Ecole Centrale de Nantes **Università degli Studi di Genova**

MASTER ERASMUS MUNDUS

EMARO "EUROPEAN MASTER IN ADVANCED ROBOTICS"

2009 / 2010

Thesis Final Report

Presented by

Boris Takač

On 23/08/2010

Title

HAPTIC COMMUNICATION IN VIRTUAL ENVIROMENTS

JURY

President:	**Wisama Khalil**	**Professor, ECN/IRCCyN**
Evaluators:	**Wisama Khalil**	**Professor, ECN/IRCCyN**
	Isabelle Milleville-Pennel	**Associate Professor, ECN/IRCCyN**
	Jean-Charles Cadiou	**Professor, ECN/IRCCyN**
	Amine Chellali	**Researcher, EMN/IRCCyN**
	Cédric Dumas	**Associate Professor, EMN/IRCCyN**
	Caroline G.L. Cao	**Associate Professor, Tufts University**

Supervisors: Cédric Dumas, Caroline G.L. Cao and Fulvio Mastrogiovanni (UG)

Laboratory: Institut de Recherche en Communications et Cybernétique de Nantes

Contents

Table of Figures

List of Tables

List of Abreviations

CVE - **C**olaborative **V**irtual **E**nvironment

VE - **V**irtual **E**nvironment

IRCCYN - **I**nstitut de **R**echerche en **C**ommunication et **C**ybernétique de **N**antes

DoF - **D**egree **o**f **F**reedom

HHI - **H**uman **H**aptic **I**nteraction

T - **T**ranslations

R - **R**otation

1D - **1 D**imensional

2D - **2 D**imensional

3D - **3 D**imensional

API - **A**pplication **P**rogramming **I**nterface

XML **- E**xtended **M**arkup **L**anguage

GUI **- G**raphical **U**ser **I**nterface

H **- H**aptic

V **- V**erbal

H->V **- H**aptic (modality) followed by **V**erbal (modality)

V->H - **V**erbal (modality) followed by **H**aptic (modality)

PTR - **P**roportoional **T**ranslation-**R**otation

IDC - **I**mpulse **D**irection **C**hange

INTRODUCTION

Collaborative Virtual Environments (CVEs) are virtual reality spaces that enable participants to collaborate and share objects as if physically present in the same place. These environments usually aim to provide users with a sense of realism incorporating realistic 3D graphics, spatial sound and other modalities to create immersive experience. CVEs are used in many applications, such as medical (surgical simulators, telemedicine), industry (CAD systems) and education (mentor guided skill learning). These CVEs offer new interaction possibilities by allowing users to share virtual workspaces. However, the design of virtual environments that support collaboration still remains an open research topic.

Since 2007, there has been a continuous ongoing research in the area of Collaborative Virtual Environments at *IRCCYN* (Institut de Recherche en Communication et Cybernétique de Nantes). Special interest was given to the investigation of the development of common grounds for mutual understanding between the collaborators in the tasks in virtual environment [1], [2]. Lately, the research focus was expanded to the investigation of the collaborative tasks with added haptic modality [3], [4].

Inclusion of haptic modality in a virtual environment opens up a new communication channel whose possibilities have not yet been fully investigated. We consider the remote haptic interaction between human operators to be a form of communication, which we designate as the haptic communication. In this work we investigate the ways in which the haptic communication through kinesthetic device is established and used to exchange the information about the ongoing collaborative task between two participants.

Using a simple spatial task in the virtual environment, we will try to prove the existence of the haptic communication for information exchange and to find the measure of its effectiveness. Additionally, we propose that for each pair of collaborators there is a possibility of developing their own haptic language. If so, we will try to analyze that language grounding our analysis on the comparison between haptic modality and verbal modality.

First, we will introduce the topic of the haptic communication, give a review of the relevant literature and pose our research questions and hypotheses. Furthermore, the experimental study encompassing the experimental system setup and experimental task description will be given. In the final part, we will provide the analysis of the experimental data and present the experimental results.

1 HAPTIC COMMUNICATION

In the first part of this chapter we will describe haptic communication and show its presence in everyday collaborative task. With given example, we will also present our initial motivation for the research in this topic. In the second part of the chapter, we will give the review of the related literature. This review was used as the point of origin for our research efforts. We conclude the chapter by summarizing the literature review and setting our research objectives.

1.1 Research motivation

Research in haptics is presently done with the final goal being the application in novel and more natural human-machine interfaces. Although, in our everyday life we receive a great deal of information using haptic feedback, current user interfaces are still highly visual in nature, with audio cues used primarily to reinforce what is shown on the visual display. Still, audio and visual senses can not transmit the same information which is transmitted through the haptic sense. In manipulating objects, haptic modality can be crucial for understanding the use of the system, and on other occasions, when audio and video modalities are already engaged in communication, haptic feedback can be used as an additional channel of communication.

1.1.1 Haptic communication in collaborative tasks

Haptic communication between two individuals collaborating on a task in the real world environment can be achieved either through direct limb-to-limb coupling, or through a mutually grasped object that we refer to as the haptic link. Everyday examples of the former can be simple handshaking or learning a hand skill which involves the need for direct physical guidance by a teacher e.g. learning calligraphy. Examples of the latter include two people exchanging some random object (a pen, a CD box) or two people picking-up and carrying an object together from point A to point B.

Imagine two people carrying a table from one room to another in a fully furnished house. In order to do so, they have to find their way around the furniture, through the door, and between the rooms without hitting anything. Imagine furthermore, that while doing so, one person is holding the table while going forward in the direction of the goal, and the other person is holding the table and walking backwards, without seeing what exactly is happening behind them. Even if these two people didn't talk to each other while doing this task, and even if it was their first time doing this task together, we could presume that they would be able to accomplish it successfully.

In the given example, two people can successfully use a haptic link in order to communicate the data about the task at hand. How can they understand each other's intentions so well? How do they convey information? What type of movements do they use? Is this an innate ability and equal for all people? These are the basic questions that we must to set out to answer if we want to be able to use haptic modality as a coequal communication channel in future CVE applications.

1.2 Related work

Hereby, we will review the literature relevant to our research in the areas of haptics, virtual environments and haptic collaboration. We will begin by giving a short introduction on human touch and haptics. Then, we will discuss the impact of the inclusion of haptics into virtual environments. After this, we will narrow our focus and describe the research on haptic interaction in collaborative tasks and present proposed models of haptic interaction. In the end, we will review the research examples in which the haptic modality is used as the explicit communication medium.

