristic is a high level of player engagement with a game. We asked players to evaluate how engaging they found cooperation in every game. The repeated measures ANOVA that was performed with a Greenhouse-Geisser correction has shown that not all games were similarly engaging ($F(3.75, 131.22) = 36.54, p < 0.01$). Again we observed that games 2 and 3 obtained the highest points based on the players ratings. These two games were significantly more engaging than all loosely-coupled games ($p < 0.01$). Though being evaluated higher than the loosely-coupled games, game 1 did not significantly differ from them.

The next step was to analyze how challenging the interaction between players in each game was. All games, except games 2 and 3, received a relatively low rating (on
Table 7.1: Hypotheses check for the closely-coupled games evaluated in the experiment.

<table>
<thead>
<tr>
<th>Pattern type</th>
<th>H1 excitement</th>
<th>H2 engagement</th>
<th>H3 challenge</th>
<th>H4 understandability</th>
<th>H5 replayability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited resources</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Complementary roles</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Interaction with same object</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

average for each game below 4 on the 0 to 10 scale). We found a significant difference among the six games ($F(5,175) = 13.54, p < 0.01$). Both games 2 and 3 have shown to be more challenging than other games considered in the study ($p < 0.01$).

As additional challenges may decrease player enjoyment while playing a game, we investigated whether any negative influence existed in our case. This was particularly important for closely-coupled games, as this type of interaction was found to be more challenging. For each game, we checked the correlation between the challenge level and player excitement. Every of the six games has shown a significant positive correlation between these two parameters, indicating that in fact additional challenges, caused by the interaction between players in cooperative games, result in a higher enjoyment. This confirmed that more challenging closely-coupled games did not negatively impact player excitement.

The following criterion evaluated by players was understandability. As casual games imply easy understandable rules that do not require much experience, it is important that the way of interaction introduced in cooperative gaming does not decrease this understandability. All games have shown a high level of comprehension, without a significant difference across the six games ($F(4.11, 143.87) = 2.18, p > 0.05$).

The last characteristic rated by players was the replay value or replayability of the game. For casual games, it is a paramount characteristic that guarantees that people will be willing to play the same game again in the future without getting bored very quickly. Repeated measures ANOVA with a Greenhouse-Geisser correction has shown that the six games were not equal in this characteristic ($F(3.45, 120.72) = 9.97, p < 0.01$). Based on a Bonferroni post-hoc test, the games of the closely-coupled group have shown a higher player preference to replay the games again with a similar type
of interaction between players ($p < 0.01$). The highest values were obtained for games 2 and 3, showing a significantly higher level of replay value in comparison with all loosely-coupled games.

The obtained results have shown the difference among closely-coupled games, explained earlier in this section. As can be seen from Table 7.1, only one hypothesis was confirmed for game 1. At the same time, games 2 and 3 were evaluated similarly based on all criteria, probably due to the design resemblance between these two games. Every hypothesis was confirmed for games 2 and 3, indicating their high potential for casual game design.

7.4.2 Observations of Players’ Behaviour

Besides the subjective player evaluation, we analyzed player experience based on the observations done during the experiment. We present these observations under three categories: players’ emotions, performance and communication. For the latter, we consider different remarks that the participants gave about the communication component in cooperative games, as well as their attempts to communicate with the other player through the in-game actions.

**Players’ emotions.** Although several players were quite concentrated while playing, almost all of them showed a lot of positive emotions (smiling and laughing). In particular, this occurred when the player encountered his/her partner’s avatar. Players were free to navigate in the environment, and therefore, could lose each other in the 3D world. This happened mainly during loosely-coupled games, where players did not stay together most of the time and rarely met each other. The positive reaction appeared also when the players were in each others’ way, making the game a bit competitive by preventing the partner to pick up his/her objects directly. When being alone in the scene, players showed to be less emotional and were more focused on the task. They indicated that the loosely-coupled games appeared to be more competitive than cooperative, with the goal of collecting more objects than the partner. Therefore, participants were focused on the task of getting more objects. Because the most positive emotions were caused by (successful or not) interaction with another game character, loosely-coupled games resulted in less smiling or laughing than closely-coupled ones. One of the most ‘emotional’ games was game 3, as it required almost constant interaction with a shared object and, thus, with the other player. Due to its nature, this game caused a lot of excitement among players. Positive emotions were not only caused by a successful play, but also, for example, while trying to move the same object in different directions.
**Performance.** Observing player performance revealed the following aspects of cooperative interaction. In the case of closely-coupled interaction, players tended to follow their partners all the time, in case help would be necessary during the game (mainly in games 2 and 3; but this also occasionally occurred in other games). If, for some reason, they lost each other in the environment, we observed players trying to find their partner as soon as possible, especially when they were waiting and could not proceed further without their help. As there was no communication, players tried to take into account all visual information in order to adjust their actions to the partner’s performance and help the partner if needed. For example in game 2, once a player saw that his/her partner experienced difficulties in reaching objects on higher platforms, he/she immediately adjusted the position of the jumping pad. In loosely-coupled games players were free to decide whether or not they preferred to be alone or stay together with the other player. In contrast with this situation, closely-coupled games forced both players to be together or to wait for each other most of the time. We observed that a player acting extremely slow, made the experience of the other player less enjoyable.

**Communication.** During the experiment players were not allowed to communicate in any form. They learned from the game rules what they had to do, but could not discuss strategy or ask for help. Nevertheless, some of the players indicated that they were not affected too much by the absence of communication. In fact, they pointed out that the absence of communication made the game more challenging, and thus, more interesting and entertaining. They stated that information, they obtained from rules and what they observed on the screen, was sufficient for a successful gameplay. Based on the observations, we concluded that this was mainly typical for the evaluated closely-coupled games, as players were together most of the time and were aware of each others’ actions. Here, it was not required to search for another player, making the need of communication less strong. In loosely-coupled games, players were not always sharing the same area of the virtual world and, therefore, they were not always aware about the partner’s actions.

While observing participants, we noticed the frequent occurrence of “communication with the screen”. Players tried to explain their partners what they had to do, yet knowing that their messages could not be heard. Being not able to talk, players tried to find out ways in which they could assist their partners when it was obvious that he/she experienced difficulties. One of the solutions, we observed, was an attempt to ‘communicate’ an advice by moving his/her own avatar in front of the other player. By his/her own action, a ‘better’ player showed where the other one had to be for an easier accomplishment of the task.

Most games were played successfully under the given conditions of the remote setup without communication. However, half of the participants stated that the presence
of communication would increase their performance. Although it was not proven by letting them play with communication, players pointed out that an ability to talk (either via text messages or voice) would make them more efficient. In particular, they mentioned an advantage of communication in order to divide areas for object search. It was often the case that players lost a lot of time by going to the areas, where their partner had already harvested all objects. In general, participants expressed a strong wish for being able to talk with the other player even when it was not absolutely necessary for the game. For instance, if the strategy or in-game tasks were clear without actual communication, players still wanted to talk in order to make fun of each other and joke together.

7.5 Conclusion

In this chapter, we have presented a study investigating synchronous cooperation in remote casual games where no form of communication was supported between players. The contribution of our work lies in a comparative analysis between loosely- and closely-coupled collaboration for this specific game genre. The results of the comparison indicate the applicability of closely-coupled collaboration for casual games, as the games based on this level of collaboration correspond to the requirements of the genre. During the conducted experiment, we have observed that two of the three evaluated closely-coupled games (with complementary roles and interaction with the same object patterns) introduced a higher level of player excitement, engagement and replayability without additional learning difficulties.

Based on the evaluation of the six games presented in this chapter, we have learned several important lessons regarding the integration of different levels of collaboration in casual games. Not all closely-coupled games were evaluated equally. Due to the possibility to design closely-coupled tasks differently, we realize the impact a game design has on player evaluation. From the results, we observed that the design of games with complementary roles and interaction with the same object patterns differs more from the one with limited resources pattern than from each other. These findings provide an indication that the integration of closely-coupled interaction together with an appropriate game design has great potential for casual games.

Together with numerous advantages, closely-coupled interaction also brings a lot of challenges to be taken into account when creating collaborative games. We will address one of the most important among them – influence of the network quality. In the next two chapters of this dissertation, we discuss the impact of network quality on
closely-coupled collaboration in games to define how different network impairments affect player experience.
Chapter 8

Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

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8.1 Introduction

In Chapter 2 of this thesis we outlined the main challenges for the successful use of collaborative virtual environments, indicating network quality as one of them. It is often the case that collaboration takes place remotely between globally dispersed people through the Internet. Applications deployed on the Internet are often affected by network quality, which may have a significant impact on user performance and experience. Among other impairments, network transmission delays and the variability thereof (jitter) are considered to have a great impact on user experience when there
are high interactivity requirements within an application\(^1\). These delays can be introduced either by physical limitations of signal transmission speed or overloading and queuing problems in intermediate nodes. The influence of this delay is far-reaching and impacts most types of interactive applications. This is particularly the case for online multiplayer video games, given the high level of interaction between players (for various genres, e.g. sports games, first-person shooters (Steed and Oliveira, 2009; Quax et al., 2004)).

Multiplayer capabilities in current games are an increasingly important revenue factor for developers, because they stimulate players to keep on playing the game after the initial release period. Typically these games focus on competitive gameplay (e.g. first-person shooter games in which players are individually competing against one another). In more recent releases and genres, collaboration between players is being utilized as the selling factor. Additionally, based on our findings from the study presented in Chapter 6, closely-coupled collaboration contributes to player experience, providing a higher level of engagement and more realistic teamplay than loose coupling. At the same time, one might imagine that these kinds of games are more sensitive to network quality, as they may require very intricate and synchronized actions between several players. If one (or more) players are impared by noticeable network degradation, the gaming experience might become annoying or it might even be impossible to complete the game.

In this chapter we discuss how the factors of network delay and jitter affect closely-coupled collaboration between users in a recent cooperative (co-op) game. We first provide a more general overview of existing research studying the impact of network quality on highly interactive performance in multi-user virtual environments (with primary focus on games). Secondly, the results of our evaluation based on a series of consecutive user studies are presented. For our user studies, Little Big Planet 2 (LBP 2) (Sony, 2008) was chosen as an example of a co-op game, as, in this game genre, the actions of one player directly affect others and synchronization of actions is required to complete the game. By performing such an evaluation, we aim to shed light on the sensitivity of closely-coupled collaboration with regards to the different levels of network impairments.

\(^1\) according to Steed and Oliveira (2009) packet loss is another factor greatly affecting interaction, but its influence has more impact on quality of audio and video communication. It is discussed in Chapter 9.
8.2 Impact of Network Delay and Jitter in Interactive Multi-user Applications

The impact of network impairments such as delay and jitter on user performance in virtual environments has been studied at great length (Park and Kenyon, 1999). However, a new wave of research, that particularly investigates the effect of network quality on player experience, has come up since the widespread use of highly-interactive games. A substantial number of studies investigating the influence of network impairments (such as delay or jitter) on player performance in highly-interactive non-cooperative video games are available (Armitage and Stewart, 2004; Chen et al., 2006; Dick et al., 2005; Garapati, 2009; Kim et al., 2007; Pantel and Wolf, 2002; Steed and Oliveira, 2009; Quax et al., 2004). These works focus on a variety of interactive games such as first-person shooters, racing or real-time strategy games. Results have shown that users perceive the same levels of network impairment differently based on the game genre.

It is shown that games such as first-person shooters or sports games have the lowest tolerance in terms of delay, mainly because the player has direct control over his avatar (Dick et al., 2005). A player constantly sees the interaction of his avatar with others as well as the environment (from a first- or third-person perspective). Therefore, one is susceptible to even low delays between the actions and the subsequent reaction of the avatar. The studies presented by Garapati (2009); Kim et al. (2007) show that for the first-person shooter game genre, players are able to detect the presence of a (constant) delay higher than 100 ms. At the same time, Quax et al. (2004) show in a similar fashion that for Unreal Tournament 2003 this boundary can be placed at around 60 ms (round trip). These results align with the ones obtained by Beigbeder et al. (2004), which indicate that shooting is the game activity most affected by latency. Pantel and Wolf (2002) analyze the impact on real-time multiplayer games using a car racing simulation. They conclude that a delay up to 50 ms can be considered non-critical for this type of game. In contrast to directly controlled games, real-time strategy games do not have such strict delay requirements (Steed and Oliveira, 2009). Here, delays may be higher without interfering with the enjoyment of the player since he just controls the units indirectly.

While being an important characteristic, jitter has not been studied so widely. In (Dick et al., 2005), the authors analyze three different games (two first-person shooter games and a car racing simulator). They have shown that jitter has a negative influence on gaming experience in general, but even with values up to 150 ms the game conditions remain acceptable. Similar results are obtained in (Armitage and Stewart, 2004; Quax et al., 2004). Here the authors have shown that jitter is less significant than the delay
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

for interactive games. A negative influence of jitter is found by Chen et al. (2006), showing that the amount of time spent playing a game drops significantly when jitter increases.

Although the previous works touch different genres of highly interactive games like racing or shooter games (which are mostly competitive in nature), the influence of network quality on games requiring a lot of cooperation between players has not been widely covered, mainly because their popularity is still growing. There are several works in existence regarding the effect of network characteristics on collaboration in shared virtual environments (Park and Kenyon, 1999; Stuckel and Gutwin, 2008; Lambeth et al., 2009; Chen, 2005; Park and Kenyon, 1999). For example, in (Chen, 2005), it has been shown that network delay has no distinct effect on task performance when network latency is less than 200 ms and only lightly affects task performance when network latency is between 200 and 600 ms (round trip). Results of studies performed by Park and Kenyon (1999) have shown that a high level of delay impacts user coordination during collaboration while jitter reduces the ability of the subjects to use prediction in performing the task. These studies have shown a significant influence of network delay and jitter on user performance in collaborative virtual environments, even though the focus of these studies was clearly outside the gaming context. To our knowledge, the impact of network conditions on games that focus on collaboration (especially closely-coupled) has not yet been studied. However, being aware of a possible negative impact of network impairments and the level of user tolerance to them may help game developers to reduce the sensitivity of games based on close coupling. The biggest challenge is to mask the possible impact of delay and jitter (e.g. adjust visualization), as not much can be done to reduce them directly.

8.3 Context of User Studies

8.3.1 Approach

To investigate the impact of delay and jitter on collaboration in a virtual environment, a series of consecutive user studies was conducted using Little Big Planet 2, one of the most recent multiplayer games with rich collaborative possibilities. Although the game involves both loose and close coupling between players, we focused on collaborative tasks based on the latter type. The aim was to see to what degree the player performance and experience depends on varying levels of network delay and jitter. A randomized group of players was placed in a controlled network environment. Their gaming session was impaired by introducing delay and jitter in the network connections. During these user studies, the focus was twofold: obtain objective measure-
ments (game score and task completion time) and subjective experience details (to ascertain the way in which players perceived the network quality).

To quantify the impact of delay and jitter a two-staged approach was used, each stage being a separate user study. In user study 1, a rough idea was gathered on what values of a more or less constant delay would lead to a decrease in experience and performance. Obviously, these figures need to be correlated to those typically found in the Internet, to avoid focusing on unrealistic test conditions. Once these boundaries were established, user study 2 additionally investigated the impact of jitter on the gameplay. The main goal of this study was to determine whether or not any influence of jitter on cooperation in games existed (part 1) and where its threshold of acceptability lied (part 2). Jitter is an important factor that is typically dependent on the last-mile technology in use (Jehaes et al., 2003) (e.g. DSL, cable or wireless connections). As users may be connected using different technologies, the goal here was to investigate how this disparity between players influences the group outcome of the game.

8.3.2 Little Big Planet 2: Game Overview

Similar to its predecessor, Little Big Planet, LBP 2 is a puzzle platformer video game created by Media Molecule and published by Sony Computer Entertainment across multiple PlayStation platforms. LBP 2 is a current title that successfully makes use of community features. The game follows the adventures of Sackperson (an avatar controlled by the player), a small, doll-like creature made of fabric. Every Sackperson can be customized with different outfits (Figure 8.1a) and express four types of emotions: happiness, sadness, fear and anger. The game put a strong emphasis on user-generated content that can be shared with other community members.

(a) Sackperson, a customizable avatar in LBP2.  
(b) Level that can be completed in a single-player mode but contains extra multiplayer puzzles shown by the arrow (x2).

Figure 8.1: Little Big Planet 2.
LBP2 allows different modes of play: levels can be completed individually or together with up to 3 more people. Although it is possible to play alone, one of the appealing features of this game is multiplayer support. Players can compete or collaborate in small groups (up to 4 people) either remotely or on the same console. Even if some level is doable in a single-player mode, to motivate group play it may often contain some optional puzzles for 2 or more players (Figure 8.1b) that allow to score extra points (or get other benefits).

Different levels of collaboration between players are supported in Little Big Planet 2. In fact, many levels (especially community levels) are constructed in such a way that closely-coupled collaboration is often required to complete them successfully. Examples of such close collaboration are carrying each other, lifting and/or throwing objects together, and pushing/pulling different buttons and triggers simultaneously (Figure 8.2).

8.4 User Study 1: Influence of Network Delay

8.4.1 Measurement Setup and Procedure

Thirty two participants were recruited for our first user study. Although they were frequent players of multiplayer video games, most of them had never played Little Big Planet 2 before. All participants were randomly grouped in pairs and played the game using two separate Sony PlayStation (PS) 3 consoles that were connected to each other over a dedicated local area network (Figure 8.3). An uplink was provided to connect both to the PlayStation Network (required for matchmaking purposes). As the traffic associated with the game is sent directly between the consoles, the presence
of a single impairment node (a Linux system running the NetEM (Hemminger, 2005) software) suffices to introduce network anomalies for this setup. The software is installed to run in bridge mode in order to obtain optimal performance and to reduce any possible impact from routing issues. Care was taken to choose delay and jitter values representative for current-generation network conditions (i.e. excessively high values were not considered). To ease observations, the participants were located in the same room separated by a portable wall so that they were not able to see their partner or their partner’s screen.

Figure 8.3: Network layout in the first study.

To measure the effect of delay, different network conditions were simulated. These conditions varied from a slightly delayed environment of 10 ms to a worst-case maximum of 300 ms (all numbers stated as one-way). There were 8 different conditions of 10, 20, 40, 60, 80, 100, 200 and 300 ms. Of these, values between 20 and 100 ms can be considered as typical realistic values for Internet applications (Leighton, 2009). A delay of 10 ms was considered as an unimpaired environment, as players are typically not located on the same local area network. For every pair two out of eight values of delay were randomly chosen. Players were not aware what value of network delay they experienced to avoid any influence on their further responses.

For our study we selected two cooperative levels which were played at least by several members of the LBP community and had several positive reviews (Coop World by Lenicolas and COOP by I-Lex). They had approximately the same difficulty level and duration. During the user study, participants often encountered situations that required synchronizing their actions. Examples of such closely-coupled tasks are shown in Figure 8.4. Here, Figure 8.4a shows a player below that has to jump between platforms which appear only if the player above pulls the appropriate trigger. Figure 8.4b shows another example of tight cooperation where one player (held by his partner) has to jump at the moment he is being thrown by the other. Other examples of shared tasks were throwing and catching objects between two players, carrying each other while shooting, and lifting and moving the same objects.

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2http://lbp.me/
3Here we provide the level name and the creator’s nickname
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

(a) The player below jumps between platforms which appear when the player above pulls the appropriate trigger.

(b) The player held by the partner jumps at the moment he is being thrown by the other player.

Figure 8.4: Examples of cooperative tasks used in the first study.

In every pair, one of the players was impaired by the network delay. By impairment of the player we mean that his PlayStation 3 was connected through the local area network by means of the impairment node (with NetEm installed). To initiate a gaming session in Little Big Planet 2, it is necessary for one player to invite the other one. The PlayStation which sends the invitation is called game leader and acts as ‘server’. The other player connects to this server and is referred to as the follower. We should point out at this time that the exact workings of LBP 2 on the network level are unknown, as the protocol has not been reverse engineered. However, we were able to deduce some of its workings based on packet traces and visual observations.
Firstly, the fact that a single party is designated as server does not mean that all network traffic is routed through this node. Actually, in a session with more than two players, data is exchanged between all parties involved (in a mesh). Secondly, the server (being the initiating party) does play an important role in the synchronization process. This machine seems to have the final say in the synchronization of actions between the various players, as it determines the time at which actions are undertaken for the global game state. Therefore, the player that uses the server as his console typically experiences the smoothest game play, as actions are directly interpreted. For the other consoles connected to the server, a delay estimation method is used to try and determine at what time the actions would arrive at the server. They are subsequently locally delayed before being visualized. At high delay levels, this results in a short (but sometimes noticeable) delay in the execution of command on a follower console. Third, once the server determines the current state of the game, it distributes the state among all parties involved and each of them corrects to the 'right' state. Visually, this is represented by the avatar taking steps back (in the optimal case) or moving through solid objects (worse case). Note that this technique relies heavily on the delay estimation method being used, which will probably not yield correct results in face of jitter.

As indicated, the player using the server console is at an advantage (because actions are directly undertaken) and is therefore referred to as 'unimpaired', while the other one is 'impaired'. It is important to state that the unimpaired player also experiences detrimental performance due to the fact that the actions of the other players take a while to arrive at the server (and may be out of order due to jitter), but not in the order of magnitude of the impaired players.

During the test, level completion time and game score were measured. After completion of each level, the participants were asked to fill in a questionnaire enabling them to evaluate the influence of the network conditions on their gaming experience (see Figure C.3 in Appendix C). With its help we wanted to determine player perception of the following factors:

- quality of the network (from 1 – unacceptable environment to 5 – perfect environment)
- influence of the network quality on the following aspects of your gaming experience: enjoyment, frustration, score and completion time (from 1 – not at all to 10 – very much)
- influence of the network quality on difficulty to coordinate cooperative activities with the partner (from 1 – not at all to 10 – very much)
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

- influence of the network quality on the wish to continue the game (from 1 – not at all to 10 – very much)

It took between 20 and 40 minutes for each pair to complete the test.