1.2.1 Touch and haptics

The sense of touch is an integral part of the human sensory system. We use it in order to extract information about our environment or in order to manipulate objects surrounding us. Touch is also very important for communication as it can convey non-verbal information. The sense of touch can be divided into cutaneous, kinesthetic, and haptic systems, based on the underlying neural inputs [5]. The cutaneous system employs receptors embedded in the skin, while the kinesthetic system employs receptors located in muscles, tendons and joints. The haptic sensory system employs both cutaneous and kinesthetic receptors, but it differs in the fact that it is associated with an active procedure controlled by body motion [6]. In the scope of this work we will consider terms “haptic” and “haptics” to be in congruence with this presented definition of the haptic sensory system, implying the use of the haptic sensory system together with active body movements in order to exchange information through haptic devices.

1.2.2 Haptic interaction in Collaborative Virtual Environments

A lot of research has been done on the technical development side of CVE in order to satisfy strict performance characteristics. Some of the main technical research topics included:

- virtual world modeling and representation
- databases
- networking and data exchange protocols
- human-computer interfaces

Ever since haptic devices became available to more research communities in the middle of 90's of the last century, haptics became an integral part of CVE. Besides the research strictly concerned with the technical development side, after the introduction of haptics to CVE, the question was raised also about the way that this new modality influences the social interaction side of CVE.

A group of authors working on this problem (between 1997 and 2003) were Basdogan, Srinivasan and Ho from MIT, together with Slater and Durlach from University College London. The overall point of interest of their research was the role of haptic communication in virtual environments and its influence on the human sense of presence and co-presence.

Herein presented articles comprise the first experiments known to us on the nature of haptic collaboration in VE. The way in which these experiments were set up (with 1 degree of freedom (DoF) task, 2 segregated participants and various experimental conditions) was a guideline for the researchers who followed later on to investigate haptic collaboration.

In [8] and [9], research was done on the effect of touch on the task performance in VE. Research results showed that the inclusion of haptics into CVE is justifiable, since task trials with included haptic modality yielded better results compared to the ones without haptics. The improved performance for collaboration with included haptic modality was later confirmed in the experiments of other authors.

In [9], authors presented a need for the development of a valid model which could simulate haptic interactions among participants of the collaborating task. As a solution they suggested a spring-damper physically based model. The proposed model was valid only for translational movements of their virtual object, and only when both participants were applying force simultaneously. This approach to the modeling demands monitoring of the user force input. Force measurements were later used in the works of other researchers trying to obtain a model of haptic interaction.

In [8] and [9] it was also shown how to approach the investigation of the social interaction aspects of collaboration. A subjective self-assessment measurement method was introduced through the use of the questionnaires.

In [10] the technical side of CVE was investigated. The given observations of temporal constraints in haptic device synchronization are important for us, since it is our wish to set up an experimental system with acceptable time attributes in which the lag between devices doesn't interfere with the haptic communication process.

1.2.3 Interaction in dyadic shared manual tasks

In the period between 2004 and 2008, a group of authors including K. Reed, M. Peshkin, E. Colgate and J. Patton from the Laboratory for Intelligent Mechanical Systems of Northwestern University conducted a series of experiments in human-human dyadic interaction. Their experiments included a special, 1 DoF robotic device, which was developed in order to give experimental access to the exchange of forces and motions between people.

In [11], it was revealed that there are certain categories of tasks for which output performances are better if two people execute them together (dyadic task). Improved dyadic task performance was confirmed for the 1 DoF category of tasks. Experiments in [11] also validated Fitts's law for two people collaborating on a simple manual task with identical targets. For a case when the targets for individuals in a dyad were not identical**,** Fitts's law didn't hold true.

The different targets approach deserves a special notice. In all previous experiments presented here, there was always visual information present in the task which was the same for both participants. The visual feedback gave each subject the main information about their common task goal, and haptic communication was used to exchange information about the manner of executing the task. It is important to highlight that in the case of different task goals, the significance of visual feedback can be considered as attenuated, giving more significance to the haptic communication channel, which now has to exchange information about the task goal and the manner of executing the task. We found this approach as useful inspiration for our experimental task setup.

The results of the Fitts's law in collaborating tasks**,** with identical targets**,** were explained by hypothesizing a theory of specialization. The theory of specialization suggests that subjects should each specialize in executing only certain parts of the task, while synchronizing control of the task through haptic communication. The nature of these cues used for indicating control transition points is not yet disclosed and deserves further investigation.

In order to prove the specialization hypothesis in [12], forces were measured between participants in dyadic experiments and two types of collective forces were deducted, net (external) forces which directly influence the task execution, and difference (interactive) forces which enable haptic communication. The possibilities for inducing temporal specialization in the dyad members were investigated in [13], where one human subject was replaced with a motor controlled**,** 1 degree of freedom device. Although experiments with a motor partner gave slightly better performance results than for tasks with the subject alone, specialization didn't occur. It can be presumed that this is the consequence of the absence of the valid model of the internal forces between participants.

1.2.4 Modeling of human-human haptic task

In the field of service robotics, it is often desirable to have direct contact of humans and robots. Also, with the haptic modality added to virtual reality, physical interaction with avatars becomes possible. In both of these examples there should exist an appropriate robotic partner, based on a model that will be able to interact with the human in a natural way. So far, control models for that kind of task were based on capturing human behavior, as presented in [12]. In that case, there was no real interaction going on, and the information exchange between subjects was unilateral. In order to fully enable inclusion of haptics in mentioned applications and achieve real bilateral communication, there is a need to obtain a dynamic model of the natural human-human interaction.

A group of authors which did noticeable research obtaining a valid model of human-human interaction, comes from the Institute of Automatic Control Engineering of Technical University in Munich, and includes D. Feth, R. Groten, A. Peer and M. Buss. Their work tries to establish the connection between existing behavior studies and system theory.

The measurement of energy flows between participants during collaboration on 1 DoF task was introduced in [14]. The introduction of energy flows enabled the research of some new aspects**,** like the efficiency of dyads [15] and the dominance of partners [16]. It is interesting to point out a proposed distinction of two types of dominance; physical and cognitive, which were mentioned in [16]. Physical dominance was analyzed based on the net forces and the analysis of the average energy flow of each participant into the system. On the other hand, cognitive dominance, which refers to decision processes in collaboration, was not elaborated. An explanation of the different ways how cognitive dominance evolves and works, could directly contribute to the understanding of natural haptic communication.

Reviewed research of energy flow, efficiency of dyads and dominance of partners, at last enabled the proposition of the new model of human-human haptic interaction [17].

1.2.5 Haptic modality as a medium of communication

In the works reviewed so far, haptic modality has been seen mainly in terms of interaction through physical forces. In the introduction of the thesis, we said that that the addition of the haptic modality to a virtual environment, could add a new communication channel. Haptic feedback could be used to send messages and haptic stimulus can be associated with the given meaning. Noticeable research on the topic of haptic messaging has been done at the SPIN lab of the University of British Columbia under the guidance of Karon MacLean [18], [19].

Haptic messages are considered to be possibly beneficial in the situations when the visual system (and maybe also the auditory system) is highly engaged in a task. A good example of this kind of situation is driving. With more complex vehicle cockpits, especially in the luxury vehicles, there are an increasing number of subsystems (audio, climate, navigation). These systems often require the driver's visual attention to be used, which can possibly create dangerous situations. For this reason automobile makers started to introduce haptics into the cockpits. An example of this is the BWMs iDrive which uses a force-feedback rotary knob in order to access the vehicular functions displayed on the screen.

1.3 Research objectives

In the literature review we have seen different approaches to the exploration in the subject of human haptic communication. Attempting to improve task performance was in the focus of researchers for a long time [8], [9], [11], [14]. Social interaction benefits were investigated in [8], [9] and [10], Fitts' law in [11], and kinesthetic interaction in [12]. Kinesthetic interaction experiments spurred the specialization hypothesis for dyads, which was examined in [12] and [13]. In order to propose a model of human haptic interaction (HHI) in [17], concepts like energy flow [14], dyad efficiency [15] and dominance [16] had to be researched first.

Haptic modality as a possible communication channel was considered in [18] and [19]. However, in these works explicit previously given haptic messages were used, and there was no inquiry in the natural way in which humans invent haptic messages on their own.

Our area of interest is collaborative virtual environments and we are using kinesthetic haptic devices in collaborative tasks. We would like to know:

1. Is there a way to use the interaction through kinesthetic haptic devices between two humans to do more than just synchronization during collaborative task, i.e. communicate data about the task they are collaborating on?

2. If point 1 is true, how can we analyze and understand this behavior?

2 EXPERIMENTAL STUDY

In this chapter we will discuss all the necessary steps that had to be taken in order to gather the data for the evaluation of haptic communication. First, we will present the development of the idea for the experiment approach and hypotheses. Next, we will give the description of the experimental task, followed by an explanation of the experimental protocol. In the end of the chapter, we will present the experimental system which we designed and developed to gather the experimental data.

2.1 "Blind people guidance" paradigm

It is year 2025. Imagine a blind person being at a rock concert which is coming to an end. The blind person decides to go for the exit. The concert hall is still full of people and bottle debris, and the person can not effectively use his blind man stick to navigate. As we are in the future, the concert hall is an intelligent environment fully equipped with surveillance cameras and a navigation system for cleaning robots. However, this navigation system also allows humans with disabilities to use it for their needs. The environment at the rock concert is too loud for the navigational system to give instructions using verbal communication over cell phone. However, this is not a problem, since the blind person has with him a portable haptic device where haptic communication can be used for spatial guidance.

2.1.1 Spatial guidance as a collaborative task

The example above can be seen as a collaborative task between the navigational system and the blind person. The navigational system knows the position of the person and the position of the hall exit at each moment and gives movement direction instructions through the haptic device. The blind person interprets these instructions and moves accordingly. If they both carry out their part of the overall task successfully using haptic communication, the blind person should be able to reach the exit without any problems.

We can consider the haptic communication research presented in this thesis to be a preparatory work of acquiring basic knowledge that could enable the emergence of advanced applications of haptics in the future (like the one described above). The first step towards that final goal is to collect data about the natural human behavior. If we imagined that in the previously described situation, instead of the navigational system there was another human giving instructions, we would obtain the example of a collaborative spatial guidance task between two humans.

In our work, we are focused on the use of haptics for collaboration in the virtual environments. We want to transfer to the idea behind the previously described collaborative situation (involving two humans) into the virtual environment and to use it as a template for our experiment. In order to do so, we will create a virtual haptic link to enable haptic communication. Furthermore, we will find an appropriate task in the virtual environment which will elicit the need for the exchange of information in a desired fashion.

2.2 Hypotheses

A collaborative virtual environment is used to examine the properties of the haptic communication in the experimental study. Human dyads work together in order to solve a spatial positioning task. The goal of the study is to asses the effectiveness of haptic communication for the given task and to observe a possible occurrence of haptic language. By using the proposed approach, we hypothesize that:

H1: It will be possible to effectively communicate through the haptic link.

H2: There will be two possible haptic device control approaches for realizing haptic communication in the given task:

a) direct spatial guidance through continuous movement,

b) use of discrete movements to which we can assign higher meaning

H3: Subjects will start with direct spatial guidance and then, later, possibly discover that discrete movements control is more adequate. The latter would happen if subjects are able to establish common grounds for their communication and recognize the meaning of the signals applied.

H4. Haptic communication will be positively influenced by verbal communication. If subjects have a prior chance to solve the task using verbal modality, they will model their haptic communication to resemble previous verbal communication, which would help them to evolve haptic communication faster and perform better overall.

2.3 Experiment

Choosing the proper collaborative task in order to correctly acquire the required data to prove our hypotheses was a crucial step of the experiment design process. We designed and tested a few different experimental tasks before finding the final solution that will be presented subsequently.

2.3.1 Search for the task

In all the tasks that we tried out, we used haptic devices connected in the bilateral haptic link. This means that two identical haptic devices with force feedback were connected in such a way that they copied directly each other movements. In a bilateral haptic link, each haptic device operator is able to apply movements and forces on his device and concurrently feel the motions and resistances produced by his partner. Our haptic devices allowed us to use the link with all 6 DoF, including 3 translations (T) and 3 rotations (R). In some of the tasks that we tested, the haptic link had less than 6 DoF (2T+3R, 3T), but in the end we decided to keep the full freedom on the link in order to allow for the most natural movements when using the devices.