8.4.2 Results

This section presents the results on how network delay influences different aspects of player experience in cooperative games. We provide an objective evaluation based on the game completion time and the game score. Afterwards, we focus on responses collected through the questionnaires. The graphs in this section represent the values obtained by averaging certain characteristic (e.g. time, score, rating) among sessions where players experience the same level of delay.

First of all we analyze how a fixed network delay affects the completion time and game score. By doing this we determine objectively whether or not the network delay influences player performance. Completion time analysis has shown that with a delay higher than 100 ms the game lasted noticeably longer (Figure 8.5a). As can be seen from the figure, the time to finish the game increases constantly when the delay exceeds 100 ms. This has been also confirmed by a significant positive correlation between completion time and the level of delay ($R^2 = 0.82, p = 0.013$). Note that this value (which represents a round trip of 200 ms) is becoming less and less common for players located on the same continent.

Further analysis has shown the correlation between the delay and the game score ($R^2 = -0.78, p = 0.024$). As shown on Figure 8.5b there is a noticeable drop in the game score once the network delay exceeds 60 ms.

Furthermore, we find it interesting to see whether or not players have perceived this degradation. In the questionnaire, participants were asked to rate the influence of the network delay on their score and task completion time. Figure 8.5c represents the user self-reported perception of the delay impact. Players seemingly do not perceive a delay up to 200 ms as disturbing (a low impact on the experience level). A positive correlation has been found between delay and both completion time ($R^2 = 0.81, p = 0.016$) and game score ($R^2 = 0.85, p = 0.008$).

For each delay level players were asked to rate the gaming environment to define when it became annoying and/or unacceptable. Additionally, we wanted to know at what level they would prefer to quit the game. Results show that up to 200 ms (one way delay), players considered the gaming environment to be acceptable without major impairment. Only when the delay exceeded 200 ms did they indicate this to be very
8.4 User Study 1: Influence of Network Delay

(a) Overall game completion time (objective).

(b) Overall game score (objective).

(c) Perception of network delay given by the impaired players (subjective).

Figure 8.5: Objective and subjective influence of network delay on the completion time and the game score.
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

annoying. At the same time delays higher than 100 ms increased the likeliness of players to quit the game.

The analysis of the aforementioned characteristics has been performed based on the data collected from the players who were directly influenced by the network conditions. However, cooperative games involve simultaneous interaction between several players, both those affected and those that are not. Therefore, players who are not directly influenced by the network delay can also be affected by an inadequate performance of their game partners. In particular, not only does an impaired player experience a delay in the events on his own site, but his actions are also delayed when delivered to the remote player. To investigate whether an impaired player impacted his/her collaborator we have asked both of them to evaluate their gaming experience. First, players evaluated how difficult it was to coordinate shared activities, and then the level of their enjoyment and frustration (Figure 8.6). By comparing these responses we aim to define a threshold that provides all players with an enjoyable gaming experience.

Figure 8.6a shows that with an increase in network delay, impaired players tend to have more difficulties coordinating actions with their partners. For unimpaired players, delays below 100 ms do not noticeably increase the difficulty level, which remains at a low value (below 5). On the contrary, a delay higher than 100 ms shows a constant growth of the perceived difficulty level. In both cases there is a significant correlation between delay and the difficulty level ($R^2 = 0.83$, $p = 0.011$). To define the threshold of acceptable delay, values should be chosen that keep the difficulty level for both players at a relatively low level (in the lower part of the rating scale, i.e. below 5). Based on the coordination difficulty scores, there is an indication that a one-way delay below 60 ms does not significantly decrease the user experience for both parties involved.

An interesting result is observed when comparing the level of enjoyment between impaired and unimpaired players (Figure 8.6b). In those cases where delay is below 80 ms, the unimpaired users have indicated their enjoyment slightly lower than those who were directly affected by delay. At the same time, when delay reaches 100 ms (and higher) enjoyment of impaired participants was considerably influenced by it. The rating of enjoyment given by the affected players has a negative trend, indicating that there is reduced enjoyment when faced with higher delays ($R^2 = 0.88$, $p = 0.004$). However, ratings given by unimpaired players do not have such a strongly pronounced regularity, being more balanced around the average value ($M = 8.72$, $SD = 0.88$). Therefore, the threshold of acceptable delay is defined here based on the evaluations by the class of impaired players. With delays higher than 100 ms, there are indications that user enjoyment decreases constantly.
8.4 User Study 1: Influence of Network Delay

(a) Difficulty to coordinate actions.

(b) User enjoyment.

(c) Level of user frustration.

Figure 8.6: Influence of the delay on the impaired and unimpaired players.
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Figure 8.6c shows the difference in the level of frustration between two groups of players. There is a significant correlation between delay and frustration for the impaired players ($R^2 = 0.85$, $p = 0.008$). We observe that after a delay of 100 ms the level of frustration of impaired players is increased dramatically. At the same time for non-affected players the level of frustration remains quite low (not exceeding 4) with a slight increase when the maximal delay (300 ms) is reached. Here, we define the delay of 100 ms as a threshold below which both of the players experience a low level of frustration (not exceeding 5).

Taking into account these findings delays between 60 and 100 ms (and below) are considered as those that provide the most enjoyable experience and adequate performance in the cooperative game being used. 100 ms delay is defined as a threshold above which players perceive network degradation as disturbing with a significant decrease in their performance.

8.5 User Study 2: Influence of Jitter

8.5.1 Measurement Setup and Procedure

For both parts of our second study we involved groups of three people playing a custom level designed within Little Big Planet 2. Three players had to coordinate their actions in order to throw a ball into a basket. The game continued until 800 points were collected. For each successful attempt, the players scored 200 points. Figure 8.7 presents a part of the environment. Two players (on the right) had to throw the ball together to the third player standing on the platform (on the left). The latter had to catch the ball and throw it into the designated area.

![Figure 8.7: Level used in the second study.](image)
Three PS3 consoles were connected through a switch over the LAN. In order to simulate different network conditions for all players, two impairment nodes with NetEm were placed between the central switch and the consoles as shown in Figure 8.8. To bring the setup closer to the real playing conditions and to avoid interactions through vocal communication, every participant was located in a different room. The amount of jitter is represented in NetEM as a value that is superposed on the ‘fixed’ delay (more precisely, the figure indicates the standard deviation). In practice and as an indication, a fixed delay of 100 ms with a jitter of 20 ms will result in values that are roughly spread between 140 ms and 60 ms, with the majority around 100 ms (due to the normal distribution chosen, as it provides more life-like results). Note that for the following discussion, values are provided for the one-way delay.

In order to analyze different amounts of jitter on user performance, the first part of the study had the following design. We fixed the amount of delay for each group and varied jitter to see whether it had any influence on players’ performance. There were four groups participating during the first part: the first two were exposed to 100 ms delay, and the other two to 200 ms delay. We varied the jitter values between PlayStation1 and PlayStation2 by assigning it to 20% and 50% of the fixed delay (simulating a cable access connection). These values were given in a different order to every group. At the same time, the jitter of the connection between PlayStation1 and PlayStation3 was fixed to 5 ms (which is typical for DSL connections). Every time the level was completed participants switched between the consoles. In such a way every player tried both the unimpaired (PlayStation1) and impaired (PlayStation2 or PlayStation3) environments.

The second part of this study was designed similarly to the previous one and an identical setup was used (Figure 8.8). We used the same custom level, but participants were asked to complete it as fast as possible. Twenty four people were recruited and randomly put together into eight groups. This time we aimed to define the level of jitter...
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

Part that is acceptable by players. Therefore, a single fixed delay value was used (100 ms) and four levels of jitter were introduced: 10, 20, 40 and 50 ms. Each group of participants tested all four levels of jitter, whose order was randomized. While testing the first given jitter value, participants switched PlayStations each time the level was completed (as earlier). To avoid too many tests for each group, for the other three jitter values players remained at the same location.

In both parts we captured the completion time. After completion of each level, the participants were asked to fill in a questionnaire similar to the one in user study 1 (see Figure C.3 in Appendix C). Each group spent between 40 and 60 minutes to complete the test.

8.5.2 Results

This section presents the results of user study 2 investigating the influence of jitter on player experience and performance in cooperative games. It consists of two consecutive parts. First, we determine whether there is any influence of jitter on cooperation (to justify further study). To accomplish this, the performance and experience of players under conditions of low and high levels of jitter are compared. To quantify the impact of jitter on cooperation, in the second part several levels of jitter are introduced. We aim to define the threshold of jitter below which players do not feel hampered in the game, when faced with the goal to finish the level as quickly as possible. Also, the discrepancy within the group of players using various network access technologies (e.g. DSL, cable connection, etc.) is studied. Similarly to Section 8.4.2, we provide both objective and subjective evaluations. The graphs in this section represent the values obtained by averaging certain characteristic (e.g. time, score, rating) among sessions where players experience the same level of jitter.

Part 1: Existence of Jitter Impact

During this first part we want to see whether jitter has any negative influence on the cooperative play. In order to perform this we have opted for certain delay values and varied jitter between PlayStations. We considered two values of fixed delay: 100 ms and 200 ms. While the first value was selected as a threshold of the game acceptability (based on the results of user study 1), the second one was used to define the worst possible condition (keeping in mind the choice of realistic values for current generation networks).

As in the previous user study, we have evaluated the impact of the network quality both objectively and subjectively. As an objective characteristic of the gaming expe-
8.5 User Study 2: Influence of Jitter

We have analyzed the level completion time. We have observed that players who were exposed to lower jitter values completed the level quicker (see Figure 8.9). Obtained results have also confirmed the finding from Section 8.4.2 proving that the level completion time increases with higher delays.

Although we have found a negative effect of jitter on player performance (objective measurement), it is still necessary to analyze whether players consider it degrading their experience (subjective). In order to reveal whether or not players feel hampered by jitter we have examined their responses given in the questionnaire.

Participants played the game in groups of three, where everyone was exposed to a different condition. One player did not experience any direct influence of jitter, while the other two were affected by it. One of the affected participants experienced varying high levels of jitter, while the other one was exposed to a constant low level of 5 ms jitter. We will refer to them as server, client (high) and client (low) respectively (Figure 8.8). We reiterate the fact that NetEM uses a normal distribution to determine the delay values; the values in the following paragraphs therefore indicate the standard deviation.

All three players found the conditions acceptable without noticeable impairment for any level of jitter when the delay was fixed to 100 ms (Figure 8.10a). When players were subjected to 200 ms delay, different levels of jitter were not perceived equally (Figure 8.10b). Jitter up to 20% (or 40 ms) was considered as an acceptable environment with minor impairments. Yet, a high level of jitter (50% or 100 ms) significantly decreases the perceived quality of the network. The server player has not experienced negative influence, but both other players have indicated these conditions to be very annoying with many noticeable impairments. Note that this is probably due to the fact

![Figure 8.9: Influence of jitter on the completion time (jitter level is calculated as 20% and 50% of the fixed delay).](image)
that the latency compensation techniques in LBP 2 cannot efficiently cope with the variations in delay.

Further, we have analyzed the user responses regarding the influence of the network quality on their enjoyment, frustration, difficulty to coordinate joint activities, game completion time and their wish to continue the game. When the delay was 100 ms players did not feel hampered by any of the jitter values (5, 20, 50 ms). They have indicated very low influence of the network quality willing to continue playing under given conditions.

An opposite situation is observed for those players that are subjected to 200 ms delay. Firstly, there is a greater discrepancy in players’ perception within the same group (between server player, client (high) and client (low)). Secondly, the analysis of results has shown the difference between responses of players that are subjected to 20% and 50% jitter, which do not occur for the 100 ms delay case. 20% jitter (or 40 ms) is found to be the worst condition for client (high) and server player, while the client (low) has indicated its influence to be less crucial. This is reflected in the players’ wish
to continue the game, which is lower for client (high) and server player than for client (low). During the trials with 50% jitter (or 100 ms), the server player has indicated the lowest influence of the network conditions on the gameplay among three people. For all aspects of the interaction investigated in this study, client (high) has indicated the highest influence of the network quality on his gaming experience. Client (low) has evaluated the influence of the network quality to be relatively high but not very different from the server player.

Part 2: Quantification of jitter impact

In part 1, we have shown that jitter negatively affects user performance in the cooperative game that is being used. We have observed that time required to complete the level increases with the level of jitter. Because we have checked this only for two different levels of jitter it is still necessary to confirm the findings with gradually increasing jitter. Therefore, we have organized a larger study where various levels of jitter were introduced.

This time we have restricted delay to 100 ms only, as an acceptable threshold value. Although we have found no influence of this network condition on players’ experience in part 1 (subjective), we have observed a negative impact on completion time of the cooperative game (objective). Therefore, we assume that the same network quality will be perceived differently if the goal of the task is time dependent. In order to check this assumption, the game level used in the previous test has been slightly modified. This time it was necessary not only to score a certain amount of points but also to achieve this goal as fast as possible.

First, we have analyzed the influence of different levels of jitter on the task completion time. A positive significant correlation \( R^2 = 0.44, p = 0.002 \) has been found between jitter and the completion time (Figure 8.11a).

Furthermore, we have analyzed how different players perceived this degradation subjectively. Seeing the influence on the completion time, we asked players to evaluate whether or not they perceived any influence of the given network condition on the time to accomplish the task. Three players have evaluated the jitter impact differently. From the graph (see Figure 8.11b) we conclude that all three players indicated jitter impact to be very low. The server player has not perceived an increase of jitter as a degradation of his experience. His evaluation remained at the same level across the conditions. At the same time we can see an increase of jitter influence on the client (high). The client (low) felt more affected than the server player, but in reality remained at the same level with exception of the highest level of jitter. While the jitter remained under 50 ms we have not observed a major difference between players.
Influence of Network Delay and Jitter on Closely-coupled Collaboration in Multiplayer Games

(a) Objective evaluation.

(b) Subjective evaluation.

Figure 8.11: Influence of jitter on the completion time.

Figure 8.12: Players’ perception of the network quality.
8.5 User Study 2: Influence of Jitter

(a) Influence of jitter on the difficulty of coordination.

(b) Influence of jitter on the player enjoyment.

(c) Influence of jitter on the player frustration.

Figure 8.13: Comparison of responses given by impaired and unimpaired players.
exposed to different conditions. Only when the jitter reached 50 ms, the difference between impaired players and the server player was elevated and greater than 1.

We have asked players to rate the overall quality of the network condition for each level of jitter. Figure 8.12 presents user evaluation according to the mean opinion score (MOS) gradation. As we can see jitter does not substantially decrease player perception of the network quality for the server player and client (low). At the same time client (high) experiences a gradual decrease of network quality, which drops to a relative low when jitter reaches 50 ms. Moreover, in cases of very high jitter the difference between player perception is more noticeable. For 50 ms jitter we observe that interaction between players becomes more unequal as the players experience different levels of degradation.

Other data gathered through the questionnaire reflects an influence of jitter on the ability to efficiently coordinate joint actions (Figure 8.13a), player enjoyment (Figure 8.13b) and frustration (Figure 8.13c).

These figures show that the server player’s experience has not been affected by the jitter increase. Ratings given by client (high) are somewhat different, indicating a low yet growing negative influence of jitter. For client (low) we observe a relatively similar evaluation among four conditions, with the exception of the highest level of jitter. Again we observe a greater difference between the server player and players that experience jitter. The existence of this difference between the server player and affected players confirms our assumption that there is a clear negative influence of jitter, as it unbalances the gaming experience between players.

The obtained findings have proven that higher levels of jitter have a negative influence on player experience in cooperative games (i.e. LBP 2). Besides a negative impact on the performance, it also results in an unbalanced experience between players. While the discrepancy between players (caused by different access technologies) remains relatively small with low jitter level, it grows significantly when jitter reaches 50 ms.

### 8.6 Conclusion

The studies presented in this chapter have shown that cooperation in games (based on the example of Little Big Planet 2) is sensitive to network quality. The main contribution of this work lies in its novelty with respect to the type of interaction investigated in this study. To our knowledge, there are no other studies that analyze the impact of network impairments on collaboration in games. With the help of the Little Big Planet 2 game, we made a first attempt to quantify the level of acceptable network quality for games involving closely-coupled collaboration.
A series of user studies have been carried out investigating the negative effect of network delay and jitter on player experience. Based on the results of our analysis, we can conclude that one-way delays up to 100 ms can still be considered acceptable for the game under investigation. Furthermore, we have found that jitter has a negative influence on user performance, in particular on task completion time. At the same time players have not perceived this influence as a degradation of their experience. However, when the goal of the game was time dependent, we have observed the difference between affected and non-affected players. This fact have confirmed our expectation of the negative influence of jitter on the gaming experience. Jitter higher than 50 ms introduces a great discrepancy between responses given by impaired and unimpaired players. Although we realize that the results obtained in our study may be game-dependent, we believe that they are applicable to other games involving similar types of interaction between players.

However, delay and jitter are not the only network characteristics that influence user experience in highly-interactive applications. According to (Steed and Oliveira, 2009), packet loss is another network impairment that can result in highly noticeable performance issues. In particular, this type of network impairment has a crucial importance for the quality of communication (Claypool and Tanner, 1999). Given the importance of communication when collaborating, it is important to also evaluate the negative impact of packet loss on communication between players in multiplayer games. The next chapter addresses the issue of communication quality degradation for a specific example of serious gaming. In particular, we will discuss collaborative gaming for rehabilitation training.
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Chapter 9

Influence of Packet Loss on Communication during Closely-coupled Collaboration in Serious Games for Rehabilitation

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9.1 Introduction

In the previous chapter we have analyzed the influence of network quality on the collaborative performance in multiplayer games, based on our experience with the game Little Big Planet 2. In particular, we have determined to what extent network delay
and jitter affect closely-coupled collaboration and how their impact is perceived by players. Besides these two impairments, interactive applications like games are also affected by packet loss that might lead to highly noticeable performance issues (Steed and Oliveira, 2009). Packet loss occurs when one or more packets of data traveling across a network fail to reach their destination. Besides the impact on user actions in multi-user environments, packet loss is distinguished as one of the main error types encountered in multimedia communication (Claypool and Tanner, 1999).

Our earlier findings indicated the importance of communication during collaboration (see Chapter 4). This necessity to communicate on the one hand, and the negative impact of network quality on the interactivity in collaborative applications (see Chapter 8) on the other hand, have motivated our research presented in this chapter. We aim to investigate to what extent degrading network quality (due to the presence of packet loss) affects communication between users in highly interactive applications. This time, we do not consider applications where communication is required only to accomplish the task. We believe that the negative impact of network impairment such as packet loss, would be more noticeable when communication is continuous between users and does not necessarily relate only to the performed actions. Therefore, for our investigation we chose a specific type of games – serious games, designed for a primary purpose other than pure entertainment, e.g. education and training. Due to their nature, we believe serious games are good examples of applications where communication is more than just a tool to accomplish a task. In particular for our research we focus on serious games created for health care, namely rehabilitation. In rehabilitation games, besides the purpose of physical training, the goal of a ‘game’ is often to support social interaction, which requires a significant amount of communication.

In this chapter, we present a study that investigates the quality of communication in case of packet loss during rehabilitation training in a virtual environment. More specifically, we study the behaviour of Multiple Sclerosis patients for whom social support from the family is regarded to be vitally important for a successful rehabilitation (Nätterlund and Ahlström, 1999; Wineman, 1990). In this case, it becomes necessary to investigate to what extent patients perceive a quality degradation. Insufficient social interaction caused by a low level of network quality may lead to a reduced motivation of the patients and an unwillingness to continue their training, negatively affecting the outcome of their rehabilitation.

We start with a general overview of virtual environments designed for rehabilitation training. Next, we address the issue of providing social support during training by discussing existing applications for rehabilitation that involve multiple users. This is followed by an overview of studies on the impact of packet loss on communication. As the chapter goes on, we discuss our approach to provide social support in rehabili-
9.2 Virtual Environments for Rehabilitation Training

As information technology has advanced over the past years, there has been a steady growth in the use of virtual environments (VE) and virtual reality (VR) in health care. The first health care VR applications appeared in the early 1990s with the main purpose to visualize complex medical data, used, for example, during surgery (Riva, 2002). A few years later, the scope of VR applications in medicine has broadened to include neuropsychological assessment and rehabilitation. In particular, virtual rehabilitation has received increasing attention from researchers and medical personnel who recognize the potential therapeutic benefits.

Rehabilitation aims to enhance the functional ability of a person experiencing certain restrictions, and his/her realization of greater participation in community life (Weiss et al., 2004). These goals are achieved by intensive intervention aimed at improving sensory, motor, cognitive and higher level-cognitive functions that can be achieved with a virtual rehabilitation. Applications for training based on VE are used to overcome the consequences and to improve the quality of life and include stroke rehabilitation, acquired brain injury, Parkinson’s disease, orthopedic rehabilitation, balance training, wheelchair mobility and functional activities of daily living training. Numerous virtual environments have been developed for the rehabilitation of these disabilities (Holden, 2005; Laver et al., 2012; Standen and Brown, 2005; Crosbie et al., 2007). Most applications share a common goal of using a virtual reality to construct a simulated environment aimed to facilitate the client’s motor and cognitive abilities in order to improve their quality of life.

The advantages associated with the use of virtual rehabilitation are numerous (Holden, 2005; Burdea, 2003; Bohil et al., 2011; Brahnam and Jain, 2011). Virtual environments are highly flexible and programmable. They enable the therapist to present a wide variety of controlled stimuli, and to measure and monitor a wide variety of responses made by the patient. Virtual rehabilitation is able to provide a natural environment making individuals forget their surroundings and situation and focus directly on a task in the simulated environment (Rizzo and Buckwalter, 1997; Schultheis and Rizzo, 2001). By "forgetting" that they are training, patients can provide insights into their typical behaviour. Additionally, VR offers a safe environment enabling patients to do things that would be hardly possible in reality. Performing activities so typical
In daily life (e.g. visiting a supermarket, driving a car) in a VE, allows patients to independently participate in their own real environments.