Likewise, for the visual channel of our virtual environment, we also had to decide how many DoF our task will use. We tested propositions of the virtual environment with 1 dimension (1D), 2 dimensions (2D) and 3 dimensions (3D). In the end, we chose the virtual environment with 2 visual dimensions because we estimated that it has enough complexity to generate the need for information exchange, and yet, it still allowed us an easier post analysis via cross-reference with haptic data. Moreover, 2 dimensions conform to the simplified version of our blind man paradigm, in which the concert hall can be considered as seen from the top view.

Furthermore, we had to decide whether the spatial task will be positioning task or trajectory tracking task. The literature research showed us that both kinds of task have already been used previously (3D trajectory tracking in [5], 1D positioning in [11], 1D trajectory tracking in [13]). We opted for the positioning task, modeling our task after the Fitts's law type task used in [20]. The use of the task modeled after Fitts's law gives easily applicable metrics to show haptic communication efficiency afterwards.

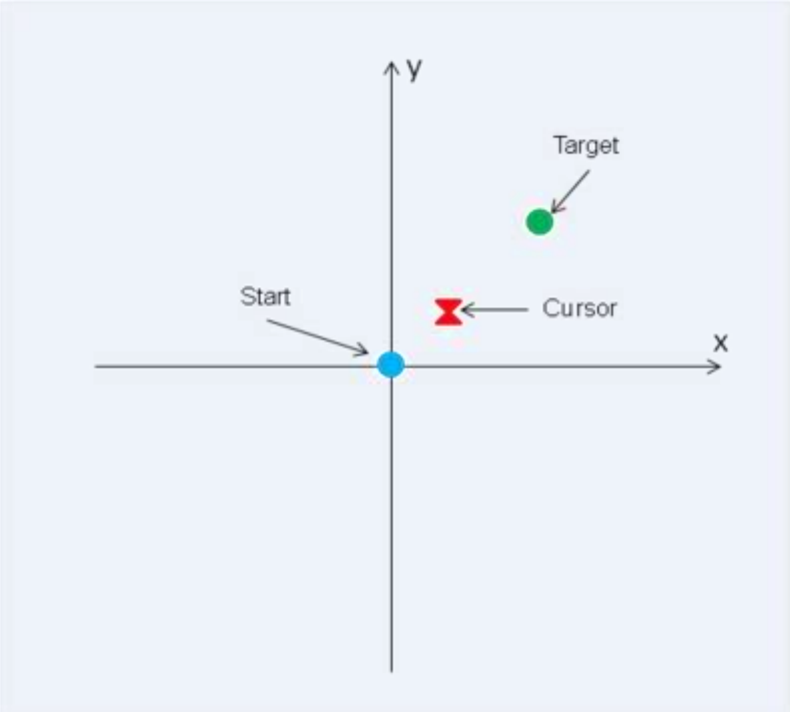


Figure 2-1. Simple 2D positioning task.

On Figure 2-1, the graphical representation of the simple 2D positioning task is given. The red hourglass cursor represents the current position of the input device on the visual display. The blue circle is the starting area, and the green circle is the target area. For each trial of the task, the blue circle appears in the center of the display, and the green circle appears elsewhere on the display. Subjects are instructed to move red cursor inside the blue circle and wait for a sound cue before beginning the trial. Subjects can take as long as necessary to prepare before moving. Timing starts when the red cursor leaves the blue circle. The goal is to move the red cursor inside the green circle, and keep it in that area for one second.

The described task is very similar to the task done by MacKenzie in Experiment 2 of [20], as previously mentioned. This task is performed by only one person who has at their disposal both input device (mouse in the hand), and all the relevant visual information (the location of the red cursor and the green target circle showed at the monitor).

2.3.2 Task

Following the previously established „blind person navigation paradigm, we wanted to transform the presented simple 2D positioning task for one person into a collaborative task. Given task was divided into two distinctive parts:

a) input control

b) visual information access

Each of these parts was assigned to one of the members of a human dyad.

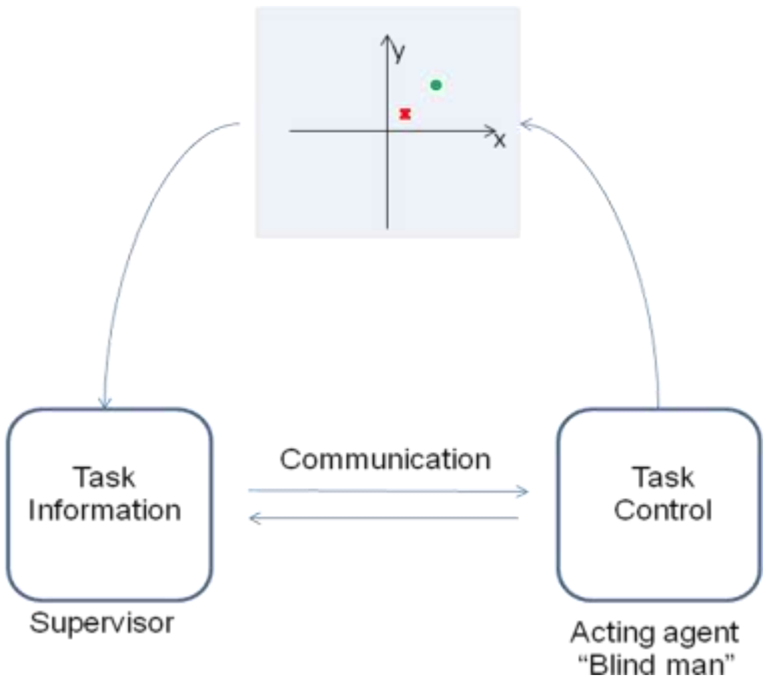


Figure 2-2. Transformation of the simple 2D positioning task into a collaborative task.

In this new collaborative version of the task, one dyad member controls the input device and has insufficient visual information. He fulfills the role of the blind person and is referred to as the “Acting agent“ or the “Actor“. The other dyad member has at their disposition all the visual information and his goal is to provide the navigational information to his partner. He is referred to as the “Supervisor“.

The *Acting agent* uses a mouse as the input device for the task. As a communication channel the participants use haptic modality (by means of the haptic link made between two haptic devices with 6 DoF) or verbal modality, depending on the condition we will be examining. There is no possibility of direct visual communication between participants, since they are not able to see each other. The only common visual information they share is the position of the red cursor which is located identically on both displays.

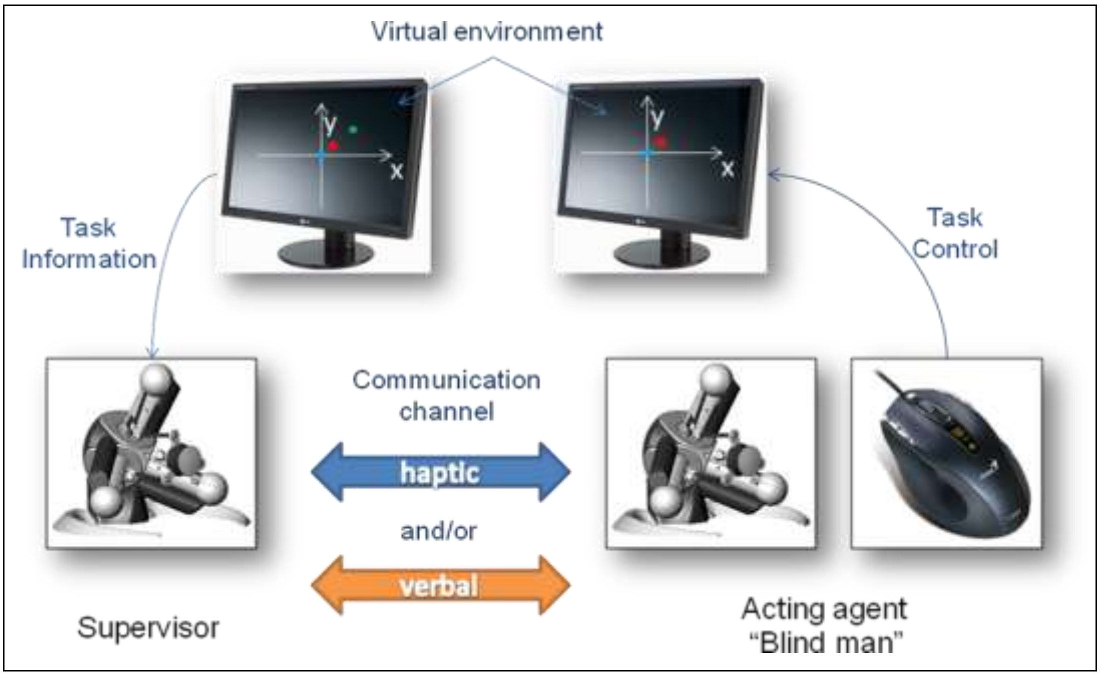


Figure 2-3. Collaborative system overview.

By moving the mouse, the *Acting agent* controls the position of the red cursor inside the simple virtual environment. However, he is not able to see where the green target circle is, since that information is not displayed on his screen. He gets the missing information from the instructions given by the *Supervisor* through the communication channel. The *Acting agent*'s goal is to interpret these instructions and to find with the cursor the position on the screen where he estimates the target area to be.

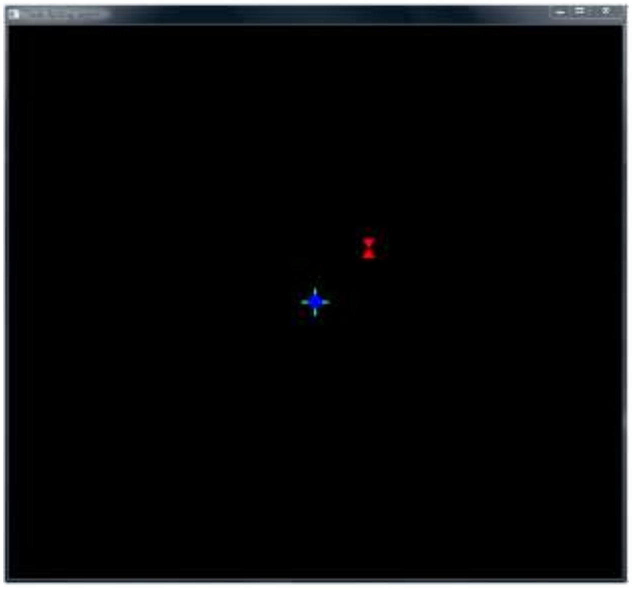


Figure 2-4. Screen display for *Acting agent* before a trial. Blue circle in the center disappears after the begging of the new trial.

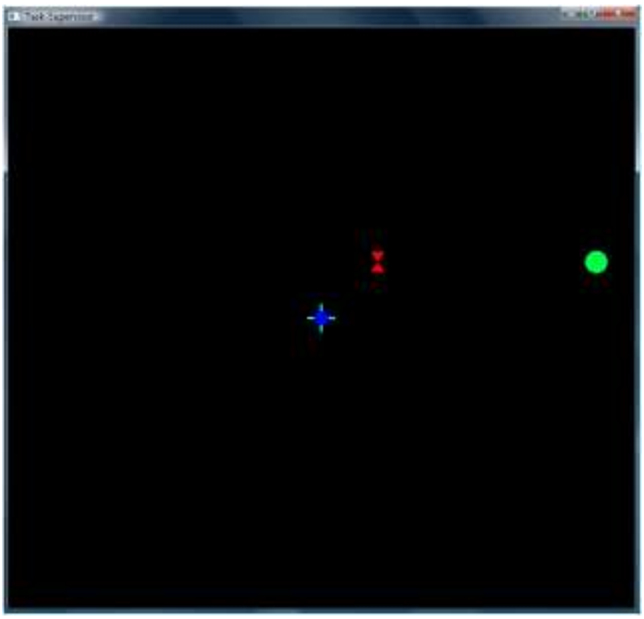


Figure 2-5. Screen display for the *Supervisor* before a trial. Blue circle in the center disappears after the begging of a new trial.

For each new target point given, the *Acting agent* starts the trial by putting the cursor in the blue circle at the center of the screen and waiting for the sound cue. After the cursor leaves the blue circle, that landmark disappears. Left visible are only the red cursor and the black background. Red cursor has to be held inside the invisible target area for one second upon reaching it for a trial to be finished successfully.

On the *Supervisor*'s screen the moving red cursor and the position of the green target circle are visible. The *Supervisor* has no direct control over the movement of the red cursor. To successfully complete the task, the *Supervisor* has to give instructions to his partner using the allowed communication channel (haptic link, speech).