In addition to being immersed, there has been an increased interest in VR due to its motivational nature (Berger-Vachon, 2006). Indeed, rehabilitation training is by nature repetitive, and repetition tends to reduce a patient’s motivation (Burdea, 2003). Opposite to the therapy in real life, individuals using VR tend to have fun and are thus more motivated to continue training. This is especially true in video game-based therapeutic approaches (Goude et al., 2007; De Weyer et al., 2011; van den Hoogen et al., 2009), where the patient performs the necessary training by playing games. Patients are motivated to exercise when they receive visual and auditory rewards typical for video games. In addition, the possibility to compete and collaborate in these game-based training environments improves a patient’s motivation to keep on training.

Traditional rehabilitation is costly, as it is done one-to-one, meaning one therapist (or sometimes even several) working with one patient. VR can provide a controlled and structured environment where little supervision is required and, thus, reduces the costs of the therapy. Moreover, it provides unlimited opportunities for acquiring and processing information, exploring and learning. Immediate feedback, prompts, cues in various sensory modalities can also be incorporated into VR so that it can reinforce the desirable response. VR also provides the capacity to individualize treatment needs, while gradually increasing the complexity of tasks.

After completion of the rehabilitation program in the center, many patients may have limited access to the training activities upon their return back home. With the help of virtual reality and modern Internet therapy services can be also delivered to users, allowing them to continue training at home (Deutsch et al., 2007). These telerehabilitation systems provide patients with necessary exercises that are remotely controlled by a therapist in a clinic (Rosen, 1999; Holden, 2005; Popescu et al., 2002).

### 9.3 Social Rehabilitation: Multi-user Virtual Environments for Rehabilitation Training

The concept of social support in health has been of interest in health-care research since the 1970s, and has been found to have a positive impact on people’s health, well-being, and their ability to adjust to the consequences of an illness (Beckley, 2006). Having others to rely on for social support, people typically find it easier to cope with their impairments when someone is there to help improve their quality of life (Casey and Stone, 2010). In particular, for stroke survivors it has been shown that social support is the key factor to maintain essential social relationships (Lynch et al., 2008).
Another study has shown that social support is critical for a stroke patients’ motivation, in order to adhere to the necessary regime of rehabilitation exercises in the chronic phase of the disease (van den Hoogen et al., 2009). The authors report that there is a perceived difficulty within the social network around the patient (family, friends) in (re)connecting to the patient. They indicate a need to engage in meaningful activities with the patient. One of such meaningful activities can be playing games together.

Utilizing the multiplayer aspect of digital games may increase social connectedness (Weiss and Klinger, 2009). Shared gameplay provides patients and their game partners with a common ground for social interaction and a joint topic for conversation. At the same time it is a great motivator for a patient to keep practicing. Several existing studies show the potential of multiplayer games (Alankus et al., 2010; Johnson et al., 2008; Loureiro et al., 2006). Additionally, with the emergence of low-cost gaming consoles such as the Nintendo Wii, new opportunities arise for therapy (especially in-home) centered on social interactions and values, which could reduce the sense of isolation (Loureiro et al., 2010).

Alankus et al. (2010) have designed and tested different multiplayer games, both collaborative and competitive, for stroke patients (Figure 9.1a). In their tests patients have indicated that these kinds of games can help them to overcome social isolation. They consider therapeutic games as a way to extend their connection with, for instance, (grand)children.

While the games mentioned in (Alankus et al., 2010) are designed to be played together while being in the same location, another study Vanacken et al. (2010) introduces a collaborative game for MS patients (Figure 9.1b) that can be played either co-located or remotely. It involves closely-coupled collaboration based on the concept of task division over several players. For this game the idea is that it is played by a patient and by a healthy person. This way, visitors of the rehabilitation center can help in the rehabilitation of their affected family member and thus enhance their motivation in doing the necessary training. Tests in a co-located setting have shown the effectiveness of this approach and highlighted the engagement of the players.

Other recent studies by Loureiro et al. (2006) and Johnson et al. (2008) involve tele-rehabilitation enabling players to perform activities together over distance. It has been proven that the concept of shared play over large distances influences people’s motivation and engagement with the task. In these studies the authors conclude on a player preference of playing with another person rather than playing alone (or against computer). Furthermore, different types of gameplay without any communication, with audio only and video with audio have been compared. Players have indicated the latter condition to be the most preferable one, providing more interaction and con-
Influence of Packet Loss on Communication during Closely-coupled Collaboration in Serious Games for Rehabilitation

(a) Under the Sea by Alankus et al. (2010): two-player game, where one player controls the mother fish to earn points and the other player controls the snail to prevent the predator from reaching the fish family.

(b) BalancePump by Vanacken et al. (2010): two-player game, where each player controls one of the ends of the beam and in such a way they make the ball rolling in order to collect stars without losing the ball.

Figure 9.1: Examples of multiplayer collaborative games for rehabilitation training.

nectedness. Although the abovementioned telerehabilitation system was developed for the training of stroke survivors, healthy subjects were involved in its evaluation.

9.4 Influence of Packet Loss on Communication

When talking about remote interaction, an important issue that has to be taken into account is the impact of network quality levels, typical for the Internet. One of the most
important network impairments influencing audio and video communication is packet loss (Cermak, 2005). Packet loss implies that (parts of) video frames and (chunks of) audio streams do not arrive at the destination, in most cases resulting in “frozen” or “jumping” images and missing words. Opposite to the other impairments (e.g. delay, low bandwidth, etc.), in case of packet loss, it is almost impossible for users to predict and compensate its negative influence. For example, if there is a delay, users often adopt their behaviour by pausing during the conversation allowing the other party to reply.

Packet loss has been the topic of many research initiatives, showing a clear relationship between packet loss and multimedia quality deterioration and the way it affects user experience. The influence of packet loss on perceptual quality of multimedia sent over the Internet is presented by Claypool and Tanner (1999). In particular, in this work the authors focus on the perceptual quality of video, showing that it degrades sharply even with low levels of packet loss as compared to the perceived quality for perfect video. The results of the experiments have shown that perceptual quality drops by over 50% in case of a low level of packet loss (the authors consider 8% packet loss as low). However, moving from a low to a high loss (22%) does not result in a significant decrease in perceptual quality.

Later work by Cermak (2005) studies the impact of packet loss on a videoconference system. In this research, packet loss above 4% is considered as high. By varying packet loss between 0% and 4%, Cermak has found that high levels of packet loss affect the users’ ability to accomplish their main task, communication. The conversation was often lost due to a frozen video and silent audio. The severe effect of packet loss made speech choppy and jerky, with dropped words.

The demand for high quality of multimedia is constantly increasing. However, it may not always be possible to have perfect quality for both audio and video concurrently. In such situations, it is often necessary to find the optimal trade-off between two modalities. In (Korhonen et al., 2010) such an attempt has been made, showing that content poses a significant impact on the preferred compromise by users between audio and video quality. Different types of videos have been compared, whose content determined the relative importance of audio and video.

All these studies confirm the importance of the discussed topic. However, they reflect on the experience of general users and may not work in the context of a specific target group (e.g. users with special needs).
9.5 Multiple Sclerosis: Importance of Social Support for Rehabilitation

Multiple Sclerosis (MS) is a chronic progressive disease which affects the central nervous system resulting in muscle weakness and difficulties with coordination and balance, as well as visual and cognitive dysfunctions. With MS, the nerves of the brain and spinal cord are damaged by one’s own immune system (WebMD, 2012). Each nerve is covered by a fatty substance called myelin, which insulates the nerves and helps in the transmission of nerve impulses, or messages, between the brain and other parts of the body (Figure 9.2). These messages control muscle movements, such as walking and talking. However, in MS, as the myelin gets attacked and destructed, the nerves will be damaged too. Based on the level of nerve injury, symptoms may be mild, such as numbness in the limbs, or severe, such as paralysis or loss of vision. The progress, severity, and specific symptoms of MS are unpredictable and vary from one person to another.

![Figure 9.2: Multiple Sclerosis (WebMD, 2012).](image)

Although there is still no cure for MS, effective strategies are available to modify the disease course, treat exacerbations (relapses), manage symptoms, improve function and safety, and provide emotional support. Although rehabilitation will not result in a complete recovery, a combination of these treatments leads to an enhance quality of life for people living with MS (National MS Society, 2012). While symptoms can range from mild to severe, most can be successfully managed with strategies that include medication, self-care techniques and rehabilitation (with a physical or occupation therapist, speech/language pathologist, cognitive remediation specialist, etc.).
MS is a life changing matter, significantly affecting the habitual life style of most people diagnosed. However, with an appropriate rehabilitation training it is possible to improve or maintain one’s ability to perform daily activities effectively and safely at home and at work. Rehabilitation professionals focus on overall fitness and energy management, while addressing problems with accessibility and mobility, speech and swallowing, and memory and other cognitive functions. In particular, one of the recent actively studied areas here is the rehabilitation of upper extremity dysfunction as it strongly influences the capacity to perform activities of daily life (ADL) such as self-care, dressing, object manipulations, etc.

Multiple sclerosis affects not only the physical capabilities of a diagnosed person, but also the social side of his/her life. As the disease progresses, a person may become more socially disconnected from others (Taming Multiple Sclerosis, 2011). In particular, when diagnosed, it becomes harder and harder for the patient to continue the social interactions she or he once was so accustomed to. Therefore, besides regular trainings provided by therapists, successful rehabilitation is more likely when facilitating social contact between patients and their immediate family and friends, whose help and support is regarded to be vitally important for a successful rehabilitation (Nätterlund and Ahlström, 1999; Wineman, 1990). A part of the ongoing research initiatives in the field of in-home tele-rehabilitation is paying particular attention to these social aspects. In this approach, the patients’ comfort is increased by staying at home and being surrounded by their family, while therapists have the means to remotely control the therapy sessions.

Unfortunately, there are circumstances in which patients cannot continue the rehabilitation at home and have to stay at the rehabilitation center or clinic. This happens for instance when a patient experiences a relapse. In this case, usually, he or she has to stay in a rehabilitation center for three months or more to complete the entire rehabilitation program (physiotherapy, occupational therapy, speech and/or psychotherapy, etc.). Although family members are allowed to visit their relatives in the rehabilitation center, it is not always possible for them to make regular visits. Therefore, the amount of time spent together decreases drastically, which may reflect on the progress of rehabilitation (Gulick, 1994).

Understanding just how important family involvement is in the rehabilitation process, we propose a collaborative game (played over the Internet) that enables rich social interaction while following the necessary intensive training. While staying at the rehabilitation center for frequent and intensive therapy and care, patients can play this game with their relatives or friends at home and communicate through audio and/or video channels. This game creates a platform for social interaction. Through connectivity with popular modern game controllers (WiiMote, BalanceBoard, Kinect, etc.)
the game is designed to motivate people of all ages to join in and play games with the patient.

However, the user experience of the applications deployed over the Internet is often negatively affected by various network impairments (delay, jitter, packet loss, etc.). Although lots of studies exist on the evaluation of communication quality in networked applications, they are mainly oriented towards the more general user. The special needs and weakened abilities of MS patients could cause totally different perceptions and by consequence communication requirements. Experiencing low quality audio or video may impact the rehabilitation negatively in the end. It could result in unwillingness to continue the training, which – in turn – could lead to insufficient social interaction. Therefore, we emphasize the importance of investigating the patients’ perception of network impairment affecting communication during training. In particular, we focus on packet loss as it has a major impact on the VoIP applications when compared to other network impairments (delay, etc.) (Cermak, 2005), severely affecting the perceived quality of audio (Hardman et al., 1995) and video communication (Claypool and Tanner, 1999).

As mentioned in the introduction, the main goal of this research is, with the help of a serious game application, to investigate the influence of network quality on communication in collaborative virtual environments. In particular, we focus on rehabilitation training for people with Multiple Sclerosis that involves the performance of required physical activities and also helps patients in the rehabilitation center to maintain a necessary level of social interaction with their families at home. However, before we can actually evaluate how patients perceive the degrading quality of communication, we first have to analyze their general ability to communicate remotely. Here, we have to evaluate how the presence of additional equipment influences the patients’ performance, since it requires them to divide attention between video images and the task at hand. To our knowledge most existing collaborative training systems require the MS patients involved to be physically present in the same location, thus enabling participants to communicate naturally. The remote gaming setup therefore may cause additional challenges for the patient, which we hope to identify during our research.

### 9.6 Experiment: Influence of Packet Loss on Communication in the Game for Rehabilitation

As has been mentioned earlier, social support provided by family and friends plays an important role in the rehabilitation of people suffering from various types of disabilities, in particular, Multiple Sclerosis. Unfortunately due to the necessity of spending
9.6 Experiment: Influence of Packet Loss on Communication in the Game for Rehabilitation

a substantial amount of time in rehabilitation centers, most MS patients experience lower social interaction with their immediate surroundings. To overcome this, we utilize a collaborative game played over the Internet that facilitates interaction during absence. In particular, a gaming environment described in (Hariandja, 2011; De Weyer et al., 2012) was used. While staying at the rehabilitation center to follow intense and necessary training programs, patients can play this game with relatives or friends communicating through audio and/or video channels.

Preliminary testing has shown a positive reaction of patients performing collaborative tasks with another person playing next to them. Seeing the high level of enjoyment and engagement caused by the collaborative nature of the game, we now investigate whether or not it is possible to use it over distance while at the same time providing an appropriate level of social support from co-players. For this purpose, an experiment was conducted. Although only small number of participants were involved in the experiment, it was designed according to the rules of experimental research. In case of special target group users (in our case MS patients), it is often very hard to perform studies with a representative number of people involved. However, studies with even small amount of real subjects can be useful, indicating general trends typical for the target population.

During the experiment, a two-stage approach was applied. In the first phase, we determined how patients perceived remote communication and which type of communication (audio only or video with audio) was preferred among them. In the second part of our study, we exposed the communication between patients and their co-players to different levels of packet loss. Although in reality network impairment negatively affects not only communication but also the game itself, in this study we solely focused on communication. By doing this we aimed to see to what extent MS patients perceived a degradation of network quality when communicating over distance. Patient performance, subjective evaluation and observations were analyzed.

For this experiment, we build further on the serious game "Social Maze" (De Weyer et al., 2012) that is realized in our HCI lab, in line with the rehab research that is performed in the INTERREG-IV project "Rehabilitation robotics 2" (IVA-VLANED-1.14, Euregio Benelux). The aim of the project is to investigate and realize technology-supported rehabilitation for upper limb training for MS and stroke patients, mainly by using virtual environments and a robot (HapticMaster) as an interaction device. The overall training concept developed in the project is called I-TRAVLE\(^1\), which stands for Individualized, Technology-supported and Robot-Assisted Virtual Learning Environments.

\(^1\)www.i-travle.eu
In the context of this training concept, the serious game "Social Maze" was developed to investigate the potential of social aspects and involvement of other patients and therapists in the training. We used this serious game for this experiment, but extended it with the communication infrastructure allowing audio or audio with video communication between the involved players.

9.6.1 Participants

Six subjects (three females and three males) with upper limb weakness due to Multiple Sclerosis participated in the experiment. They were patients undergoing a training program in the Rehabilitation and MS Center of Overpelt, Belgium. Their average age was 60.2 and varied between 47 and 71 years of age. The average diagnosis time was 15.5 years (ranging from 3 till 27 years). One therapist was involved in the study and played together with every patient.

During the experiment, three patients trained their left hand, while the other three used their right hand. It was the therapist who decided for every patient which hand to train. To evaluate the patients' clinical condition the Motricity Index (MI, maximal value is 100) and the Action Research Arm Test (ARAT, maximal value is 57) were utilized. While the first characteristic reflects upper limb strength, the second one is used to assess the patient’s functional capacity. Personal information of each participant as well as the clinical characteristics are presented in Table 9.1.

Table 9.1: Personal information and clinical characteristics of MS patients in the experiment.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Diagnosis (years)</th>
<th>MI</th>
<th>ARAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male</td>
<td>64</td>
<td>14</td>
<td>76</td>
<td>41</td>
</tr>
<tr>
<td>2</td>
<td>Female</td>
<td>47</td>
<td>14</td>
<td>76</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>71</td>
<td>10</td>
<td>84</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>Female</td>
<td>58</td>
<td>3</td>
<td>83</td>
<td>56</td>
</tr>
<tr>
<td>5</td>
<td>Female</td>
<td>64</td>
<td>25</td>
<td>72</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>57</td>
<td>27</td>
<td>55</td>
<td>41</td>
</tr>
</tbody>
</table>

9.6.2 Apparatus

During the experiment, patient and therapist were located in two separate rooms in the rehabilitation center. Figure 9.3 shows an overview of the patient setup. The MOOG
HapticMaster (Moog, 2011) input device equipped with an ADL gimbal (to train for ADL – Activities in Daily Life) was used to interact with the environment (Figure 9.4). It also functions as an output device, providing haptic feedback during the training. For output, a large 40” TV screen was placed behind the HapticMaster, approximately 1.5m in front of the patient.

To support voice and video communication between players, the voice over IP software X-Lite by CounterPath was used (GSM codec for audio and H.263 for video). It was installed on a separate laptop, to which both the Polycom Communicator C100S with a wired headset and a 1.3 megapixel Logitech Quickcam webcam were connected. This laptop was placed in front of the patient, a bit lower than the main screen.

The therapist setup consisted of two separate laptops: one with the game and another one with the X-Lite software. The game supports a wide range of input devices, including modern game controllers as WiiMote and Kinect. The latter was chosen as the input device for the therapist during this experiment.

All computers were connected through a switch to a 100 Mbit local area network. To introduce different network conditions for the communication between players, a linux system running the network emulator NetEM (Hemminger, 2005) was used. As the traffic associated with the X-Lite application was sent directly between computers, the presence of a single impairment node sufficed to introduce network anomalies for this setup. In this way we could vary the level of packet loss affecting communication while not interfering with the game itself. Care was taken to choose packet loss values representative for current-generation network conditions (Steed and Oliveira, 2009). The complete setup is schematically depicted in Figure 9.5.

9.6.3 Design

During the experiment, a within-subject design was adopted. The independent variable was a type of communication with four conditions, discussed further in Section 9.6.4 (Table 9.2). All participants, in groups of two (one patient and therapist), had to test every condition. The order of the conditions was counterbalanced using a balanced Latin square design. The dependent variables were score, task completion time, the amount of collected symbols and the amount of lost lives. Subjective evaluation of each condition was obtained through a questionnaire (see Figure C.4 in Appendix C).
Influence of Packet Loss on Communication during Closely-coupled Collaboration in Serious Games for Rehabilitation

Figure 9.3: Patient setup.

Figure 9.4: Moog HapticMaster with ADL gimbal used by the patient.

Figure 9.5: The complete setup used during the experiment.
9.6 Experiment: Influence of Packet Loss on Communication in the Game for Rehabilitation

9.6.4 Procedure

Six pairs of participants (one patient and one therapist) were asked to complete a collaborative game called "Social Maze". The game involves a lot of closely-coupled interaction and requires well coordinated interaction between players. The goal of the game is to collect six objects placed inside a virtual labyrinth. The whole scene is split into two separate fields with the same objects (Figure 9.6). One field belongs to the patient, while the other one is controlled by the therapist. During the game, players can see both parts of the scene: their own field and the field of the partner. Players are represented as small fish-like avatars in different colors.

![Figure 9.6: Screenshot of "Social Maze" - collaborative multiplayer game for rehabilitation.](image)

In order to score points, both the patient and the therapist have to pick up the same objects in their own part of the maze and bring them to the collecting area (in the middle of the screen). When one of them places the object, the other player has 10 seconds to put the same object in the collecting area of his own part. Because of this time limitation, it is necessary to continuously discuss the strategy, namely what item the players are going for next. The amount of points received, is equal to the amount of remaining seconds. If non-corresponding objects are placed in the collecting area, they both are reset to the original position. If one of the players cannot bring the second object within the given time interval, the object that was placed first is reset to its original position.

Two types of obstacles are present in the game – lasers and bombs – which are placed randomly throughout the maze. Lasers open and close automatically for a few seconds blocking the path for the users. Players have to run through the lasers, when they are
influence of packet loss on communication during closely-coupled collaboration in serious games for rehabilitation

open. If a player touches the laser, a life is lost. Bombs, in contrast, can only be removed with the help of the remote player who has to detonate it by pulling the trigger on his side of the maze.

The game continues until one of the following criteria is achieved: all six objects are collected; players lose all their lives (maximal amount was six); or the game timer has expired (7 minutes). It is possible to collect lives during the game by picking up the hearts that appear occasionally in the scene. The final score consists of two components: a score based on the collected objects and an extra point for every remaining heart. Because players have only a time frame of 10 sec to bring the same object and maximum 6 lives available, the maximum possible score is 66 points.

Patients used the HapticMaster to control their avatars during the game. The therapist controlled his avatar by hand movements tracked with a Microsoft Kinect. The communication between remote players appeared through the X-Lite application, a voice over IP software that supports both audio and video chats.

There were four sessions during the experiment, each corresponding to one of the four given conditions (Table 9.2). After each session, patients were asked to fill in a questionnaire in order to obtain information about their gaming and communication experience (see Figure C.4 in Appendix C). This questionnaire reflected the level of their satisfaction with the multimedia quality; the ability to understand the remote player; the necessity of video, etc. Additionally, we observed the patients’ performance during the experiment in order to find out the relationship between their responses and actual behaviour. As we wanted to discover whether or not patients experienced any additional difficulties caused by the necessity to split attention between two screens, we were particularly interested in how often they were looking at the video.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>audio communication only (unimpaired)</td>
</tr>
<tr>
<td>B</td>
<td>video with audio communication (unimpaired)</td>
</tr>
<tr>
<td>C</td>
<td>video with audio communication that was slightly impaired by packet loss (3%)</td>
</tr>
<tr>
<td>D</td>
<td>video with audio communication that was highly impaired by packet loss (5%)</td>
</tr>
</tbody>
</table>

No practice session was given immediately before the actual test, but the patients had played at least the initial levels of this game earlier as part of their normal training program, while being co-located with the therapist in the same room. One week before
9.6 Experiment: Influence of Packet Loss on Communication in the Game for Rehabilitation

the actual test, every patient conducted a short remote trial during which the concept of audio and video communication (with the use of additional equipment) was introduced. On average it took approximately one hour for each patient-therapist team to complete the actual experiment.