2.3.3 Participants

The participants' pool consisted of 20 volunteers, divided into 10 pairs. Volunteers who aged from 19-55 were recruited amongst master students, doctoral students and staff of *IRCCYN*. There were 17 male (2 left handed) and 3 female (1 left handed) volunteers. All the participants had no experience with either virtual environments or with haptic devices.

2.3.4 Design

For the experiment we used mixed repeated measurements design, with both within-subjects and between-subjects approach.

The two communication modalities on which we based experimental conditions for our collaborative task were:

- haptic modality (H)
- verbal modality (V)

First of all, we wanted to be able to evaluate efficiency of communication with haptic modality and compare it to communication with verbal modality. That imposed the necessity for between subject-design. We split our participants into two groups and assigned to each group one modality as a primary condition. A group for each condition consisted of 5 dyads.

Furthermore, we wanted to be able to investigate the elements and the evolution of the possible haptic language for each dyad. We expected that a comparison of haptic communication to verbal communication inside the dyad could give us necessary clues.

Lastly, we expected that the order of the presentation of modalities could have influence on the overall communication development during the experiment. This required within-subjects design in which we would have one modality, followed by the other one for the same dyad.

Table 1. Experimental design. Role changes of subjects during sessions.

		Block 1 (**B1**)	Block 2 (**B2**)	Block 3 (**B3**)	Block 4 (**B4**)
Group 1 (H->V)	Dyad 1 (**S1**)	Haptic; A =Actor	Haptic; A=Supervisor	Verbal; A=Supervisor	Verbal; A= Actor
	Dyad 2 (**S2**)	Haptic; A =Actor	Haptic; A=Supervisor	Verbal; A=Supervisor	Verbal; A= Actor
	Dyad 3 (**S3**)	Haptic; A =Actor	Haptic; A=Supervisor	Verbal; A=Supervisor	Verbal; A= Actor
	Dyad 4 (**S4**)	Haptic; A =Actor	Haptic; A=Supervisor	Verbal; A=Supervisor	Verbal; A= Actor
	Dyad 5 (**S5**)	Haptic; A =Actor	Haptic; A=Supervisor	Verbal; A=Supervisor	Verbal; A= Actor
Group 2 (V->H)	Dyad 6 (**S6**)	Verbal; A = Actor	Verbal; A = Supervisor	Haptic; A =Supervisor	Haptic; A=Actor
	Dyad 7 (**S7**)	Verbal; A = Actor	Verbal; A = Supervisor	Haptic; A =Supervisor	Haptic; A=Actor
	Dyad 8 (**S8**)	Verbal; A = Actor	Verbal; A = Supervisor	Haptic; A =Supervisor	Haptic; A=Actor
	Dyad 9 (**S9**)	Verbal; A = Actor	Verbal; A = Supervisor	Haptic; A =Supervisor	Haptic; A=Actor
	Dyad 10 (**S10**)	Verbal; A = Actor	Verbal; A = Supervisor	Haptic; A =Supervisor	Haptic; A=Actor

The experiment for each dyad consisted of one session divided into four blocks. Each block consisted of 16 trials, where each trial consisted of one new target point. Dyad members were designated either as Subject A or Subject B. For each block in the session there was either a change of the role between the members of the dyad while keeping the same communication modality (i.e. Haptic; A=Actor → A= Supervisor), or a change of the modality while keeping subjects' roles the same (A=Supervisor;

Haptic → Verbal). The example of how the member roles changed for all the dyads is given in Table 1.

In all the blocks of all the sessions, we used the same 16 target points. The positions of the target points were preselected to have 4 different indexes of difficulty and to be distributed in an equal number for all four quadrants of the visual workspace. The index of difficulty for the target points was calculated following Shannon's formulation of Fitts's law:

$$ID = \log_2(1 + \frac{D}{W}),$$

where D is the distance from the starting point to the center of the target, also known as the amplitude of the movement, and W is the width of the target measured along the axis of motion.

When calculating index of difficulty of target points, the target circle width was kept constant while the distance between the target circle and the starting circle was varied as a controlled variable. The order in which the points were presented inside the block was randomized before the start of each block.

2.3.5 Protocol

At the beginning of each session, members of the dyad performing the experiment were allowed to choose their workstation without having prior knowledge about what they would have to do. The dyad member who sited himself first at the workplace for the *Acting agent* role was labeled "Subject A", while his partner was labeled "Subject B".

Participants were told that the experiment is about haptic communication, and that they will have to collaborate using haptic devices or words in order to solve a simple task. Then, the collaborative positioning task was presented, where both participants were able to see each other's screens simultaneously.

After making sure that the participants understood the task, the presentation of the haptic device was made for the dyads using haptic modality first (Group1). They were shown all the possible degrees of freedom of the haptic device and were informed about the limited workspace. The demonstration of the haptic device was done verbally and practically, with each participant handling the device under the haptic link jointly with the experiment conductor for around a minute. After initial familiarization with the device and the haptic link, participants were allowed to solve 4 trials of the task with full visual communication, along with haptic communication. However, they were not allowed to talk about future strategy they could use. Upon finishing 4 training points, the curtain was placed between participants in order to prevent the visual contact so that experiment could begin.

For the dyads of Group 2, the same presentation of the haptic devices was done after the trials for the two blocks with verbal modality had been done first. They were instructed to start their experiment with verbal modality immediately after being familiarized with the collaborative task.

For all sessions the participants were not allowed to verbally communicate during the haptic portion of the session, while for the verbal portion of the session they were told that they can use verbal communication of any form as long as the language was English or French.

All sessions were filmed with a digital camera for the later analysis.