9.6.5 Hypotheses

Two goals are defined in this study. First, we want to investigate how MS patients perceive the ability to communicate over distance (and their preference for particular audio/video settings). Secondly, our goal is to analyze how the occurrence of packet loss affects communication between remote players. The following hypotheses are suggested to achieve this goal:

H1: the presence of video (condition B) leads to a higher level of satisfaction and better understanding of the other player compared to audio only (condition A);

H2: the presence of video communication improves player performance;

H3: there is no significant difference between patients’ preference comparing unimpaired video (condition B) with slightly impaired (condition C);

H4: the patients have a definite preference for unimpaired video (condition B) over highly impaired video (condition D).

Our first hypothesis is based on the presumption that the presence of video increases the feeling of more actively co-playing in the game. A higher satisfaction from training is the consequence of this higher level of interaction. Similar results have already been shown in (Johnson et al., 2008; Loureiro et al., 2006), but there the telerehabilitation system for stroke patients was only tested with healthy subjects. Our second hypothesis states that video also improves performance besides contributing to player enjoyment and contentment. The co-player’s moves and the corresponding avatar behaviour can serve as a visual guidance for patients, leading to a better understanding of game rules and actions to be performed.

We realize that adding an extra video screen may bring cognitive difficulties since it obliges players to spread their attention between the video screen and the actual game. However, we do not expect patients to constantly look at the video screen but rather to keep attention on the conversation itself. As low levels of packet loss do not have a great impact on audio, patients are not likely to differentiate unimpaired conditions if merely a slight degradation is present. At the same time, high packet loss will noticeably degrade both audio and video. This explains our third and fourth hypotheses.
9.7 Results

According to the experiment design, every participant tested all four conditions (Table 9.2). We performed repeated measures (RM) ANOVA in order to find a statistical difference between these conditions. In case a statistical difference was found, a Bonferroni post-hoc test was performed to determine which conditions were different. Because the following subsection refers only to the first two conditions (A and B) we immediately present the results of the post-hoc test omitting the details of RM ANOVA. They will be discussed afterwards in Section 9.7.2 where all conditions are compared. Table 9.3 presents mean values and standard deviations for every characteristic discussed in this section for all four test conditions. Taking into account the scattered nature of patients’ responses we also provide graphs representing individual responses. This allows us to search for general regularities characterizing the MS population.

9.7.1 Comparison Between Audio and Video with Audio Communication

First of all, we wanted to compare which type of communication is preferred. We realize that video images can increase the cognitive load for patients or even be distracting. Therefore, it is paramount to determine whether or not it is more preferred above pure voice communication.

In order to compare the audio only and the video with audio communication conditions, we asked players to evaluate their satisfaction level with every communication medium. We found a significant difference between the conditions \( p = 0.041 \) indicating a clear patients’ preference towards interaction with both audio and video. Furthermore, they reported that it was significantly easier to understand a remote player when video was included \( p = 0.019 \). These results confirmed hypothesis H1.

Four out of six patients reacted positively on the presence of video and they explicitly indicated its contribution towards game enjoyment. Two players stated that video played an interesting role in better understanding the game rules, while observing explanations given by the remote player. Only one player found video to be distracting. She indicated that the availability of video required a lot of additional attention making it difficult to focus on the game.

Finally, we analyzed player performance. Although we are aware that the performance of MS patients mainly depends on their physical abilities, we tried to compare game results under different conditions. The game performance was analyzed in terms
Table 9.3: Means (M) and standard deviations (SD) of the characteristics for the four test conditions (A, B, C, D).

<table>
<thead>
<tr>
<th>Characteristics (evaluation scale)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Satisfaction with the communication (0 – not at all to 10 – very)</td>
<td>6.53</td>
<td>1.84</td>
<td>8.58</td>
<td>0.97</td>
</tr>
<tr>
<td>Ease of understanding other player (0 – easy to 10 – difficult)</td>
<td>1.92</td>
<td>1.87</td>
<td>1.32</td>
<td>1.75</td>
</tr>
<tr>
<td>Video quality (1 – bad to 5 – excellent)</td>
<td></td>
<td></td>
<td>4.33</td>
<td>0.52</td>
</tr>
<tr>
<td>Audio quality (1 – bad to 5 – excellent)</td>
<td>3.50</td>
<td>0.84</td>
<td>3.67</td>
<td>0.82</td>
</tr>
<tr>
<td>Frequency of looking at the video (1 – never to 5 – most of the time)</td>
<td>2.67</td>
<td>1.63</td>
<td>3.00</td>
<td>1.26</td>
</tr>
<tr>
<td>Player performance:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Game score (points)</td>
<td>49.67</td>
<td>21.29</td>
<td>51.83</td>
<td>21.19</td>
</tr>
<tr>
<td>- Task completion time (sec)</td>
<td>299.78</td>
<td>86.92</td>
<td>275.70</td>
<td>84.56</td>
</tr>
<tr>
<td>- Amount of collected symbols</td>
<td>4.83</td>
<td>1.83</td>
<td>5.00</td>
<td>2.00</td>
</tr>
<tr>
<td>- Amount of lost lives</td>
<td>2.00</td>
<td>2.10</td>
<td>1.33</td>
<td>1.97</td>
</tr>
</tbody>
</table>
of game score, task completion time, amount of collected symbols and lost lives. No significant differences were found among the given conditions (rejecting hypothesis \( H2 \)). However, the mean values of each characteristic showed results in favor of video communication, resulting in a higher score and a higher amount of collected items, while decreasing the amount of lost lives and task completion time.

### 9.7.2 Influence of Packet Loss on Communication

As the next step, we wanted to determine how MS patients would react to degrading multimedia quality due to packet loss, resulting in missing words and/or corrupted image. A lower quality of communication may lead to a decreased amount of perceived social interaction and support. Therefore, the main question here was to what extent MS patients would notice a difference between the conditions.

Firstly, the level of patient satisfaction with the provided communication was analyzed (Figure 9.7a). We found a significant difference between the four conditions \( F(3, 15) = 6.628; \ p = 0.005 \). A Bonferroni post-hoc test indicated that condition B was not significantly different from condition C, confirming hypothesis \( H3 \). At the same time we observed a difference between conditions B and D \( (p = 0.022) \). This confirms hypothesis \( H4 \). Similarly to the analysis in the previous subsection, we analyzed how easy it was to understand the remote player (Figure 9.7b). Significant differences existed between the four conditions \( F(3, 15) = 13.995; \ p < 0.01 \). A Bonferroni post-hoc test showed a difference between conditions A and B (reported earlier) and conditions A and C \( (p = 0.027) \). We concluded that even slightly impaired video still allowed better understanding of the remote player’s explanations comparing to the voice communication only.

Figure 9.7 represents individual responses given by the patients. Despite an obviously very diverse evaluation we observe a general trend characterizing their preferences. In both cases the unimpaired video communication (condition B) was assessed as the best one, and condition D as the worst one.

We asked players to evaluate perceived video quality in order to find out whether or not they perceived the network impairment as disturbing (Figure 9.8a). We found a significant difference in their evaluation \( F(2, 10) = 10, \ p = 0.004 \). A performed Bonferroni post-hoc test revealed that patients perceived condition D significantly worse than condition B. At the same time no difference was found between conditions B and C. That allows us to conclude that patients found only highly impaired video to be noticeably disturbing.

Moreover, because packet loss affects both video and audio we also asked players to assess the quality of the latter (Figure 9.8b). Although we did not find any signifi-
9.7 Results

(a) Satisfaction with the level of communication.

(b) Ease to understand remote player.

Figure 9.7: Individual evaluation by patients.

cant difference across the conditions, an interesting observation was made here. Even though conditions A and B were not deteriorated by any network impairment, patients indicated better audio quality when video was involved. We discovered from the subjective evaluation through the questionnaire that audio was the main source of exchanging information between the players, being more important than video. As it was important to continuously communicate game strategy in order to successfully complete the game, patients became more critical about audio quality, rating non-impaired cases relatively low.

Additionally, we discovered a correlation between audio quality and the frequency of players looking at the video of their remote partner. When the audio quality was perceived lower, we observed that the patients compensated this degradation by looking more often at the image of the co-player.

Finally, we checked if any influence of communication quality on player performance (objective measurements) exists. The comparison of score, completion time, amount of collected symbols and lost lives showed no significant difference between the con-
Influence of Packet Loss on Communication during Closely-coupled Collaboration in Serious Games for Rehabilitation

Figure 9.8: Evaluation of quality of communication medium (averages based on the users’ responses).

Therefore, we can conclude that the presence of network impairment in communication does not affect user performance, but still is important to support a high level of social interaction between the patient and his/her game partner.

9.8 Discussion of the Results

Recognizing the importance of social support from the families for effective rehabilitation, we attempted to investigate a technological approach to maintain it while MS patients are undergoing treatment in a rehabilitation center. Due to the special needs and requirements of particular target users (in our case, MS patients) it is important to analyze their performance and preferences in a collaborative play where different means of communication are involved.
For research purposes it is often very hard to perform studies with a representative number of patients involved. An additional challenge lies in the heterogeneity of MS patients making it difficult to generalize the outcome of the studies. However, even studies with a small amount of real subjects can provide insights into the MS population and often show general trends characterizing the behaviour or preference of a target group.

Our experiment with the communication-enhanced collaborative game showed that patients preferred to see their game partners although they admitted that it was not absolutely necessary. The main reasons being the importance of eye contact and the ability to follow the partner’s actions which comes naturally during co-located interaction. Although the additional equipment involved for voice communication did not introduce any new challenges to the gaming experience, it was often difficult for the patients to spread their attention across the screens.

When introducing different levels of multimedia quality, they pointed out the importance of good quality voice communication as the primary source for sharing information between players. Higher levels of packet loss resulted in frequent moments of silence, and as a consequence missing words during the conversation, which noticeably decreased the patients’ experience. Observations have shown that players primarily discussed game tactics and only occasionally touched some non-game related topics (e.g., jokes, family, etc.). This explains the relatively higher patients’ preference towards good quality audio which contributes to a successful gaming experience. Nevertheless, patients were more satisfied with the level of communication when they could observe another person. The presence of different levels of network impairment also affected the players’ enjoyment of the game. Three out of six patients equally enjoyed the four conditions. Two patients said that they would prefer to play when video is present, irrespective to its quality. One patient found it crucial to have unimpaired communication (both audio and video) indicating the second condition as the best one.

When analyzing the quality of communication, we observed that patients did not always notice if the video was slightly impaired. The impact of the packet loss on video resulted in frozen images of the co-player, but it was not considered disturbing by the patients. One of the possible reasons for that could be the difficulty for the patient to spread attention between the game and the video (on a separate screen). We observed that patients were looking a lot at the video of the co-player while waiting for his/her actions. If they did not have to wait, they were focused on the game screen. Yet, when the audiovisual communication was greatly impaired, they noticed this degradation. This result has an important impact on the further development of telerehabilitation systems with (video)communication support. In particular, it shows the necessity
Influence of Packet Loss on Communication during Closely-coupled Collaboration in Serious Games for Rehabilitation

to perform an efficient network bandwidth allocation between different information streams (audio, video, game traffic) taking into account the specificity of target users (i.e. MS patients).

Furthermore, we compared our findings with the results of the experiments performed by Cermak (2005) to see whether or not there is a difference in evaluation between general users and users with special needs. Based on the results of our experiment, we observed that patients were always able to perform the task when the communication was affected. Opposite to the work of Cermak (2005) where the influence of packet loss on teleconferencing system has been evaluated, in our experiment the highly impaired video did not affect the task accomplishment. Patients have not perceived a low level of packet loss (2%) in our experiment as degrading, while in the case of general users, the same level has been indicated as poor. By knowing these differences it is possible to avoid a negative affect on rehabilitation caused by insufficient social interaction due to a low level of network quality.

9.9 Conclusion

In this chapter we have discussed the influence of packet loss on the quality of communication when collaborating. In order to quantify its influence we chose a serious game application for rehabilitation training of people with Multiple Sclerosis. First, we analyzed what the challenges of remote communication for MS patients were and the type of communication they preferred. Afterwards, we impaired communication by varying the level of packet loss in order to discover whether or not patients perceived this degradation. The results of our study have shown that audio was considered as the primary means of sharing information between patient and therapist. Therefore, patients noticed its degrading quality when high level of packet loss was introduced. Players indicate their preference towards communication with video, however the latter was considered as a supporting tool for audio rather than a direct source of information.

Although there are a substantial number of studies evaluating the user perception of network quality in multi-user applications, they solely focus on general users. The main contribution of our work is that such evaluation has been performed within an application for people with special needs, whose weakened abilities may cause totally different perceptions and communication requirements. In particular, from our case study with MS patients, we have learned that it is important to address the quality of audio communication. Video quality on the other hand has been indicated to be not so crucial as the patients did not always pay attention to the images of the remote player. Nevertheless, the presence of video contributed to the patients’ performance and sat-
isfaction while playing, thus, we believe, it has a positive impact on their motivation to continue the training.

So far, we have discussed how to improve collaboration when several users are remotely located. In case of a co-located setting, the high level of collaboration between users is often taken for granted, as the users can see each other and communicate naturally. In the next chapter, we will present our approach to additionally enhance the collaborative player experience in co-located games. For this purpose, we analyze player experience while playing a game on a tabletop surface.
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Chapter 10

Enhancing Co-located Collaboration in Tabletop Games via Game Help

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10.1 Introduction

In the previous chapters we have been discussing some ways how to improve remote collaboration between players in multiplayer games. We have shown that closely-coupled collaboration significantly contributes to the player experience, thus, increasing their satisfaction and the perceived level of collaboration. Due to its nature, a co-located setup is often considered by default ‘more collaborative’. In a co-located setup people can see and perceive each other’s activities naturally. Taking this high level of collaboration for granted results in neglecting the necessity to investigate how the collaborative experience of users can be enhanced in such co-located virtual en-
Environments. Therefore, at the end of this dissertation we wanted to focus on possible solutions to provide even better collaborative experiences in virtual environments.

To explore the ways closely-coupled interaction can be further enhanced, we have chosen an application type which has a very collaborative nature. In particular, we address the issue of improving the collaboration for multiplayer games on interactive surfaces or tabletops. Tabletop technology encourages group interaction around one setup in a way that other computer workstations and video gaming systems do not. Computationally enhanced tables allow face-to-face interaction and multiple simultaneous inputs from a group of users.

Although multi-touch technology already has shown its great potential to facilitate collaborative work, its usage remains often difficult for many people. This complexity is caused by the unfamiliarity of users with the application and the ways how they can interact with it. One of the solutions, commonly used to familiarize users with the tabletop applications, is introducing different forms of help systems to explain possible interactions. Although these help systems are mainly integrated in single-user applications, there are several works utilizing them for collaborative settings. This growing tendency raises the question of the possible contribution of help in a multi-user setting to the collaborative player experience. In this chapter, we attempt to answer this question by performing a user study that compares two commonly used types of help: text and animation.

We start with a brief description of tabletop technology, which is followed by a discussion on the existing multiplayer games for interactive surfaces. Then, we present an overview of the existing help systems used in tabletop applications. Afterwards, the description and findings of our study are presented, where two types of help systems are compared and analyzed from the perspective of their contribution to the collaborative player experience.

10.2 Collaboration Around the Table

The recent introduction of interactive table technology has enabled new types of co-located collaborative computing applications. Tabletops provide space and give access to multiple users, invite them to gather around the table and allow for a playful interaction while keeping the technology at the background. Tables provide a large and natural interface for supporting direct manipulation of visual content for human-to-human interactions. Such surfaces support collaboration, coordination and parallel problem solving (Shen et al., 2006). They provide a convenient physical setting for
10.3 Game Applications for Tabletop

people to examine documents, lay out and navigate maps, sketch design ideas, and carry out tasks that require face-to-face collaboration.

Several benefits of using interactive tables have been defined when compared to the traditional displays:

**Natural input**
As the tabletop serves as both output display and direct input device, it can perceive natural hand gestures for data input and thus support more intuitive manipulation.

**Enhanced collaboration**
A tabletop surface, similar to the traditional ‘around table’ collaboration, allows face-to-face interaction and provides opportunities for building and enhancing co-located collaboration.

**Large work areas**
Tabletop surfaces, especially large displays, have a spacious work area that can positively influence working strategy and group dynamics.

Taking computer technology away from the desktop into a more physical, manipulative space provides many benefits and is generally considered to result in a system that is easier to learn and more natural to use. A substantial number of work has been done in the domain of multi-user tabletop interaction, showing the advantages of this technology for the outcome of group performance. These research initiatives investigate different aspects of user interaction with the multi-touch tables themselves and also between users working together around interactive tables (Wu and Balakrishnan, 2003; Ryall et al., 2006). Numerous applications have been developed for tabletops, including those for planning, design and problem-solving tasks (Figure 10.1). Besides the ‘serious’ purpose to assist collaborative work, tabletops have also actively been used in multiplayer games. We discuss such games separately in the next section.

10.3 **Game Applications for Tabletop**

Playing on an interactive surface resembles the gameplay that is typical for board games, where several people sit around a table. Though often requiring turn-taking, the player that is not currently active remains engaged or even has a role to play (e.g., the ‘banker’ in Monopoly shown in Figure 10.2a). Other examples can be assembling a puzzle together (Figure 10.2b) or constructing models from blocks. These examples
show a shared pattern that the gameplay around a table supports co-located interpersonal play, where players are engaged with both the game and each other. People monitor the game surface, as well as each other’s actions. With the growth of multi-touch technology, these characteristics have been widely applied to the tabletop digital games.

Tse et al. (2007) have claimed that the digital tabletop is an appropriate form factor for co-located gameplay as it lets people easily position themselves in a variety of collaborative postures while giving all players equal and simultaneous opportunities to reach into and interact over the surface. In their studies, the authors have shown...
that allowing people to monitor the digital surface, gesture and speech acts of collaborators, produces an engaging experience for all those involved.

A number of games have been developed for tabletop use to research how users interact with each other while playing and what contributes to their experience. Magerkurth et al. (2004) have proposed STARS, a hardware and software platform to realize computer augmented tabletop games. With its help the authors aimed to unify the strengths of traditional board and computer multiplayer games, by preserving the social situations typical for them. Several games were designed for this platform (e.g. Monopoly, KnightMange) and evaluated, showing a very positive and enjoyable experience of players.

Researchers at Mitsubishi Electric Research Laboratories (MERL) have designed a set of simple multiplayer games for the DiamondTouch table (Esenther and Wittenburg, 2005). DiamondTouch is a touch technology, suitable for electronic tabletops, that affords simultaneous multi-user multi-touch events. It can reliably associate touch events, both multi-finger or multi-handed, with specific users. Figure 10.3a shows the competitive game *Ballpit* in which players drag or flick balls out of the way to be the first to find a striped ball hiding underneath one of them. An example of the collaborative game *SpaceBalls* is shown in Figure 10.3b. In this game, players use either their finger tip or the rectangle created by multiple fingers, to delete colorful 3-D balls that bounce off the sides of the screen. This game involves closely-coupled collaboration by means of the cooperative gestures. In particular, there are a few ‘super’ balls which can only be deleted if two or more players touch it at the same time.
While analyzing the existing work on tabletop game applications, we have encountered numerous studies where multi-touch technology is used to facilitate education and the well-being of its users. The use of gameplay has been shown to be an excellent educational tool, especially if such games are supported by innovative and engaging technologies. Antle et al. (2011) have presented a collaborative learning game on a tabletop called *Futura*, which was presented at a 2010 Winter Olympics Celebration Site. The goal of the game is to work with other players to support a growing population as time passes while minimizing a negative impact on the environment (Figure 10.4). With their game the authors aim to help players improve their understanding of the importance and difficulty of achieving sustainable development, through active participation in a simulated land use activity.

Sluis et al. (2004) have designed a learning application for children between 5 and 7 years old to learn how to read called *Read-It*. The authors have shown that children can benefit from learning to read with the support of an augmented tabletop application. *Read-It* combines the advantages of physical tabletop games and desktop exercises in a multimodal, collaborative and tangible tabletop environment. The game is based on the classical Memory game but it is altered in such a way that players have to complete a turn together. Children are stimulated to help each other to remember the locations of wanted cards and perform certain actions together (e.g. pressing buttons, reaching for the cards together). Different strategies are used in the game to support the learning process – recall, rehearsal and collaboration.

Work by Ardito et al. (2010) presents several games implemented on a large multi-touch screen, designed to support young students learning about historical sites like archaeological parks during school visits. Students are encouraged to collaborate to
solve the proposed challenges, but they can also play against each other, since direct competition is known to be another way to stimulate and reinforce learning. It has been shown that such games make visits to historical sites more effective and exciting.

A substantial number of games have been designed to accommodate different needs of special target groups. In particular, Battiocchi et al. (2009) have presented the Collaborative Puzzle Game developed for fostering collaboration skills between children with Autism Spectrum Disorders. In this game, players are forced to tightly collaborate. For example, puzzle pieces must be touched and dragged simultaneously by the two players as shown in Figure 10.5a. Such enforced collaboration has shown its effectiveness for children in triggering behaviours associated with coordination of tasks and negotiation.

A game for development of social skills, SIDES, has been presented by Piper et al. (2006). SIDES is a tool designed to help adolescents with Asperger’s Syndrome practice effective group work skills using a four-player cooperative computer game that runs on tabletop technology (Figure 10.5b). The obtained findings indicate that cooperative tabletop computer games are a motivating and supportive tool for facilitating effective group work for this target population. The application effectively encourages cooperative decision making and fair participation by group members, aspects of group work that are particularly difficult for adolescents with Asperger’s Syndrome to learn. In their work, the authors also discuss the advantages of this game technology in comparison to traditional therapy.

Cleveringa et al. (2009) have designed a game for the development of social skills for children diagnosed with a ‘pervasive developmental disorder not otherwise specified’. The game teaches children the basic social skills that are needed for working together. In this game pairs of children have to build a rocket together (Figure 10.5c). By solving math problems they can collect parts and an inventory for the rocket. Gradually while proceeding through the levels, the children have to collaborate in order to complete the game.