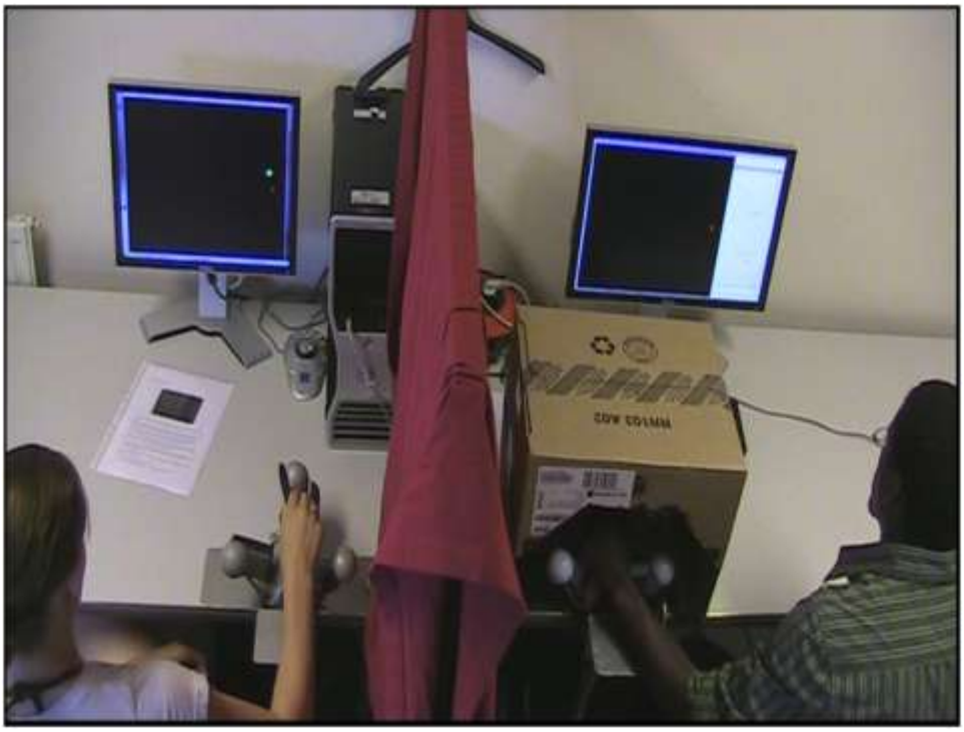


Figure 2-6. Participants using haptic link during one of the sessions.

2.4 Experimental system

We designed the experimental system to collect data. The system is based on the idea presented in Figure 2-3, and it has four main functions:

- to connect two haptic devices with a haptic link and to supervise the established connection
- to display the virtual environment for the experimental task on two screens
- to log the available physical data of the haptic link together with the corresponding information from the virtual environment
- to manage and automatize the experimental process.

The system development required our effort mostly on the software side, since all the necessary hardware was purchased as off-the-shelf products.

2.4.1 Haptic link

As mentioned earlier, haptic link is defined as the connection of two identical haptic devices with force feedback in such a way that they directly copy each other's movements. In order to consider haptic link effective, translations, rotations, velocities and forces produced by one device must be reproduced by the other device as close as possible.

At our disposition we had two Haption's *Virtuose Desktop 6D* haptic devices. The *Virtuose 6D Desktop* device is a fully parallel robot with three legs and a platform used as a grasping tool. Each of the three robot legs has 3 links. The first, second and third joints from the base of the robot are revolute joints, while the fourth joint, connecting the third link with the platform, is a spherical joint. The first and second revolute joint of each leg are actuated. Position encoders are utilized on all revolute joints. This gives the 6 DoF kinematics, with force-feedback available on all DoF. The structure of the *Virtuose 6D Desktop* makes it possible to work in a volume encompassing a sphere 12 cm in diameter. The resolution in position is of 1.5 10^{-2} mm.

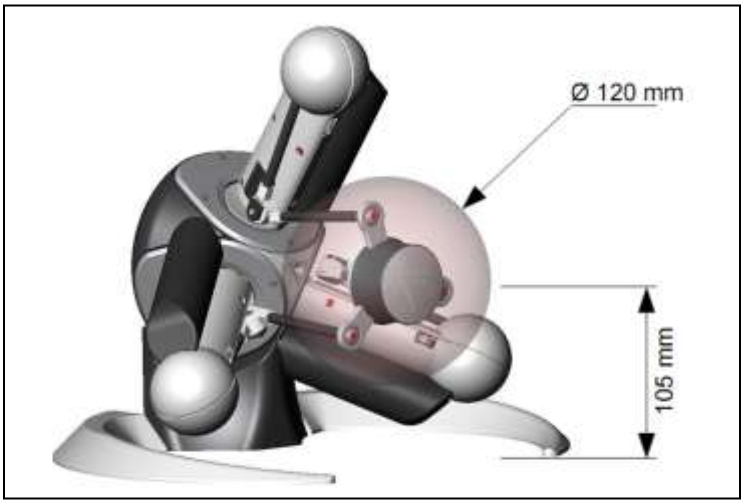


Figure 2-7. Workspace of the *Virtuose Desktop 6D*.

The devices are delivered together with the API [21]. The technical approach to establishing the haptic link between the given devices is to mutually copy all the positions, velocities and efforts between the devices in each cycle of the programming loop that supervises the link connection. The connection supervising routine runs on the server computer to which both the devices have to be connected beforehand. In the device API, positions are expressed as displacement vectors with seven components [*x y z qx qy qz qw*]. The first three components of the vector express translation, while the other four express rotation in the form of the normalized quaternion. Velocities are expressed as kinematic tensors [*vx vy vz wx wy wz*], while efforts are expressed as dynamic tensors [*fx fy fz cx cy cz*].

All the kinematic and dynamic values express the relationship of the center of the platform (base of the gripping tool) in reference to the center of the base of the device. The referent axes of the haptic device frame are given in Figure 2-8.

Figure 2-8. Axes directions for the referent frame of the haptic device.

2.4.2 Virtual environment and the task input device

The appearance of the virtual environment for both participants was previously given in Figures 2-4 and 2-5. The graphical environment representation is very simple and can be produced in OpenGL using basic geometric shapes.

Besides graphical representation, two additional things must be observed about the virtual environment; First, the relationship of the visual task frame compared to the haptic device frame, and second, the relationship between the task input device (mouse) displacement and the haptic device displacement.

The task frame axes are labeled considering the fact that we use the mouse as the independent input device for moving the cursor during the task. Since our task in the virtual environment is two dimensional, only two axes are needed to define the task frame. The left-right displacements of the mouse on the table determine the X-axis (horizontal cursor displacement), while forward-backward displacements of the mouse determine the Y-axis (vertical cursor displacement).