Although tabletop applications, and in particular games, recently became very popular, there are still problems with their use. Many people remain unfamiliar with this relatively new multi-touch interaction. In order to interact with tabletop applications users have to know a set of available gestures, which may be not always intuitive and straightforward. The necessity to overcome this unfamiliarity of (novice) users has been defined as one of the important goals among researchers in the area of multi-touch technologies. In the next section, we will discuss one of the possible solutions to this problem, namely introducing different forms of help systems within tabletop applications.
(a) The Collaborative Puzzle Game for children with Autism Spectrum Disorders by Battocchi et al. (2009).

(b) SIDES: cooperative game for adolescents with Asperger’s Syndrome (Piper et al., 2006).

(c) Collaborative game for children with a ‘pervasive developmental disorder not otherwise specified’ by Cleveringa et al. (2009).

Figure 10.5: Examples of tabletop games for special target groups.
10.4 Help Systems for Tabletop

Being not familiar with how exactly to use a multi-touch display, users often come to a tabletop to merely try one or two movements/gestures and then leave it without using it for what it was intended. For example, Hornecker (2008) has investigated how people interact with a tabletop in a museum setting without being instructed on how to use it (Figure 10.6). The author has concluded that if a person encounters even minimal troubles or does not see an immediate reward for his/her efforts, he/she often stops using it. The results have shown rather critical remarks from tabletop users, indicating the obscurity of the application purpose and the way to perform a certain action. As a consequence, such a negative experience may lead to a hesitation to use similar technologies in the future.

The findings of Hornecker (2008) clearly state the necessity for tabletop users to experience early success and understand both the purpose of and the interaction with the application. Many researchers have addressed this challenge of designing intuitive and effective user interfaces for multi-touch displays by introducing different forms of help systems into applications. While using these systems, users learn how to interact with the applications. For example, before the actual use a person may need to complete a tutorial during which he/she learns a set of gestures that are required further in the application.

A lot of work has been done with regard to assisting gesture interaction on interactive surfaces (Figure 10.7). One of the main ideas behind such assistance is to introduce available gestures to the users in advance. Otherwise, they might have a hard time figuring out how to achieve a certain application behaviour (e.g. opening a menu).
Many gestures may have no intrinsic meaning, which leads to difficulties in learning gestures, depending on the number of available gestures and their complexity. Novice users may experience additional troubles when deducing what gestures are available to them.

Vanacken et al. (2008a) are among the first to explore different help systems on tabletop. They introduce the idea of using virtual instructors, TouchGhosts, on touch screens: avatars that can demonstrate possible interactions (Figure 10.7a). TouchGhosts are activated while using an interface, providing guidance on the fly and within the context of use. In their approach, the authors define reconfigurable strategies to decide how or when a TouchGhost should be activated (e.g. explicitly by touching the avatar or implicitly by measuring hesitation) and which particular visualization is presented to the user.

Another early help system, OctoPocus, that assists gesture learning, is presented by Bau and Mackay (2008). It is a dynamic guide that combines on-screen feedforward and feedback to help users learn, execute and remember gesture sets. OctoPocus can be applied to a wide range of gestures and helps users progress smoothly from a novice’s to an expert’s performance. It has been compared to conventional help menus, showing a faster and improved learning of arbitrary gestures.

GestureBar (Bragdon et al., 2009) is a user interface for learning gestural interactions that enables a walk-up-and-use experience. It is built similar to the standard menu and toolbar interfaces (Figure 10.7b). Instead of executing commands, it discloses how to execute certain actions with gestures through animated images, detailed tips and an ‘out-of-document’ practice area. The advantage of this system is that users encounter relevant gesture details only when needed, after they have formed a mental goal, searched for, and found an appropriate command. Evaluation of GestureBar has shown users’ ability to perform complex tasks without training, introduction, or prior gesture experience, while discovering and learning a high percentage of the gestures needed to perform the tasks optimally.

Another approach suggested by the same group of researchers (Bragdon et al., 2010) to learn gestures is based on positive reinforcement for motivating the learning of multi-touch gestures. The authors present a Gesture Play system that introduces simple, gamelike elements to make gesture learning fun and enjoyable. In such a way, they believe, users will consider learning gestures as an engaging activity that would result in a quicker transformation from a novice to an expert user. Furthermore, the advantage of Gesture Play over more ‘traditionally’ used video demonstrations has been shown.
10.4 Help Systems for Tabletop

(a) TouchGhosts by Vanacken et al. (2008a).
(b) GestureBar by Bragdon et al. (2009).
(c) ShadowGuides by Freeman et al. (2009).
(d) Gestures preview by Cleveringa et al. (2009).

Figure 10.7: Examples of help systems for tabletop applications.

ShadowGuides presented by Freeman et al. (2009) is yet another example of a system for in-situ learning of multi-touch and whole-hand gestures on interactive surfaces. It provides on-demand assistance to the user by combining visualizations of the user’s current hand posture as interpreted by the system and available postures and completion paths necessary to finish the gesture (Figure 10.7c). By comparing this system to the video-based instructions, the authors have claimed that participants have remembered more gestures and expressed a significantly higher preference for learning with ShadowGuides.

The studies mentioned earlier address the problem of gesture learning from the perspective of a single user. At the same time, the multi-touch displays create opportunities for the collaboration between people, and therefore often involve cooperative gestures (Morris et al., 2006). These gestures are more complex due to the involvement of multiple users performing a certain action. Therefore, introducing the help systems to a collaborative application can improve the learning of cooperative gestures, and thus, improve the group performance. One of such examples is presented
by Cleveringa et al. (2009). They have developed an interface that detects if a user hesitates while drawing a gesture. With this solution the authors aim to improve gesture interaction by providing previews of possible gestures or possibilities to complete gestures (Figure 10.7d), both for single-user gestures and collaborative gestures. They have indicated several requirements for the help systems to introduce gestures to the application, main being (1) user knowledge about the possible gestures; (2) clearness when and how cooperative gestures can be initiated and (3) indication what actions are coupled to gestures that can be performed. To support collaborative interaction, a gesture preview shows a cooperative gesture when a new user touches the tabletop.

The variety of help systems for interaction learning on tabletop on the one hand, and their only partially discovered potential for the collaborative applications on the other hand, have motivated our research. We do not aim to construct a new help system for collaborative gestures, the main goal is to determine how different existing types of help systems can contribute to the collaboration between users, particularly in tabletop games.

10.5 Experiment: Role of Game Help in Collaborative Player Experience

Our previous studies with the desktop collaborative virtual environments have shown that the level of collaboration has positively influenced the overall player experience in games. By introducing closely-coupled collaboration in multiplayer games, we achieved a better perception of collaboration and in such a way increased player satisfaction. Now we would like to see how we can additionally enhance the level of collaboration of the players. In particular, we investigate whether or not a certain type of help triggers a higher level of enjoyment and collaboration between players.

To achieve this goal we designed a simple puzzle game for tabletop that involves close coupling between players. Pairs of participants were asked to play this game without any prior introduction to the interactions needed for success. To introduce the game rules and the way players could interact with an environment, two commonly used types of help systems have been chosen: help based on the textual description and help based on animation. These help systems are referred to as text help and animation help further in this chapter. Text help is considered as a standard way to provide explanations within different applications. It also resembles the way the rules are typically presented in modern games. Animation help generalizes the class of help systems, some being mentioned in Section 10.4 (e.g. work by Vanacken et al. (2008a); Cleveringa et al. (2009)). We did not intend to see which system results in a better
gesture performance, but were more interested in how the presence of such a system affects collaboration. The main question here is to what extent each type of help contributes to the perceived level of collaboration and overall player satisfaction with the game.

This study was done in collaboration with Davy Vanacken, another PhD student in our HCI lab. While the research presented here focuses on the effect of different help systems on the collaborative aspects of interaction, his primary goal was to investigate the help systems themselves (e.g. how they improve user learning of required gestures).

### 10.5.1 Participants

Twenty-eight unpaid volunteers (twenty-five males and three females) participated in the experiment. They were randomly divided in 14 pairs. The average age of participants was 29 years, ranging from 22 to 45 years. All of them had a computer science background and were recruited among university staff and students. Most participants indicated a very limited experience with a tabletop and 6 participants had no experience with it at all. All except two participants had previous experience with multiplayer games. According to self evaluation, the average player experience with any type of multiplayer games was 2.9 on a scale from 1 (never played) to 5 (playing/played almost every day).

### 10.5.2 Apparatus

During the experiment two players were standing next to each other at the same side of the tabletop as shown in Figure 10.8. We used a custom-built tabletop, based on Frustrated Total Internal Reflection (FTIR) (Han, 2005). The tabletop has a 50-inch (127 centimeters) multi-touch surface, providing a 1920x1080 resolution. The setup can handle an arbitrary amount of concurrent touch points. The recognition software of the tabletop, FTIRCap, handles the calibration, analyzes the input and sends the detected touch points to client applications using the TUIO protocol (Kaltenbrunner et al., 2005) at a frequency of 60 Hz, for fluent interaction.

### 10.5.3 Design

During the experiment, a between-subject design was used. The independent variable was the help type with two conditions: text and animation. Participants, in pairs, performed one session for which the condition was randomly assigned. The following
dependent variables were logged during the performance or extracted from the videos recorded during the experiment:

- task completion time;
- amount of time players performed individually;
- amount of time players performed collaboratively;
- amount of time players spent watching animations together;
- amount of time players spent reading text together;
- amount of time players communicated;
- when players communicated for the first time;
- when players collaborated for the first time.

A subjective evaluation of each condition was collected through a post-experiment questionnaire\(^1\) (see Figure C.5 in Appendix C).

\(^1\) for the study presented in this chapter, the first half of the questionnaire was used (questions 1 – 10); the second half was used for the research of Davy Vanacken
10.5 Experiment: Role of Game Help in Collaborative Player Experience

10.5.4 Procedure

During the experiment fourteen pairs of participants were asked to complete a 3D puzzle game. The puzzle task consists of assembling a picture from 12 pieces that are dispersed on the surface of a virtual table (Figure 10.9). Puzzle pieces are represented as cubes, with the picture on one face. There are two types of cubes in the environment: light and heavy. To indicate this difference to the users, blocks have a different texture on their sides (except for the face with a picture representing a part of the puzzle). A sky texture is used for the light cubes, while a brick texture represents the heavy ones. Additionally, besides the normal light blocks, there are 6 little special cubes, that must be enlarged prior to their placement in the puzzle.

Figure 10.9: Collaborative puzzle game.

Due to the fact that the tabletop, used during the experiment, does not distinguish touch points from different users, we had to define the player generating the input within the application itself. To do that, we have introduced two avatars, through which users can manipulate the virtual objects, while we can track the actions of each player individually. In the game, users interact with the objects in the environment through circle-like avatars, each being assigned a different color. In order to manipulate an object, users first have to select it with the help of the avatar. To select a block, the player needs to drag his/her avatar towards it and, when they collide, it is necessary to tap the avatar twice in quick succession. Similarly, a double tap is required to deselect an object. Visual feedback is provided to indicate whether or not the user is touching the interactive surface. Every touch point is shown as a green dot on the tabletop. A bounding box is used to indicate successful object selection. The color of the bounding box corresponds to the color of the avatar who selected the object.
Once the object is selected, players can manipulate it. While the light cubes are manipulated individually by players, manipulation of heavy ones is possible in two ways, either individually or collaboratively. If one person tries to move or rotate a heavy cube, the speed of the performed actions remains very slow. However, when the object is selected by two players, the same actions happen at a faster speed. Similarly to a single player selection, when the object is selected by two players a visual feedback is provided by means of the colored bounding box. But in this case, the object is highlighted with a green color, which does not correspond to any of the avatars.

Players can perform three types of actions with the blocks: movement, rotation (2D and 3D) and enlargement.

**Movement**

Before the block can be moved it is necessary to lift it off the ground. This is achieved by pressing the avatar with one finger. While pressing the avatar, the user drags the block around with the other finger (Figure 10.10a).

**Rotation**

Similarly to movement, a block first has to be lifted off the ground to be rotated. Two types of rotation are available: 2D and 3D. To rotate in 2D, the user has to put two fingers on the block and move one of them, while pressing the avatar with the third finger (Figure 10.10a). To rotate in 3D, four fingers are involved: one to lift an object and three for the actual rotation. Two fingers are located on the block, to define the rotation axis, and then spin the block around this axis by moving over it with the third finger (Figure 10.10b).

**Enlargement**

By enlargement we mean making one cube of a normal size from two little ones, therefore fitting the puzzle: one with a puzzle picture fragment and the other with a special texture (blue plus sign over a sky background). Both users have to bring these two blocks close to each other (Figure 10.10c). While both blocks are selected, players have to simultaneously press the two confirmation buttons (round button with a tick) located at the top of the screen. As the result of the enlargement two blocks are transformed into one heavy cube.

In the experiment, participants were not instructed about the application in advance. They had to discover the application functionalities themselves by using the help system of the game, which explains the ways in which objects are manipulated. Two types of help systems were used during the experiment: text and animation, which were randomly assigned to the pairs of participants. This resulted in half of the participants playing the game with text help, while the other half experienced help in the
10.5 Experiment: Role of Game Help in Collaborative Player Experience

(a) Movement of the block by the player on the left (orange) and 2D rotation of the block by the player on the right (purple).

(b) 3D rotation of the heavy object performed by two players.

(c) Enlargement.

Figure 10.10: Types of object manipulation supported in the puzzle game.
form of animation. When the game starts, help opens automatically. Each player had an individual screen where the rules were shown. Help systems, both text and animation, were individualized for each player, containing representations of avatars of corresponding colors.

In the case of the text help, the complete set of rules is shown to the players (Figure 10.11a). The text consists of information regarding all possible manipulations. In such a way it resembles the representation of rules as in most modern games, where the complete description of rules is presented at once and can be accessed at any moment during the game.

In the case of animation, help is provided gradually on a step by step basis. Each animation presents the way the objects are manipulated by showing (the) finger(s)
that need(s) to actually perform each action. As it is not always possible to explain all the nuances of object manipulation by just showing the animation, a minimal amount of text tags is inserted. Once the game has started, the animation on how to select an object is played (Figure 10.11b). After the object is selected, the next animation explaining movement is shown. It is followed by the animation of 2D and 3D rotations. If a player selects one of the small blocks, the animation of enlargement is shown. If the heavy object remains selected for a while by one player he/she gets a reminder that indicates that this block can be manipulated faster together with a partner.

Help can be activated any time during the game by clicking a question mark button located in the upper corners of the screen (a separate button for each player). Players are allowed to manipulate objects while the help is open. In games with text, the whole set of rules is shown when the help is requested. In games with animation, players get a menu consisting of several buttons – one for each type of manipulation (Figure 10.12). The amount of buttons depends upon the current status of the avatar of the player who activates the help. If a player has not yet selected an object, he/she would see only the Select button (player on the left in Figure 10.12). If the object is already selected, the buttons Deselect, Move and Rotate are shown on the screen. Additionally, a player will see the Enlarge button, if he/she selects one of the little blocks (player on the right in Figure 10.12).

The game continues until all the blocks are correctly placed. In Figure 10.13, an almost assembled puzzle is shown. Players were not limited in communication and could talk at any moment during the experiment. After completing the game, either with the text or animation help, players were asked to evaluate their perceived experience through a post-experiment questionnaire (see Figure C.5 in Appendix C). In particular, we asked them to quantify different aspects of collaboration with the game.
partner (e.g. amount of collaborative and individual contribution to the task, per-
ceived level of collaboration, etc.). For evaluation purposes, a visual analogue scale
(VAS) was used. The participants marked on the 10 cm line the point that they felt
represented their perception of the current state from not at all to very much. It took
approximately 30 minutes for each pair to complete the puzzle task. During the whole
experiment players’ actions and communication were recorded for the analysis.

10.5.5 Hypotheses

To investigate the benefits and drawbacks of the two help systems (text and anima-
tions) and to study their influence on collaborative player experience in the tabletop
puzzle game, we set up this experiment. We did not have expectations in favor of a
particular type of help used in the experiment. However, we did expect that one of
them provides a better collaborative experience to the players. Therefore, we formu-
lated the following hypotheses in a neutral way, without expressing preference towards
animation or text:

H1: the perceived amount of collaboration between players (collected through the
questionnaire) differs between text and animation help;

H2: the amount of time spent on individual performance differs between text and
animation help;

H3: the total amount of time spent on collaborative performance\(^2\) differs between
text and animation help;

\(^2\)includes both logs and observations
H4: the amount of time spent using a certain type of help together differs between text and animation help;

H5: the amount of time spent on communication differs between text and animation help.

10.6 Results

The main goal of our study was to investigate how different types of help can contribute to the level of player collaboration during a gaming experience. As a case study we have chosen a puzzle game for a tabletop setup. Similarly to the previous studies (see Chapters 4 and 5), this type of task has been used because it requires a lot of highly detailed interaction. However, this time we have integrated closely-coupled collaboration into the puzzle, in particular, to manipulate heavy objects and to enlarge little blocks. For our study we chose two types of help commonly used in existing tabletop applications: text and animation.

In this section we provide the analysis of text and animation help in the puzzle game for tabletop setups. The findings presented here are based on the subjective evaluation provided by players through the questionnaire, performance logs, analysis of video recorded during the experiment and conversational analysis (extracted from the video recording).

10.6.1 Subjective evaluation

First of all, we have analyzed the player’s subjective perception of collaboration. We asked players to evaluate their level of collaboration, individual and collaborative contribution and whether or not the provided help type contributed to the level of collaboration. The performed independent samples t-test has shown that participants rated two help systems almost equally with respect to their impact on collaboration, as no significant difference was found. This rejects hypothesis H1. As can be seen from Figure 10.14, text and animation were evaluated very similarly, both contributing a lot to the level of collaboration between players. At the same time, the level of individual performance has been indicated as low. Further analysis using paired samples t-test revealed that using both help systems players performed significantly more collaboratively than individually (t(13) = −4.56, p = 0.001 for text; t(13) = −3.72, p = 0.003 for animation). Values on the graph represent players’ answers to the following questions (from the questionnaire shown in Figure C.5 in Appendix C):
Q3: I contributed a lot individually.

Q4: I experienced a high level of collaboration.

Q5: Everyone contributed equally to solving the task.

Q6: When a certain task could be performed both collaboratively and individually (e.g. the manipulation of heavy blocks), it was mostly accomplished together with my partner.

Q7: The provided help contributed to the level of collaboration.

Q8: It was clear when it was necessary to collaborate.

Q9: I was always aware of my partner’s actions.

Q10: We had problems when performing collaborative tasks.

10.6.2 Analysis of game logs

We also analyzed the game logs in order to find out whether there was any difference between the subjective player evaluation and the actual performance. During the experiment we logged the amount of time players were collaborating and also the amount of collaborative actions. We determined the collaborative actions as those when objects were selected by two players simultaneously (Figure 10.15). As the

Figure 10.14: Player subjective evaluation of text and animation help.
10.6 Results

Length of sessions varied from pair to pair, we did not compare the collaboration time directly. Instead, we calculated the percentage of time that each pair collaborated (as a ratio between collaborative time and the task completion time). The obtained results have shown that during the game with animation, the amount of collaboration (both in terms of time and number of collaborative actions) was higher (Figure 10.16). However, the performed independent samples t-test has shown that this difference was not significant.

Figure 10.15: Two players manipulate heavy object together.

Figure 10.16: Analysis of game logs.

10.6.3 Video and conversation analysis

While observing players during the experiment, we have noticed that collaboration was not only limited to the actual performance of the task together. In reality, the
players collaborated also by watching an animation or reading a text together and explaining or showing each other how to perform a certain action. Moreover, during the experiment, participants communicated a lot with each other about various (not always task related) topics, which is also considered as a form of collaboration. Figure 10.17 shows several examples of the collaborative performance that occurred while solving the puzzle.
With this in mind, we performed an analysis of the video recorded during the experiment. Directly from the video, we captured the following data:

- time during which players performed individually;
- time during which players collaborated;
- time during which players read text or watched animation together;
- the time of the first moment players collaborated;
- the total amount of time players communicated;
- the time of the first moment players communicated.

Table 10.1 summarizes the results regarding individual and collaborative performance, as well as communication, obtained from the videos for both text and animation help.

**Table 10.1: Comparison of collaborative performance and communication for text and animation help in tabletop puzzle game.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Text</th>
<th>Animation</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
<td>M</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual performance, %</td>
<td>31.44</td>
<td>13.81</td>
<td>16.93</td>
</tr>
<tr>
<td>Collaborative performance, %</td>
<td>29.03</td>
<td>9.24</td>
<td>41.06</td>
</tr>
<tr>
<td>Using help together, %</td>
<td>1.76</td>
<td>1.34</td>
<td>5.02</td>
</tr>
<tr>
<td>Time of the first collaboration, %</td>
<td>37.72</td>
<td>16.54</td>
<td>19.11</td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of communication, %</td>
<td>32.60</td>
<td>13.26</td>
<td>37.29</td>
</tr>
<tr>
<td>Time of the first communication, %</td>
<td>5.69</td>
<td>2.72</td>
<td>1.21</td>
</tr>
</tbody>
</table>
To calculate the time players performed individually, we considered those moments when both players were focused on different things and did not communicate with each other. Figure 10.18a demonstrates an example of such individual performance where one player is reading the explanation while his partner moves the object. Another example of individual object manipulation is presented in Figure 10.18b, where two players manipulate objects individually. Similar, to the log analysis, we did not compare the completion time directly, but for each pair calculated the percentage of individual time during the session. This percentage was calculated as the time players performed individually divided by the total task completion time. Independent samples t-test has shown that in case of text help, players have performed individually significantly more than during the games with animation. This confirms hypothesis H2.

In the next step we compared the amount of collaboration under the two conditions. From the videos we captured the time during which players collaborated in all possible forms. This included communication between two players, watching or reading help together, showing/explaining to the other player and watching the other player’s actions. To these results we added the time players actually performed shared actions together (e.g. manipulation of heavy blocks or enlargement of the little blocks), logged during the experiment. Here, we also calculated the percentage of time separately for sessions with text and animation help. A statistical analysis has shown a significant difference across these two conditions, showing that players collaborated more during the games with animation and confirming hypothesis H3.

Once this difference between the amount of individual and collaborative performance was established, we aimed to find out what actually caused it. As we found from the log analysis, the actual performance of closely-coupled tasks (e.g. manipulation of heavy objects) did not differ significantly between games with text help and games with animation help. This implies that there is no direct impact of the actual performance (obtained from the logs) on the difference found for the total amount of collaboration.

One of the possible reasons may lie in the difference between the two provided help systems. Therefore, we have analyzed separately the amount of time players have watched animation or read the text together. Earlier, we have found that there was no difference between these two systems in their contribution to the level of collaboration between players based on their subjective perception. Now we aim to see if such a difference exists objectively. In case it does exist, this would explain the significant difference in the amount of collaboration between the two systems. The independent samples t-test has shown a significant difference, indicating a higher contribution of
10.6 Results

(a) One player reads text help and the other player moves the object.

(b) Both players manipulate objects independently from each other.

Figure 10.18: Examples of individual performance during the puzzle game.

animation towards the overall amount of collaboration between players. *This confirms hypothesis H4.*

Additionally we wanted to see whether there is any difference between the two conditions from the perspective of *beginning of collaboration* and if it has any negative impact on the perceived player experience. Due to the chosen approach to gradually provide players with the new animations regarding possible actions in comparison with reading the whole text, we expected that in the case of animation they would
also start to collaborate earlier. We observed that not all pairs read the whole text but
started collaborating while reading, this assumption has been confirmed statistically.
We have found a significant difference, indicating that \textit{players started collaboration much earlier in games with animation than in the case of text}. As a next step, we
wanted to determine whether or not player experience (subjective) is affected by the
fact that collaboration starts earlier or later. In fact, we found a significant negative
correlation ($R = -0.55, p = 0.043$), that implies that \textit{the later collaboration between
players starts, the lower is the perceived level of collaboration}.

Finally we analyzed the \textit{intensity of conversation} between players. We measured the
time each pair communicated during the experiment. We have found a higher amount
of communication when the games with animation were played. Although in this case
communication started much earlier, the difference in its quantity was not significant
when compared to the games with the text, \textit{rejecting hypothesis H5}.

\section*{10.7 Conclusion}

In this chapter, we have investigated how an already high level of collaboration, present
during a co-located collaboration, can be additionally improved. In particular, we have
studied the user’s collaborative experience when playing together on an interactive
surface. The contribution of our work lies in the utilization of different help systems
in order to improve the player experience, and more specifically to the level of col-
laboration between players besides their ‘traditional’ function of explaining available
gestures to the tabletop users.

Our findings provide indications regarding the use of help systems in order to enhance
 collaboration in games that are based on close coupling. During the experiment we
have compared two commonly used types of help, text and animation, within a simple
puzzle game that involves close-coupled collaboration between players. Our results
have shown that the participants found both games (one with text help, and the other
with animation help) very collaborative. Both types of help systems contributed al-
most equally to the perceived level of collaboration. However, analysis of the actual
performance revealed that the amount of collaboration differs between these two con-
ditions. For the game used in our experiment, we have observed a higher contribution
of animation help to the collaborative player experience, although players have not
perceived this difference.

We realize that there is no unique help system that can facilitate all types of applica-
tions and contribute equally high to the user experience. Certain types of help might
work better in comparison to others, depending on the purpose of the application and
the required interactions. Nevertheless, we believe that the results obtained from our experiment are applicable in a range of applications where similar types of interactions are involved.
Conclusions and Future Research Directions

11.1 Conclusions

This dissertation investigates several ways to enhance collaboration in a virtual environment by studying simultaneous interaction. In this final chapter, we formulate conclusions regarding the research presented earlier by discussing the findings. We then proceed with a discussion of possible future directions for follow-up research.

The research focus in this dissertation is twofold. Firstly, it consists of a thorough investigation of factors that might contribute to a better user experience in collaborative virtual environments in general. This includes making the performance efficient and enjoyable, while providing a high level of collaboration. This is followed by an investigation on how to achieve a better collaborative experience in multiplayer video games. Our research approach consisted of a number of formal experiments and user studies. By doing so, we attempted to determine the factors that make interaction between users in virtual environments more satisfactory and natural, resembling real life collaboration.

To achieve this overall goal, we formulated seven research questions in the beginning of this dissertation. In this chapter we provide a summary of our findings and contributions with respect to each research question. The contributions are divided in two parts. While the earlier Chapters 3 – 5 focus on collaboration in virtual environments in general (RQ1 – RQ4), Chapters 6 – 10 deal with the integration and support of realistic collaboration in a specific domain, multiplayer games (RQ5 – RQ7).
RQ1 How can the introduction of different levels of collaboration improve the user experience in collaborative virtual environments?

Many researchers are trying to make virtual worlds seem as realistic as possible. However, this realism is often based on powerful graphics and immersive settings that truly can place a person into a virtual environment. Realistic interaction within these environments, and especially collaboration with other immersed users, is not widely supported in most applications. By answering this first research question we look into one possible solution to overcome this limitation of existing CVEs. To achieve more realistic collaboration between people, we suggest to introduce different levels of collaborative work in virtual environments that are similar to those we encounter in our everyday life.

We integrated two levels of collaboration into a virtual environment: loosely-coupled and closely-coupled. Though both levels are equally common in real-life collaboration, in virtual environments they are not represented in the same quantity. In particular, we were interested in the applicability of closely-coupled collaboration in CVEs as the one that is not yet widely utilized in the existing applications due to its more complex nature. At the same time, it is this type of collaboration that forces people to interact with each other, coordinate and synchronize their activities, and, thus, collaborate more.

By conducting a user experiment presented in Chapter 3, we compared these two levels of collaboration and studied the effect of applying closely-coupled collaboration in virtual environments. Our findings indicated the potential of this level of collaboration, providing both a higher level of collaboration and engagement. During the experiment, the users showed their preference towards closely-coupled collaboration as the one that allowed more realistic and engaging performance, with a higher level of collaboration than loose coupling. The experimental results confirmed our expectations towards a better user experience when performing closely-coupled tasks, allowing for a more common way of collaboration and providing a real team work experience. These results indicate the usage of closely-coupled collaboration in virtual environments as a prospective solution to add more realism to collaborative interaction between users, resembling performance of group tasks in a real environment.

RQ2 How do the different technologies, used by people working together in a virtual environment, influence their experience?

When interacting in a collaborative virtual environment, a user might be using a different technology than other members of the team. Such heterogeneity may have both
11.1 Conclusions

a positive and negative impact. On the one hand, the combination of diverse technologies used by the collaborators, provide a wide spectrum of possibilities to optimize the outcome of group performance. On the other hand, these differences make collaboration unbalanced and may result in unequal contribution of people involved in the task performance. Knowing how the combinations of different technologies influence virtual activities, makes it possible to strengthen their positive and avoid their negative impacts on the collaborative user experience.

We approached our second research question by studying the impact of heterogeneity of input devices. Motivation, description and results of the formal experiment were presented in Chapter 4. One of the main findings obtained during the experiment was the absence of an interaction effect of the devices that can be combined in the CVE. This result indicated that the combination of different devices did not significantly influence the collaboration when performing the given task. With this in mind, we can conclude that for similar tasks it is not necessary to impose a certain device and in such a way to limit possible combinations. In our experiment, we did not achieve more efficient performance by introducing a heterogeneous setup of input devices, but we did achieve a better collaborative user experience. In fact, the presence of the heterogeneous setup contributed more to the feeling of collaboration perceived by the participants. These results indicate the positive impact of a heterogeneous setup on the collaborative user experience in CVE. However, to increase the efficiency of such collaboration a solution is needed to allocate different activities among users according to their devices and abilities.

RQ3 How does the support for communication between people working together in a virtual environment influence their experience?

When people work together in a real environment, they often need to negotiate task related content, such as task structure, roles, activities and task/sub-task allocations. The same necessity is most likely to appear when collaboration takes place in a virtual environment. However, support of rich communication typical for real-life collaboration in virtual environments is not a trivial task. There can be situations where it is not desirable or possible to provide communication between several people involved in a shared task.

In the same experiment presented in Chapter 4, and mentioned for the previous research question, we studied to what extent the user collaborative experience changed when team members could or could not communicate. One of the important findings was the influence of communication on the efficiency of collaboration: inclusion of communication resulted in a longer task completion time. At the same time, the presence of communication contributed to the different aspects of the user experience,
with a higher level of collaboration being one of them. *These results indicate that the ability to communicate contributes to the collaborative user experience, namely it increases the perceived level of collaboration between users. However, if the primary goal of the task is to complete it quickly, inclusion of communication may worsen the results.*

**RQ4 How to accommodate the user diversity in a virtual environment in order to enhance the outcome of the group performance?**

Collaboration in virtual environments often involves people with different backgrounds, experiences and characteristics. Some people can be more experienced, be able to learn quicker than others or have different preferences. Being aware of the diversity of users collaborating together in a shared virtual environment and its possible impact on the group performance, we have explored how collaboration can be improved through adaptation based on a user context.

In Chapter 5, we described an approach to adapt users’ roles by modeling the group behaviour when performing a highly-interactive task in a virtual environment. We proposed four different approaches to model group behaviour based on the goal of the collaboration: *minimum total time, exclusion of worst individual performance, minimum performance gap, maximum preference*. As a result of such adaptation, every collaborator obtained the most suitable role. By providing this role division we achieved a better group performance. *These results indicate that applying adaptation in collaborative virtual environments helps to prevent the negative effect caused by the user diversity and, thus, enhances the outcome of collaboration.*

In Part 2 of this dissertation we wanted to apply the general knowledge obtained in Part 1 into a specific domain, namely video games. We chose this type of multi-user virtual environments as the one that widely utilizes collaboration between users as a motivational factor. Therefore, integration of different forms of collaborative activities that provide realistic and engaging gameplay is considered beneficial for the video games.

**RQ5 To what extent are findings from RQ1, regarding levels of collaboration, applicable in a specific domain, namely multiplayer games?**

Seeing the potential of closely-coupled collaboration for more general tasks in a virtual environment, we wanted to analyze whether or not it contributes to the player experience in games. The results of the experiment investigating two levels of collaboration presented in Chapter 3, have shown a user preference towards closely-coupled
collaboration as the one that provided a more realistic interaction between users and supported a higher level of collaboration. However, in order to be able to draw conclusions about the contribution of closely-coupled collaboration in games, we conducted a separate study where we compared loosely- and closely-coupled collaboration based on the cooperative game patterns.

One of the differences between collaboration in games and in general virtual environments is the ability to communicate. Although we have found the important impact of communication on the collaborative user experience, communication in games may be not desirable, limited or even impossible. Therefore, for the experiment presented in Chapters 6 and 7, we studied the influence of closely-coupled collaboration in multiplayer games without communication. We observed that players still preferred closely-coupled collaboration, even if they could not communicate. This type of collaboration has shown a lower efficiency, but did not affect player enjoyment, which is a very important factor in games. Although the lack of communication had a certain negative impact on player enjoyment and performance, its absence was not crucial, making games with closely-coupled interaction playable even without communication. Irrespective of the presence of communication, close coupling provided players with a higher level of collaboration, making them play as a real team. These results indicate the applicability of closely-coupled collaboration in multiplayer games. Even if there is no communication, players preferred this level of collaboration as a step towards realistic teamplay.

RQ6 How does the network quality affect multiplayer video games based on the closely-coupled collaboration?

Together with numerous advantages, closely-coupled collaboration brings a lot of challenges when designing collaborative games. The quality of the network is one of the main challenges. Games incorporating closely-coupled collaboration, that requires a lot of coordination and synchronized activities, are the type of application where presence of network delay, jitter and packet loss can hinder user interaction and decrease the player experience. Being aware of the possible negative impact of network impairments and the related level of user tolerance may help game developers to reduce the sensitivity of games based on close coupling by masking the possible impacts of these impairments.

The influence of these impairments on player experience in multiplayer games was addressed in Chapters 8 and 9. First we studied the impact of network delay and jitter when closely collaborating. By studying collaboration in one of the recent commercial games, Little big Planet 2, we established the boundaries of the network impairments above which the user experience starts to decrease. In particular, we established
that in the game used during the experiment users perceived their experience as degraded when one-way delay values exceeded 100 ms. At the same time, jitter had a negative impact on the user performance though players did not perceive this impairment as degrading.

As the next step, we studied the influence of packet loss. This type of impairment affects, first of all, multimedia communication. Therefore, taking the importance of communication (RQ3) into account, we wanted to see how it is affected when the network is impaired. We carried out an experiment for which a closely-coupled serious game for rehabilitation of people with Multiple Sclerosis was chosen. Motivation behind this choice and the experiment were presented in Chapter 9. During the experiment we analyzed how different types of communication (audio and audio with video) were affected by the packet loss, and how this degradation was perceived by the users within the application that involves a high level of communication (not necessarily related to the task). The results of our study showed that due to the specificity of our target group, degrading video quality was not always perceived by the players. At the same time, audio was considered as the main channel of sharing information. Therefore, its degrading quality was noticed when a high level of packet loss was introduced. These results indicate that closely-coupled games are sensitive to the quality of the network. Although not always perceived by players, the network impairments, and more specifically delay, jitter and packet loss, influence their performance.

**RQ7** How can co-located collaboration be enhanced in multiplayer games?

While all research discussed so far addressed collaboration between people located remotely, in the end of this dissertation we aimed to study how to improve the user experience in a co-located collaboration. The high level of collaboration in a co-located setting is often taken for granted, as people see each other and communicate naturally. However, as we showed in Chapter 10, it is still possible to provide even better collaborative experiences in virtual environments in a co-located setting.

In particular, we proposed a solution to use help systems as an additional component contributing to a higher level of collaboration. Generally speaking, before playing a game or using a certain application, users first get familiar with the rules and the ways they can use these applications using a certain form of help. In our work, we studied such help systems to define their added value towards a better collaborative experience. As a particular example of an application, we chose a tabletop game. Due to the high amount of possible gestures available on tabletop applications, it has become quite common to introduce some forms of help that can teach the user all necessary gestures before actually interacting. By comparing two commonly used types of help
systems for tabletop, namely text and animation, we showed that they contributed differently to the amount of collaboration occurring between players. Although the perceived level of collaboration was almost equal, the amount of actual collaboration differed between these two conditions. We discovered that involving animation based help resulted in more time spent performing certain actions together. This result indicates the potential to use different forms of rules representation to players to additionally enhance the collaborative experience in a co-located setting.

**Final Considerations**

In this dissertation, we have studied collaboration between people that are working and playing together in virtual environments. Collaborative virtual environments, although promising a lot of benefits to their users, are still more challenging when compared to single-user virtual environments. In this dissertation, we tried to address some of these challenges, targeting the overall goal of natural, realistic and satisfying collaboration between people in virtual environments. However, achieving a high level of realism and user satisfaction is a complex task that is hard to address as a whole. There is probably an infinite number of factors that may influence (both positively and negatively) collaborative user experience, depending on the conditions of collaboration, types of group activities and users themselves. Therefore to address this overall goal, we have divided it into a number of more concrete research questions. Each of these questions represents a certain factor (or combination of several), affecting shared work in virtual environments, that has been thoroughly studied. Realizing the large number of possible factors, in this dissertation, we addressed only a few of those factors that we believe are among the most relevant to the research in the area of collaborative virtual environments.

In order to study and evaluate the impact of the selected factors we carried out a number of user experiments. These experiments allowed us to make initial conclusions regarding what exactly contributed to an increased users’ performance, level of collaboration and the overall satisfaction from such collaboration. By answering these research questions we have proposed several possible solutions to achieve a better collaborative user experience. Although modern technology does not stand still but advances with rapid strides, we believe that the lessons learned during this research are not only important for modern collaborative virtual environments but also applicable for the next generation virtual worlds.

Although we have covered only a small part of the possible solutions, we hope that the research performed in the context of this dissertation will facilitate designers of CVE applications. By studying collaboration between users, we have shown several
important implications with regard to providing natural collaboration. We believe that applying these findings will lead to the design of better collaborative virtual environments and as a result to more satisfied users.

11.2 Future Research Directions

A large amount of applications built on top of collaborative virtual environments are appearing nowadays, indicating the growing interest in this technology within the community. In this dissertation, we have covered only a small part of the possibly interesting research in the domain of collaborative virtual environments, related to satisfying and natural collaboration between users. Below we outline some directions for future research.

During our experiments, users indicated a high preference for the ability to collaborate in a closely-coupled manner in virtual environments, being similar to real life collaboration. In our research, we have studied loosely-coupled and closely-coupled levels of collaboration separately, and defined the benefits and drawbacks of each by comparing them. In real life, most collaborative tasks support a smooth transition between loosely-coupled and closely-coupled activities. For example, during the meetings people tend to switch from a group discussion to individual work on their computers or documents (e.g. entering the date of the next gathering, that has been just discussed in the group, in the personal agenda). Therefore, further research might be directed to achieve a more natural collaboration by looking into the solutions that make such a transition smooth in virtual environments.

When introducing closely-coupled collaboration, we considered only collaborative manipulation of the objects in virtual environments. Manipulation is one of the most fundamental tasks for both physical and virtual environments. Besides manipulation, it may be interesting to investigate how closely-coupled collaboration can be achieved for other tasks such as selection and navigation. In case of collaborative selection, it is necessary to come up with collaborative selection techniques that improve the collaborative user experience when selecting and manipulating virtual objects. Furthermore, one can think about efficient collaborative navigation techniques that resemble group navigation in real life.

In Chapter 4, we have studied how interaction is affected when users are accessing the virtual environment using different technologies. For the experiment, we involved a combination of input devices mainly used in research labs, due to their high cost. However, many cheaper 3D devices are available on the market, that are more likely to be used in a home setting. Studying the combination of these devices may reveal
additional factors that contribute to the user experience. Moreover, combinations of
different input and output devices together may have another impact on the user ex-
perience and should therefore be further investigated.

In Chapter 5, we have proposed a solution on how to accommodate user diversity by
providing adaptation according to the context of users. In our study, we suggested
several approaches to model group behaviour to provide users with the most suitable
roles. The best suitable role for every user was estimated after the actual performance
(offline). Further research may be directed to provide such adaptation at runtime (on-
line). In such a way, all information related to the user performance has to be analyzed
immediately and applied within the application, automatically providing users with a
better condition. At the same time, applying run-time adaptation raises another issue
related to the user awareness. It is important to indicate in a non-obstructive way what
changes took place after the adaptation. Solutions are required that support a smooth
transition between the current role and the one assigned based on the adaptation (es-
pecially, if the adaptation is applied constantly throughout the task performance).

Throughout this dissertation, we have investigated enhancement of group collabora-
tion in virtual environments involving a small amount of people (two or three users).
As the nature of collaborative virtual environments is to accommodate multiple users,
we find it challenging to investigate to what extent our solutions for enhanced collabora-
tion are applicable in a large scale virtual environment (e.g. massive online games).
A high level of consistency needs to be supported in the environment to maintain a nat-
ural interaction. It is clear that, for a limited amount of users, it is possible to achieve
consistency without a major performance impact, because only a limited amount of
data needs to be distributed. In case of hundreds or thousands of simultaneous users
however, an appropriate network architecture should be conceived to achieve the re-
quired efficiency to support detailed interactions. For any multi-user environment,
it is important that every participant, connected through the network, sees the same
objects and is presented with the same world representation at any particular moment.
However, introducing closely-coupled collaboration increases the complexity of this
requirement due to the necessity to constantly synchronize and coordinate the shared
activities.

With an increasing number of users in a virtual environment it is also important to
know what facilitates effective work of virtual teams. Many organizations involve ge-
ographically distributed knowledge workers to collaborate on a variety of tasks. One
of the open questions here is how to achieve efficient collaboration and obtain results
similar to the face-to-face performance. A lot of virtual teams work in asynchronous
manner, rarely engaging in real-time collaboration. Therefore, further research can
be focused on the solutions for the effective combination of synchronous and asynchronous collaboration to achieve better results of the group performance.

In the second part of this dissertation, we focused on the ways to improve the collaborative user experience in multiplayer games. For our research we have mainly used casual games (existing and custom developed), however, other game genres may also benefit from providing a higher level of realism when collaborating with other players.

In our research, we investigated the ways to improve a collaborative user experience and to increase the realism of collaboration as a motivational factor to play games. Besides games, collaborative virtual environments have become the basis for many other application types. Therefore, we believe that the results obtained during this research are valuable in other application domains, that require interaction of multiple people. We hope that the obtained results can be considered as a preliminary step contributing to the development of collaborative systems for teleoperation, assembly and design tasks, e-learning, e-medicine, etc. More and more applications from these domains are built on top of virtual environments, often requiring realistic interaction not only with the environment itself but also with other people present in it. In such applications, realistic interaction between users can be important in order to achieve the required accuracy and efficiency of the virtual collaboration (e.g. training environments and simulations) or serve as a motivational factor (e.g. virtual learning environments and applications for rehabilitation). Therefore, the lessons learned from the conducted experiments, we believe, may serve as the preliminary guidelines for the researchers in other domains, and be further developed in accordance to the specificity of each application domain separately.

11.3 Scientific Contributions and Publications

The results presented in this dissertation were collected during four years of research. During this period, several scientific articles and contributions in proceedings were published, reflecting different parts of the research presented in this dissertation.

- We analyzed different levels of collaboration in virtual environments. By comparing loosely-coupled and closely-coupled collaboration, we presented the benefits and drawbacks of each level (Chapter 3).

11.3 Scientific Contributions and Publications

- We investigated the influence of the combination of different interaction devices on the outcome of a group performance. Here, we also studied the role of communication on the task performance and the level of collaboration between the users (Chapter 4).


- We investigated how to accommodate the diversity of users working together in a virtual environment by providing adaptation according to their context (Chapter 5).


- We integrated and compared different levels of collaboration in multiplayer games. We showed the high potential of closely-coupled collaboration for games in general (Chapter 6), and also in a specific game genre – casual games (Chapter 7)


Conclusions and Future Research Directions

We analyzed the influence of the network quality on the collaborative games involving a lot of closely-coupled collaboration. We studied the impact of network delay and jitter on player performance (Chapter 8). We also investigated how packet loss affects communication when playing together based on the example of the serious game for rehabilitation (Chapter 9).


Appendices
Samenwerking tussen mensen is een essentieel onderdeel van onze samenleving. Door het toenemend gebruik van computertechnologie in de laatste decennia is het mogelijk geworden om niet enkel menselijke maar ook virtuele coöperatie te faciliteren door gebruik te maken van virtuele omgevingen. Deze computertoepassingen stellen geografisch gescheiden gebruikers in staat om binnen dezelfde virtuele omgeving aanwezig te zijn en samen te werken.

Eén van de belangrijkste uitdagingen bij de creatie van een dergelijke virtuele omgeving is het tot stand brengen van interacties tussen gebruikers die tegelijkertijd realistisch en natuurlijk overkomen. Op dit gebied werd reeds veel onderzoek verricht maar dit spitste zich meestal toe op het realisme van de applicatie, onder meer door gebruik te maken van geavanceerde driedimensionale visualisering en geluid. Ondanks het feit dat in het echte leven van elkaar afhankelijke interacties frequent voorkomen is dit in de virtuele wereld helaas nog geen vanzelfsprekendheid. In ons onderzoek richten we ons bijgevolg op manieren die de samenwerkingservaringen van gebruikers in virtuele werelden kunnen verbeteren met als doel een meer realistische en bevredigende samenwerking.

Het eerste deel van deze dissertatie bestudeert samenwerking in virtuele omgevingen in het algemeen. Door middel van een aantal formele experimenten bepalen we welke factoren bijdragen tot een bevredigende gebruikerservaring bij het uitvoeren van taken met hoge interactiviteit. Als eerste onderzoeken we de toepasbaarheid van de verschillende niveaus van samenwerking die voorkomen in de echte wereld en in een virtuele omgeving met veel gebruikers. In het bijzonder analyseren en vergelijken
we de invloed van zwak en sterk gekoppelde samenwerking tijdens coöperatie in een virtuele omgeving en hoe deze de ervaringen van de gebruikers beïnvloeden. Vervolgens bestuderen we de verschillende uitdagingen die in overweging dienen genomen te worden bij de creatie van een gebruikersomgeving voor samenwerking. Meer bepaald onderzoeken we in welke mate het combineren van de verschillende technologieën – gebruikt door de deelnemers om met de virtuele omgeving te communiceren – de gebruikerservaring beïnvloedt. Naast de verschillende technologische aspecten dienen we ook rekening te houden met de uiteenlopende bekwaamheden en voorkeuren van gebruikers. Daarom bekijken dat we vervolgens hoe we tegemoet kunnen komen aan de verscheidenheid van gebruikers om de prestaties van de groep te verbeteren.

Het tweede deel van deze dissertatie is gewijd aan de factoren die bijdragen tot de samenwerkingservaringen van gebruikers in een specifiek domein, namelijk multiplayer games. Op basis van de als positief gekezen sterk gekoppelde samenwerking in driedimensionale omgevingen uit het eerste deel van ons onderzoek bekijken we nu in hoeverre dit tevens het geval is multispeeler games. Hierna bediscussiëren we de problemen die naar voren komen bij de integratie van sterk gekoppelde samenwerking in games; met name de impact van kwaliteitsproblemen in het netwerk op de samenwerking en de communicatie tussen spelers. Ons onderzoek over samenwerking in games wordt afgerond met het bekijken van mogelijke oplossingen voor het verbeteren van de samenwerkingservaringen van gebruikers die spelen in een zelfde locatie, i.e. games voor interactieve tafelbladen. Doorheen het tweede deel van de dissertatie benadrukkken we bovendien de belangrijkste factoren die de samenwerkingservaringen van gebruikers faciliteren door het afnemen van verschillende testen met bestaande en specifiek hiervoor ontworpen games.

Door het bestuderen van samenwerking tussen gebruikers in virtuele omgevingen en multiplayer games, hebben we verschillende belangrijke implicaties geïdentificeerd die bijdragen tot een natuurlijke samenwerking. Wij zijn ervan overtuigd dat het toepassen van onze bevindingen zal leiden tot het ontwerpen van betere virtuele samenwerkingsomgevingen en als gevolg een hogere voldoening bij gebruikers.
This appendix contains copies of the questionnaires used during the user experiments in Part I of the dissertation: *Collaboration in Virtual Environments.*
Figure B.1: A copy of the questionnaire used after each session of the user experiment described in Chapter 3.

<table>
<thead>
<tr>
<th>Test#</th>
<th>Participant#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Gender**

Please pick one of the answers below.
- [ ] Male
- [ ] Female

**Age**

Please use the blank space to write your answers.

.................................................. .................................................. .................................................. ..................................................

**Please indicate your level of experience working in**

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D virtual environments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D collaborative virtual environments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Please explain**

Please write your answer in the space below.

.................................................. .................................................. .................................................. ..................................................

.................................................. .................................................. .................................................. ..................................................

.................................................. .................................................. .................................................. ..................................................

.................................................. .................................................. .................................................. ..................................................
<table>
<thead>
<tr>
<th>Test#</th>
<th>Participant#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Session</td>
</tr>
<tr>
<td></td>
<td>Collaboration</td>
</tr>
</tbody>
</table>

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th></th>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
<tbody>
<tr>
<td>To what extent did you experience that you and your partners were collaborating rather than working on your own?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>To what extent was your collaboration with other participants natural?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>To what extent would you like to perform collaborative activities together with the same people in real life (based only on your collaborative experience during the task)?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>

|       | Activity      |

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th></th>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
<tbody>
<tr>
<td>How active was your performance in the virtual environment?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>How active were you communicating with other participants?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>How well could you manipulate objects?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>To what extent did you feel comfortable using the device?</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>
### Awareness

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th></th>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To what extent were you aware of events occurring in the virtual world?

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

### If you have any remarks, please use the space below.

Please write your answer in the space below:

```

```

```

```

```

```

```

```

```

```
**Figure B.2**: A copy of the questionnaire used after the user experiment described in Chapter 3.

<table>
<thead>
<tr>
<th>Test#</th>
<th>Participant#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Comparison sessions 1 and 2</strong></td>
<td></td>
</tr>
<tr>
<td><strong>To what extent did you enjoy collaboration in</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Please mark the corresponding circle - only one per line.</strong></td>
<td></td>
</tr>
<tr>
<td>1 (very small)</td>
<td>2</td>
</tr>
<tr>
<td>session 1</td>
<td>◯</td>
</tr>
<tr>
<td>session 2</td>
<td>◯</td>
</tr>
</tbody>
</table>

**Please select which session you found more "collaborative" (more interaction with other participants)**

*Please pick one of the answers below.*

- ◯ session 1
- ◯ session 2

**Please explain why**

*Please write your answer in the space below.*

```

```

**Please select in which session you communicate more with your partners**

*Please pick one of the answers below.*

- ◯ session 1
- ◯ session 2
To what extent communication with you partners was important

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In session 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In session 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please explain why

Please write your answer in the space below:

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

Please select in which session you performed more actively

Please pick one of the answers below.

- session 1
- session 2

Please explain why

Please use the blank space to write your answers:

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________

__________________________________________________________________________
<table>
<thead>
<tr>
<th>Test#</th>
<th>Participant#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group evaluation</td>
<td>1 (very small)</td>
</tr>
</tbody>
</table>

Please mark the corresponding circle - only one per line.

To what extent did you enjoy session 1?  

To what extent did you enjoy session 2?  

To what extent did your group perform actively in session 1?  

To what extent did your group perform actively in session 2?  

To what extent did you experience that you were collaborating with other people in session 1?  

To what extent did you experience that you were collaborating with other people in session 2?  

To what extent was it difficult to coordinate and communicate with other group members

Please mark the corresponding circle - only one per line.

<table>
<thead>
<tr>
<th>Difficult</th>
<th>Neutral</th>
<th>Easy</th>
</tr>
</thead>
<tbody>
<tr>
<td>in session 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in session 2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure B.3:** A copy of the questionnaire used after each session of the user experiment described in Chapter 4.

<table>
<thead>
<tr>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
</tr>
<tr>
<td>Please pick one of the answers below.</td>
</tr>
<tr>
<td>○ Male</td>
</tr>
<tr>
<td>○ Female</td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>Please use the blank space to write your answers.</td>
</tr>
<tr>
<td>Leadership</td>
</tr>
<tr>
<td>Please mark the corresponding circle - only one per line.</td>
</tr>
<tr>
<td>1 (very small)</td>
</tr>
<tr>
<td>To what extent do you consider yourself as a leader?</td>
</tr>
<tr>
<td>○</td>
</tr>
<tr>
<td>To what extent do you consider your partner as a leader?</td>
</tr>
<tr>
<td>○</td>
</tr>
<tr>
<td>Who did the most talking? (for &quot;Talkative case&quot;)</td>
</tr>
<tr>
<td>Please use the blank space to write your answers.</td>
</tr>
<tr>
<td>What did other person do if he/she wanted to communicate with you? (for &quot;Non-talkative case&quot;)</td>
</tr>
<tr>
<td>Please write your answer in the space below.</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
### Collaboration

**Please mark the corresponding circle - only one per line.**

<table>
<thead>
<tr>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
</table>

To what extent was there a desire to perform the same task together with the same person in real life?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
</table>

To what extent did you experience that you and your partner collaborating?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

### Contribution to the task

**Please mark the corresponding circle - only one per line.**

<table>
<thead>
<tr>
<th>1 (very small)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10 (very large)</th>
</tr>
</thead>
</table>

How would you estimate your share in solving the task?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
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<th></th>
</tr>
</thead>
</table>

How would you estimate your partner's share in solving the task?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

To what extent did you contribute to placing the cubes?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

To what extent did your partner contribute to placing the cubes?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

To what extent did you feel comfortable using device?

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

### Remarks

If you have any remarks, please use the space below.

*Please use the blank space to write your answers.*
Figure B.4: A copy of the questionnaire administered after each session of the user experiment described in Chapter 5.

POST-EXPERIMENT QUESTIONNAIRE (PART I)

Test No.: _________

Participant Number: _________

Gender:   Male  ... in performing Placing with the Phantom?

1 2 3 4 5
Very Bad Bad Neutral Good Very Good

4. How good do you think you were in performing Placing with the Phantom?

1 2 3 4 5
Very Bad Bad Neutral Good Very Good

General remarks:

__________________________________________________________________________________

__________________________________________________________________________________

__________________________________________________________________________________
POST-EXPERIMENT QUESTIONNAIRE (PART II)

1. In the free collaboration session, to what extent did you experience that you and your partner collaborating?
   - When you used the SpaceMouse
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |
     
   - When you used the Phantom
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |

2. In the task-based collaboration session, to what extent did you experience that you and your partner collaborating?
   - When you performed Placing with the Phantom
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |
     
   - When you performed Rotating with the Phantom
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |
     
   - When you performed Placing with the SpaceMouse
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |
     
   - When you performed Rotating with the SpaceMouse
     
     |   | 1 | 2 | 3 | 4 | 5 |
     |---|---|---|---|---|---|
     | Very Small | Small | Neutral | Large | Very Large |

3. Which session do you think is more collaborative? Please explain why.
   - Free collaboration session
   - Task-based collaborative session

General remarks:
Appendix C

Questionnaires Part II

This appendix contains copies of the questionnaires used during the user studies in Part II of the dissertation: Integration of Closely-coupled Collaboration in Multi-player Games.
Figure C.1: A copy of the questionnaire used after each session of the user experiment described in Chapter 6.

Please mark with an ‘x’ the position on the line corresponding your gaming experience the most.

Questionnaire

1. Did you feel the necessity to discuss the game (strategy, ask your partner for help, etc.)?
   not at all ................................................... very much

2. Did the type of interaction encourage you to collaborate with your partner?
   not at all ................................................... very much

3. How often did you wait for the other player during the game?
   not at all ................................................... very much

4. Were you aware of your partner’s actions?
   not at all ................................................... very much

5. Was your efficiency decreased by:
   - the absence of communication ........................................ very much
   - the physical distance (playing remotely) ............................ very much
   - the necessity to wait for the other player .......................... very much
   - the actions of the other player ....................................... very much

   Please explain: ................................................................

6. Was the level of your enjoyment decreased by:
   - the absence of communication ........................................ very much
   - the physical distance (playing remotely) ............................ very much
   - the necessity to wait for the other player .......................... very much
   - the type of interaction with the other player ..................... very much

   Please explain: ................................................................

If you have any comments or remarks, please provide them below: ________________________________
Questionnaire after all trials

1. In your opinion, which games, if any, are not suitable for the remote play due to the way of interaction between players? (as played during the experiment remotely without communication)

____________________________________________________________
____________________________________________________________
____________________________________________________________

2. Based on the way of interaction with your partner, please rate the games according to the level of your enjoyment (as played during the experiment remotely without communication)

Game #__________ (least enjoyable)
Game #__________
Game #__________
Game #__________
Game #__________ (most enjoyable)

General information

Gender: ☐ Male ☐ Female
Age: _____

Please indicate the level of experience

<table>
<thead>
<tr>
<th>with multiplayer video games</th>
<th>never played</th>
<th>played once or twice</th>
<th>playing occasionally</th>
<th>playing often (at least every week)</th>
<th>playing a lot (almost every day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>with casual games (e.g., on social networks, mobile devices), both single and multiplayer</th>
<th>never played</th>
<th>played once or twice</th>
<th>playing occasionally</th>
<th>playing often (at least every week)</th>
<th>playing a lot (almost every day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>
Figure C.2: A copy of the questionnaire used after each session of the user experiment described in Chapter 7.

**Questionnaire #1**

1. Was the interaction between players exciting? ___________________________________________ not at all very much
2. Was the interaction between players engaging? ___________________________________________ not at all very much
3. Was the interaction between players challenging? _________________________________________ not at all very much
4. Was the interaction between players easy to understand? _________________________________ not at all very much
5. Would you like to play the game with the similar interaction between players in the future? _________________________________ not at all very much

If you have any comments or remarks, please provide them below: ___________________________________________

---

**General information**

- Gender: [ ] Male [ ] Female
- Age: _______

Please indicate the level of experience

<table>
<thead>
<tr>
<th></th>
<th>never played</th>
<th>played once or twice</th>
<th>playing occasionally</th>
<th>playing often (at least every week)</th>
<th>playing a lot (almost every day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>with multiplayer video games</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with casual games (e.g., on social networks, mobile devices), both single and multiplayer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Figure C.3:** A copy of the questionnaire used after each session of the two user studies described in Chapter 8.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Please indicate your level of experience

- never played
- played once or twice
- playing occasionally
- playing often (at least every week)
- playing a lot (almost every day)

### Quality of network connection

- unacceptable environment, impossible to play game
- very annoying environment, clearly impaired
- minor impairment noticeable, very good environment
- no noticeable impairments, perfect environment

### Did you notice any influence of the network quality on your gameplay? If yes, what exactly? What elements/artifacts/actions of the game were impaired due to the quality of the network?

### To what extent does the network quality (negatively) influence the following items:

- enjoyment of the game
- level completion time
- the difficulty to coordinate activities with your partner(s)?
- frustration of the game

### Based on the quality of the network condition, to what extent would you like

- to continue the game

### If you have any comments or remarks, please provide them below
Figure C.4: A (translated from Dutch) copy of the questionnaire used after each session of the user experiment described in Chapter 9.

Participant # ________
Gender: M F
Age: ________

AUD (ONLY)
1. How easy was it to understand the other participant during the game?

(very easy) (very difficult)

2. How would you rate the overall quality of the audio during the game?

Bad Poor Fair Good Excellent
1 2 3 4 5

3. If you were dissatisfied with the audio in any way, what factors contributed most to this? Please tick the factors that caused you dissatisfaction.

Tick
___ missing words/incomplete sentences
___ background hiss, crackle
___ 'unnatural'/metallic sounding voice
___ Other:

4. How would you rate the overall satisfaction with the level of communication in the game?

(not satisfied) (very satisfied)
AUDIO AND VIDEO

1. How easy was it to understand the other participant during the game?
   (very easy) (very difficult)

2. How would you rate the overall quality of the audio during the game?

<table>
<thead>
<tr>
<th>Bad</th>
<th>Poor</th>
<th>Fair</th>
<th>Good</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

3. If you were dissatisfied with the audio in any way, what factors contributed most to this? Please tick the factors that caused you dissatisfaction.

   Tick
   ___ missing words/incomplete sentences
   ___ background hiss, crackle
   ___ 'unnatural'/metallic sounding voice
   ___ Other:

4. How would you rate the overall quality of the video during the game?

<table>
<thead>
<tr>
<th>Bad</th>
<th>Poor</th>
<th>Fair</th>
<th>Good</th>
<th>Excellent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

5. During the game, how often did you look at the video of the other participant?

   Never   Infrequently   Some of the time   A lot of the time   Most of the time
| 1   | 2    | 3    | 4    | 5         |

6. Why did you look at the video of the other participant?

7. How would you rate the overall satisfaction with the level of communication in the game?
   (not satisfied) (very satisfied)
General questions:

1. How would you rate the overall enjoyment of the game?
   (not enjoyable)  (very enjoyable)

2. Did you enjoy game more when you played with the video?
   (Yes)  (No)  (Don't know)

3. How important was the presence of video during the game?
   (not important)  (very important)

4. Did you feel that the availability of video images of the other participant helped you to understand the game better?
   (Yes)  (No)  (Don't know)

5. Did you find the availability of video images to be distracting?
   (Yes)  (No)  (Don't know)

6. Which session did you like the most? Why?
   (Session 1)  (Session 2)  (Session 3)  (Session 4)

7. Was there any session where you were not satisfied with video quality and would prefer to have only audio?
   (Session 1)  (Session 2)  (Session 3)  (Session 4)  (None)
Figure C.5: A copy of the questionnaire used after the user experiment described in Chapter 10.

**TEST #________ PARTICIPANT #________**

**Gender:** ☐ Male ☐ Female  **Age:** ______

**Please indicate your level of experience**

<table>
<thead>
<tr>
<th>With multiplayer video games</th>
<th>Never played</th>
<th>Playing/played occasionally (once or twice a year)</th>
<th>Playing/played often (at least every week)</th>
<th>Playing/played a lot (almost every day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never used</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>With multi-touch tabletop systems</th>
<th>Never used</th>
<th>Using/used occasionally (once or twice a month)</th>
<th>Using/used often (at least every week)</th>
<th>Using/used a lot (almost every day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

**Please mark with an ‘x’ the position on the line that corresponds the most to your gaming experience. If you want to explain your answer, please use the blank space after each question.**

1. I enjoyed the puzzle game.
   
   Not at all ___________________________ Very much

2. Solving the puzzle collaboratively increased my enjoyment.
   
   Not at all ___________________________ Very much

3. I contributed a lot individually.
   
   Not at all ___________________________ Very much

4. I experienced a high level of collaboration.
   
   Not at all ___________________________ Very much

5. Everyone contributed equally to solving the task.
   
   Not at all ___________________________ Very much

6. When a certain task could be performed both collaboratively and individually (e.g. the manipulation of heavy blocks), it was mostly accomplished together with my partner.
   
   Not at all ___________________________ Very much

7. The provided help contributed to the level of collaboration.
   
   Not at all ___________________________ Very much

8. It was clear when it was necessary to collaborate.
   
   Not at all ___________________________ Very much

9. I was always aware of my partner’s actions.
   
   Not at all ___________________________ Very much
10. We had problems when performing collaborative tasks.  
   Not at all ____________________________ Very much  
   Specify what problems: ____________________________  

11. It was clear how to use the help without any explanation.  
   Not at all ____________________________ Very much  

12. The help explained the required actions clearly.  
   Not at all ____________________________ Very much  

13. After consulting the help, I could easily replicate the actions.  
   Not at all ____________________________ Very much  

14. It was clear how to perform cooperative tasks.  
   Not at all ____________________________ Very much  

15. The help allowed me to discover the required actions quickly.  
   Not at all ____________________________ Very much  

16. I learned most of the actions through the help.  
   Not at all ____________________________ Very much  

17. I learned a lot by talking to my partner.  
   Not at all ____________________________ Very much  

18. I learned a lot by watching my partner’s actions.  
   Not at all ____________________________ Very much  

19. I had to consult help multiple times for a particular action.  
   Not at all ____________________________ Very much  

20. Help took me out of the game experience.  
   Not at all ____________________________ Very much  

If you have any comments or remarks, please provide them below:  
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
Appendix D

Extended Study on Adaptation in Collaborative Virtual Environments

This appendix includes a manuscript submitted to the International Journal for Infonomics (IJI) in September 2012, containing an extension to the user experiment presented in Chapter 5 for a commercial game.
Providing Context-Based Adaptation in Collaborative Virtual Environments and Video Games

Abstract

This paper addresses our effort in investigating context-based adaptation as a prospective solution to enhance group interaction in collaborative virtual environments and video games. Through our work, we aim to provide adaptation of assigning users roles based on the context by users when collaboratively interacting in a virtual world. We first describe a user experiment in a fully controlled environment to assess whether or not the adaptation results in improved group collaboration in virtual environments. Afterwards, we investigate to what extent the suggested approach for adaptation can be applied in a real-life scenario. In particular, we identify some of the challenges that arise when employing role-based adaptation in existing multiplayer video games. From the experiments, we learned that the context-based adaptation of assigning roles to users improves the group performance.

1. Introduction

Collaboration in virtual environments has become more popular during the last decades due to the rise of Massive Multiplayer Online Role-Playing Games (MMORPG) such as World of Warcraft\(^1\) and virtual communities such as Second Life\(^2\). Collaboratively interacting in virtual environments has its own challenges compared to other types of collaborative work. A collaborative virtual environment involves a group of users performing highly interactive tasks with the use of three-dimensional (3D) user interfaces, while trying to achieve effective and efficient collaboration. Another complexity of working in collaborative virtual environments is the variety of 3D interaction tasks and techniques. The performance and preferences of every single user may differ, which in the end may influence the group collaboration. Providing adaptation according to the context of users is considered beneficial to improve their interaction in virtual environments, not only individually but also as a group collaboratively.

Adaptation may play an important role in elevating user performance in dynamically changing virtual worlds. Therefore, to enhance group interaction in collaborative virtual environments, we envisage that providing adaptive interaction, according to the individual context of users, would be a prospective solution.

Through our work, we would like to investigate if context-based adaptation leads to enhanced group interaction in collaborative virtual environments. In particular, we propose an approach of assigning a certain role and device to the users based on their performance. After analyzing this approach for a general task in a controlled virtual environment, we investigate its potential in a real-life scenario based on the example of an existing commercial video game. Here, we identify some of the challenges that arise when employing the suggested approach for adaptation in games. The results of our studies reveal the advantages of applying adaptation in collaborative virtual environments and video games.

2. Background

2.1 Context-based Adaptation in Virtual Environments

Interacting in virtual environments is mostly associated with complex interaction where users have to perform complicated tasks with highly interactive 3D user interfaces. Differences in user characteristics influence user interaction in virtual environments and lead to performance deviation among users. Adaptive user interfaces can be considered as one way to accommodate these individual differences and level up users' performance [1]. Integrating adaptation into virtual environments, by providing adaptive user interfaces according to users and other contexts, is considered as a key to comply with users' differences and enhance user interaction.

We acknowledge the importance of providing adaptation in virtual environments to enhance user interaction. The adaptation should take place according to the current context, for instance the environment conditions of the virtual world and the preferences and abilities of the users.

\(^1\)http://www.worldofwarcraft.com
\(^2\)http://www.secondlife.com
Over the past few years, a considerable amount of research has been done in context-aware computing. Dey [2] described the general definition of context, which is likely the most popularly used in every HCI field: "Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between the user and the application, including the user and the applications themselves."

The use of context for making decisions about adaptation for a variety of user interfaces has raised significant interest in the research community. For instance, many web applications utilize personalization and adaptation based on the user’s history and preferences [3].

Not much research has been done on adaptation in virtual environments compared to WIMP applications. Nonetheless, few works have yielded adaptivity in interaction in virtual environments by means of learning user behavior and preferred method of interaction [4]. In [5], the authors have investigated an approach for detecting and switching context for contextual interaction in virtual environments, and integrating adaptation in virtual environments using a context-aware design process.

In those works context was defined by the available input and output devices, and also external parameters such as the experience level of the user, whether or not there are collaborative partners in the environment or even the pose of the user (sitting or standing).

In [6], the author has experimented with interaction techniques such as switching between interaction techniques (based on personal preference) and adapting the interaction technique itself (based on user capabilities and the context of the user interfaces and interactions to the context of used devices, the user’s needs and the environment has also been studied in [7]).

2.2. Adaptation in Video Games

Video games are an increasingly popular kind of virtual environments. The amount of video games in the market constantly grows. So does the number of players, whose characteristics, needs and preferences are getting more and more diverse. Therefore, to ensure a longer time a game is being played, producers need to take into account the differences among potential players and create conditions that motivate the widest possible range of users to keep playing. This triggers a need for tailoring games to individual playing experiences, making them adaptive and personalized to the characteristics of each player. In particular, this can be achieved by modeling of player experience, an approach which has been identified as one of the key components to achieve a high level of player satisfaction [8]. The player model incorporates any relevant information, such as playing style and current emotional and cognitive state, which are used for steering the adaptive components of a game (e.g., adaptation of task, character, game mechanics, sound, difficulty, etc.).

Player modeling and adaptive technologies facilitate an improved player-centered game design by providing a more appropriate level of challenge, a smoother learning curve, and enhance the game-play experience for individual players. A substantial amount of research has successfully attempted to incorporate the adaptation in games such as the modification of difficulty levels [9], enemy’s behavior [10], or graphic elements of the game environment itself [11]. While most of these research initiatives focus on the adaptation in single-user environments, our work investigates adaptation in a collaborative setting, discussed further in Section 3.

2.3. Collaboration in Virtual Environments

Collaboration in virtual environments has been studied quite extensively for the last few decades. Many collaborative virtual environments (CVEs) have come into existence. However, most of them have limited interaction possibilities and have not widely supported highly interactive activities yet. Nevertheless, there are few studies [12,13] which have investigated people collaborating to perform interactive tasks. For example, in [13] all participants had to complete different subtasks in order to achieve the task goal. The variation of performance based on the available output devices was investigated in this work. In our opinion it is interesting to see if the adaptation of the tasks based on the devices would increase the performance, as explored further in the article.

Another example of highly interactive collaboration can be found in [12] which investigated the collaboration of two participants on a Rubik’s cube task. The authors compared performance between a real and an immersed setup, which showed to be almost the same. Their analysis revealed higher rates of these two setups comparing to the desktop one. It also showed that the participant using the desktop contributed less to the task and did not enjoy the collaboration. Based on this, it may be interesting to improve collaboration by adjusting the desktop user performance by assigning him certain activities that can be done easily by him. This can be seen as one example where adaptation based on the devices and performance can enhance the collaboration of several people.

The research presented in [14] investigated different factors that influence collaboration in a virtual environment, namely communication and variety of input devices. The experiments showed that there is a correlation between the devices used with the roles taken. It was natural that participants
divided their roles based on their convenience with the device. But this division was done explicitly only when communication was allowed. For no communication cases, it was not possible to divide the roles explicitly. We believe that this issue can be solved by automatic adaptation of users' roles in collaborative virtual environments.

3. Context-Adaptive Collaboration in Virtual Environments and Multiplayer Games

Numerous works in the field of CSCW and mobile applications have tried to provide adaptation based on context to improve group collaboration [15]. However, context-adaptive interaction has received less attention in multi-user virtual environments.

One phenomenon of recent CVEs is their rapidly increased popularity and ability to unite thousands of people all over the world. The main aim for developers now is to support interaction between these users, which can be achieved for example by providing different services based on their context [16]. Another approach to provide enhanced collaboration is context-aware communication support for remote gamers [17], which can improve a gaming experience by integrating voice interaction between users based on the game context.

To our knowledge, there are only very few works which describe how collaborative virtual environments or multiplayer games can benefit from adaptation based on the users' context. In [18] a collaborative virtual environment for training is presented, where different elements (virtual world, virtual humans' behavior, scenario, etc.) can be adapted to a specific training situation. In [19] the authors suggest the use of adaptation in two-player competitive games such as tennis and air hockey, which allows both players enjoying the game in spite of their different levels. More specifically, if a player is playing too badly (the game is too difficult for him), the game gets easier for him so he does not get frustrated. If a player is playing too well (the game is too easy for him), the game gets more difficult for him so he does not get bored. Adaptation happens according to the context of user performance (i.e. amount of hits done by each player).

In [20], an attempt to integrate adaptation based on a user context has been made in the domain of multiplayer video games. Here, the adaptation was provided based on an individual player's performance and preferences, while interacting in a 3D game. The authors have shown that the player experience in collaborative games can be significantly improved by adapting the means of interaction based on the players' model.

Four different approaches to build a player model were suggested based on the game goal. The aim of collaborative virtual environments should be to achieve group goals, not individual goals of each user involved in the collaboration. Group interaction and performance may be enhanced by integrating adaptation into collaborative virtual environments. To provide adaptation in a collaborative setting, we consider an approach of employing a group context which is based on the individual context of users involved in the group collaboration. Therefore, we would like to investigate the possibility of combining individual contexts into a group context. We believe that single-user based adaptation for a collaborative environment, where adaptation is performed separately for each user involved in the collaboration, does not lead to an adaptive collaborative environment. Additionally, it is essential to examine the integration of exogenous context factors (e.g. location, device used) with endogenous ones (e.g. users' roles, experiences) to provide better and more adequate adaptation in collaborative environments.

The goal of the work presented in this article is twofold. First of all, we aim to investigate how the adaptation can be applied in collaborative virtual environments in general. We investigate a combination of endogenous and exogenous factors to assess if context-based adaptation leads to enhanced group interaction (i.e. higher productivity) in collaborative virtual environments. For this purpose, we carry out an experiment to investigate how adaptation based on the context of the users' roles and devices used can benefit collaboration within a virtual world. While performing a collaborative 3D puzzle solving task, users' roles are divided based on their individual performance in executing a 3D object manipulation task.

Secondly, we investigate the applicability of the same approach in a specific application domain, namely video games. Based on the example of the existing commercial game Trine1, we identify what challenges occur when integrating the role-based adaptation in a real-life scenario.

4. Proposed User Modeling Approach

In our work, we propose adaptation of users' roles such that it will result in a better group interaction. To determine the adaptation, we propose an approach to construct a collaborative user model based on users’ individual performances. The purpose of this user modeling approach is to come up with the best prediction of role combination for providing adaptation by assigning users' roles (i.e. deciding which roles are appropriate for the users) to

1 http://trine-thegame.com
enhance the group interaction. In this work, we suggest a ‘minimum time’ approach as a way to build the collaborative user model. In this approach, we estimate the task completion time for every possible role combination and then select the combination which gives the minimum estimated total time as the best role combination. To estimate the task completion time, firstly, we calculate for every user the time to perform each role separately. Then for all combinations of roles, we calculate the total time to perform both roles collaboratively. To validate this approach, we compare the findings based on our model with the actual role-based performance. Besides validation of our approach, we also study whether or not role-based collaboration enhances the group performance.

The presented approach has been applied in two experiments: for a general collaborative virtual environment and in a multiplayer video game. The differences that have occurred due to the different task nature during the user performance modeling are discussed in the following sections.

5. Experiment I: Adaptation in a Collaborative Virtual Environment

As a first step we want to investigate how to enhance group interaction by providing context-based adaptation in a general collaborative virtual environment, not a specific application like a commercial game investigated later in Section 6. The adaptation is determined based on the context of users’ role and device used when collaboratively interacting in a virtual world. To achieve this, we conduct an experiment to investigate the performance of users in pairs while executing an interactive 3D puzzle solving task, which is considered to be highly collaborative. The experiment is designed based on [14] which showed that users explicitly divided their roles during collaboration based on their convenience with the device being used. With our experiment, we aim an improved group interaction by constructing a collaborative user model that suggests the adaptation of assigning users’ roles based on their individual performance when executing a certain task (e.g. rotation, translation) using a certain device (e.g. SpaceMouse, Phantom). Through this experiment, we would also like to validate our proposed approach in constructing the collaborative user model described in Section 4.

5.1. Hypotheses

For the best combinations predicted by the collaborative user model, three hypotheses were formulated in this experiment: (1) The estimated task completion time based on the model will not differ from the actual task completion time, (2) The estimated task completion time based on the model will be lower than the free-collaboration task completion time, and (3) The actual task completion time will be lower than the free-collaboration task completion time.

5.2. Participants

Ten randomly coupled pairs of unpaid volunteers (four females and sixteen males, 23 to 34 years old) participated in the experiment. Most of the participants had little experience with a virtual environment and also with the devices involved. All participants were right-handed and used their dominant hand to operate the device during the experiment.

5.3. Apparatus

For the experiment, two input devices, a SpaceMouse and a Phantom, were available for each user. Two desktop computers with 19 inches displays were used in the experiment. During the experiment, participants were located in the same room and close to each other, however, they were seated such that it was impossible to see each other’s screen. Figure 1 illustrates the experiment apparatus and settings.

Figure 1. The setup in the first experiment.

5.4. Design and procedure

The experiment consisted of three parts: an individual session, a free-collaborative session, and a role-dependent collaborative session. The first session aimed to gather the data of each user’s performance individually, with regards to the combination of roles and devices. The second and third sessions aimed to gather the data of the users’ performance in pairs; in the second session there was no division of roles while in the third session the division of roles was specifically defined. Two roles were defined in the experiment: rotation and
translation, which were performed using either SpaceMouse or Phantom. Table 1 presents the complete overview of the experiment sessions.

A within-subjects design was used for the collaborative sessions of the experiment. For the free collaborative session, the independent variable was the device used. For the role-dependent collaborative session, the independent variable was the combination of role and device, which order was counterbalanced. Task completion time was measured as the dependent variable.

Table 1. Sessions in the first experiment (puzzle solving task).

<table>
<thead>
<tr>
<th>Role-dependent collaboration</th>
<th>Participant 1</th>
<th>Participant 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual session</td>
<td>Rotation SpaceMouse</td>
<td>Rotation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Translation SpaceMouse</td>
<td>Translation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Rotation Phantom</td>
<td>Rotation Phantom</td>
</tr>
<tr>
<td></td>
<td>Translation Phantom</td>
<td>Translation Phantom</td>
</tr>
<tr>
<td>Free collaboration</td>
<td>Free SpaceMouse</td>
<td>Free Phantom</td>
</tr>
<tr>
<td></td>
<td>Free Phantom</td>
<td>Free SpaceMouse</td>
</tr>
<tr>
<td>Role-dependent collaboration</td>
<td>Rotation SpaceMouse</td>
<td>Translation Phantom</td>
</tr>
<tr>
<td></td>
<td>Translation SpaceMouse</td>
<td>Rotation Phantom</td>
</tr>
<tr>
<td></td>
<td>Rotation Phantom</td>
<td>Translation SpaceMouse</td>
</tr>
<tr>
<td></td>
<td>Translation Phantom</td>
<td>Rotation SpaceMouse</td>
</tr>
</tbody>
</table>

We asked every pair to complete ten puzzle-solving tasks. Each puzzle consists of 12 cubes representing a picture, where one cube was already placed to serve as a visual guide. The cubes, with a part of the picture on one side, were dispersed in the virtual environment (see Figure 2).

During the experiment, participants needed to indicate the starting and ending time of the session by selecting the menu items (“Rotation/Translation" to start the first and third session, “Start” to begin the second session, and “Finish" to end all sessions as soon as the task was completed). Participants were allowed to talk during the experiment. At the end of each session, we asked the participants to fill out a questionnaire about their experience and preference. Each pair completed the experiment in 60 minutes on average.

5.5. Results

In this article, we focus on improving group interaction in a collaborative virtual environment by providing adaptation of assigning users’ roles based on a collaborative user model. The collaborative user model is built based on the users’ individual performance and gives information about the best combination of roles and devices for a particular group. To investigate the efficacy of the model, suggested in Section 4, we compared the estimated task completion time based on this model with the actual task completion time of that particular combination. Furthermore, we found it interesting to compare the model and actual time with the task completion time measured during the free collaborative session, in order to see whether or not implementing adaptation for role-dependent collaboration would significantly decrease task completion time, thus enhance group interaction.

We employed the proposed ‘minimum time’ approach to determine the best role combination as the collaborative user model. In this approach, we estimated the task completion time by first estimating the time to perform each role per cube for every user (e.g. to translate one cube with SpaceMouse). Then for all combinations of roles and devices, we calculated the total time to rotate and translate one cube. Afterwards we estimated the total time to complete the whole task collaboratively. As a result, we determined the minimum estimated total time which then defined the best role combination as well.

For the first hypothesis, a paired-samples t-test showed no significant difference between the model time and the actual time \[ t (9) = 0.212, p = 0.837 \]. This indicates that task completion times do not differ significantly across the model and actual times. Based on this finding, we can conclude that the constructed model can be considered as a good approximation to the actual condition. As no difference across model time and actual time was found, we can conclude that we have successfully
selected the right combination of roles and devices, indicating the model’s efficiency.

For the second experiment, each pair of the participants was asked to complete two sessions: an

6. Experiment II: Adaptation in Multiplayer Video Games

In the previous section we have shown that providing adaptation based on the user performance (in form of assigning users with a certain role and device) leads to improved group interaction in a general collaborative virtual environment. An experiment was conducted in a fully controlled environment where two users had to complete a puzzle solving task that consisted of two basic manipulations: translation and rotation.

However, in real-life collaborative applications, the task division does not happen at such atomic level. Usually each collaborator has a number of tasks assigned to him/her and that he/she is responsible for. Therefore, as a next step, we aim to investigate the potential of role-based adaptation adapted to the user context in a more realistic scenario. As an example of such scenario, we have chosen multiplayer video games. In some existing collaborative games, task division and role playing become important to improve the collaboration and win the game at the end. For example in Battlefield games, the players need to divide their tasks when one player has to control the vehicle while the other is responsible for shooting the enemies. In the Little Big Planet game, sometimes the players need to closely collaborate to overcome certain obstacles which can only be moved away when players do this at the same time.

Little research has investigated ways of improving collaboration in games through the act of dividing tasks between players. Therefore, we intend to investigate the assignment of specific roles to players based on their individual characteristics (i.e. performance) as a form of adaptation in collaborative games. Furthermore, due to the differences that exist between applications designed for research experiments (like the one used for the first experiment) and real video games, we aim to outline some of the challenges that occur when applying the modeling approach presented earlier in Section 4 in the context of games.

In order to achieve the aforementioned goals, a user experiment was conducted. For the experiment, a recent commercial game Time was chosen, which involves several characters, each playing specific role, and requires collaboration between them in order to complete the game. Similar to the case of general virtual environments, the same type of adaptation based on assigning users’ roles and devices has been considered.

6.1. Hypotheses

During the second experiment, the primary focus was on the applicability of the proposed ‘minimal time’ approach for adaptation in video games. Therefore, here, we only checked hypothesis (1), which validated the proposed approach: the estimated task completion time by each pair of the participants based on the model will not differ from the actual task completion time. Hypotheses (2) and (3) are not considered here, as the game chosen for the experiment does not support collaboration without roles.

6.2. Participants

Eight pairs of randomly coupled unpaid participants (two females and fourteen males) participated in the experiment. The average age of the participants was 28 years old, varying from 22 till 36 years. All participants were recruited among the university staff and had a computer science background. Part of the subjects participated in the first experiment presented in Section 5.

6.3. Apparatus

For the experiment, two different setups were used: one for the individual session and the other for the collaborative session. During the individual session two separate laptops with 15 inches widescreens were involved, each used by a different player. For the collaborative sessions one laptop was connected to a 40 inches screen, which was shared by two players. A keyboard with mouse and the Xbox controller were used as the input devices. The setup of a collaborative session is shown on Figure 3.

6.4. Design and procedure

During the second experiment, each pair of the participants was asked to complete two sessions: an
individual session and a role-dependent collaborative session. Similarly to the experiment in a general virtual environment, data collected during the individual session was used for constructing a model, which was validated by comparison with an actual role-based performance collected during the collaborative session.

In the game Trine, a commercially available game used for this experiment, each player is represented as one of three characters: the thief, the knight or the wizard. Each character has a certain set of actions available only to him. Therefore, to complete the game collaboration of all characters is needed.

To interact with the character and the environment players used one of the following devices: keyboard with mouse or Xbox controller. Similarly to the first experiment, a within-subject design was applied for the collaborative sessions, where the independent variable was the combination of role and device. The task completion time was measured as the dependent variable. Table 2 presents the complete overview of the experiment sessions.

<table>
<thead>
<tr>
<th>Table 2: Sessions in the second experiment (Trine).</th>
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<tbody>
<tr>
<td>Individual session</td>
</tr>
<tr>
<td>Participant 1</td>
</tr>
<tr>
<td>Thief Keyboard</td>
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<tr>
<td>Knight Keyboard</td>
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<tr>
<td>Thief Xbox controller</td>
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<tr>
<td>Knight Xbox controller</td>
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<tr>
<td>Thief Keyboard</td>
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<td>Thief Xbox controller</td>
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</table>

To avoid an excessive number of test conditions and to have a similar pair-based experiment as in Section 5, only two roles were involved during the experiment (thief and knight). During the individual session, every participant had to complete two short levels, each introducing abilities of these two characters. Participants had to perform these levels twice: once using keyboard with mouse, and then using an Xbox controller.

During the collaborative session participants were asked to complete the actual game level, where all game characters were involved. The same level was played four times, involving all possible combinations of two roles and two devices (see Table 2). We did not involve a third person to play as the wizard. However, players were allowed to switch to the wizard character only when it was not possible to progress within the level otherwise. Afterwards, players were obliged to switch back to the character they were playing. An example of a screenshot of the gaming environment with two characters is shown in Figure 4. It took approximately 1 hour for each pair to complete the entire experiment.

6.5. Results

As stated earlier, with the help of a user experiment we wanted to investigate to what extent the approach suggested in Section 4 for a controlled virtual environment is applicable in a real-life scenario. In particular, we chose the domain of video games as one of the most popular types of collaborative virtual environments. With an attempt to apply the proposed approach in an existing video game, we aim to identify some challenges that occur when introducing role-based adaptation in video games. Therefore, we present our results in two steps. First, we describe the challenges arising when applying the modeling approach presented in Section 4. Secondly, we report on the validation of the model for a video game.

One of the immediate challenges that we have encountered when applying the ‘minimal time’ approach, was the modeling itself. In accordance
with the presented approach, we calculated the minimal time for all trials. The results showed a significant difference among them (t(7) = 0.303, p = 0.77), indicating that our model (M = 481.40) can be considered a good approximation to the actual (M = 498.38) condition. The obtained results indicate the effectiveness of the proposed modeling approach (based on the amount of obstacles and distances passed within the game) to determine the right combination of roles and devices for the commercial game being used in the experiment.

7. Conclusion

We presented an investigation of context-based adaptation as an approach to enhance group interaction in collaborative virtual environments and in multiplayer video games. First, we have described an experiment to examine how adaptation according to the context of users (i.e., user role and device used) leads to improved group collaboration (i.e., faster task completion time) in virtual environments. We found that assigning roles to users, as described by our model, improves the group performance.

Secondly, we have applied the same approach to provide adaptation in a multiplayer video game to investigate its potential in a real-life scenario. Based on the example of a recent commercial game Trine, we have revealed some of the challenges that occurred when applying adaptation of assigning roles to users in this game. One of these challenges was the necessity to adjust the modeling approach to estimate the completion time (model time). We have shown that for the modeling it is important to take into account task related information, in our case the amount of manipulated blocks in the collaborative virtual environment and the amount of obstacles and distance in the game. Considering this task specific parameterization, the “minimal time” approach provides enhanced group collaboration.

In this article we have considered only few types of collaboration in virtual environments and games. Further investigation is absolutely necessary to verify whether or not the proposed “minimal time” modeling approach is working for other collaborative tasks. Additionally, the possibility to integrate the proposed approach for a run-time adaptation needs a thorough investigation.

8. References


Extended Study on Adaptation in Collaborative Virtual Environments


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