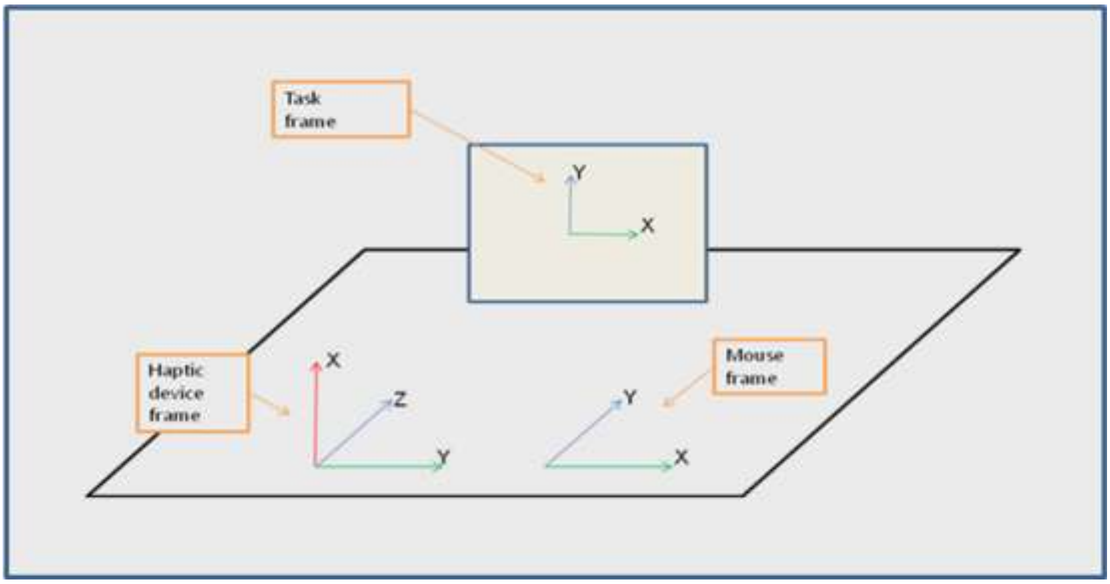


Figure 2-9. Frames and axes.

The relationship between the mouse axes and the referent haptic device axes is shown on Figure 2-9. As it can be observed, the X-Y plane of the mouse is parallel with the Y-Z plane of the haptic device. In this case, the Y-axis of the haptic device corresponds to the X-axis of the mouse, and the Z-axis of the haptic device matches the Z-axis of the mouse. Knowing these frame relations is important for successful cross-referencing of the haptic link data with the mouse data, since each of these devices operates using their own reference frame.

Furthermore, we want the measured displacement of the mouse along one of the axes to correspond in value and measurement units to the displacement of the haptic device along the same axis. This could help us to easily recognize the case when there is present direct movement copying between the *Actor*'s left hand holding the haptic device and right hand holding the mouse.

The information about the mouse displacement is initially obtained from the virtual environment window. The mouse displacement is collected in pixels. The setup of the mouse device sensitivity and precision, together with the calculation of the scaling factor, had to be done in order to get the final setting in which mouse displacement is measured in meters, which makes the mouse displacement directly comparable with the haptic device displacement.

2.4.3 Data logging and experiment management

If we want to get insight in the communication process on the haptic link, first we need to find a way to observe the link. The literature review already showed us the importance of measurement of the physical data, such as position and force, in the previous similar haptic experiments.

In our system setup we have an easy access to the physical values of the haptic devices, since these values are directly used in the supervisor routine which maintains the haptic link. In each loop cycle of the supervisor routine there is a possibility to read the physical values from the haptic device controllers and write them into a log file. The same applies for the mouse device position coordinates.

A custom XML format is used for data logging during an experiment session. The basic data about the haptic device settings and experimental task settings is recorded at the beginning of the XML log file. Afterwards, only the so called "Dynamical data" is written to the file with the chosen logging rate. Logging rate can not be higher than 1000 Hz, since 1000 Hz is the frequency of the supervisor routine loop. In order to limit the log file to a rational size, and still have enough temporal resolution in the data, we used 50 Hz as the logging rate in all the sessions.

The variables pertaining to the continuously recorded *Dynamical data* during the experiments are given in Table 2.

Table 2. Variables logged for *Dynamical data*.

Label	Description	
X	displacement along X axis	haptic device translational
Y	displacement along Y axis	
Z	displacement along Z axis	
fX	force along X axis	
fY	force along Y axis	
fZ	force along Z axis	
velX	velocity along X axis	
velY	velocity along Y axis	
velZ	velocity along Z axis	
mX	mouse displacement along X axis	mouse
mY	mouse displacement along Y axis	
mZ	mouse displacement along Z axis (always zero)	
Q1	first element of the rotation quaternion	haptic device rotational
Q2	second element of the rotation quaternion	
Q3	third element of the rotation quaternion	
Q4	fourth element of the rotation quaternion	
TqX	torque around X axis	
TqY	torque around Y axis	
TqZ	torque around Z axis	
vAlfa	angular velocity around X axis	
vBeta	angular velocity around Y axis	
vGama	angular velocity around Z axis	

In sections 2.3.4. and 2.3.5. the descriptions of the experiment design and protocol were given. From these descriptions it can be seen that the experiment session was divided into 4 blocks, which were subsequently divided each into 16 trials. Our wish was to be able to easily find and analyze the data for each of the conducted trials. With that in mind, we recorded the data for each trial into a separate log file. For each trial, data logging was active from the instant in which the red cursor exited the starting circle, to the moment in which the red cursor resided inside the green target circle continuously for more than one second.

During each block of the session the experimental conditions and the participants' roles were firmly set. The only experimental variable that changed was the position of the target point between the two trials. Hence, the experimental automatization was designed for one block of 16 trials. Before the block started, the order of the appearance of the target points inside the block was randomized using a pseudo randomizing function. Afterwards, experimental automatization functions checked the conditions for start and stop of the each trial, switched the data logging on and off depending if the switching terms were met, and automatically changed the position of the target circle when the conditions for the presentation of the next trial point arose.

2.4.4 Developed software

As previously mentioned, the main portion of the work on the experimental system was tied to the software development in order to implement the described system functions.

The software was developed under Windows operational system using the C++ programming language. Visual Studio 2005 with the MSVC compiler was used as the development platform. The additional libraries used in the project were Haption's VirtuoseAPI libraries, QT user interface framework with the addition of the QWT plotting library, and the CMarkup XML library.

Since C++ was used as the programming language, the object oriented approach had to be adopted. Each of the developed main classes of the program was modeled after one of the experimental system's physical elements or desired functions. In addition, utilization of multithreading was recognized as a necessity, since there were multiple contemporaneous tasks that needed to be supported; maintaining the haptic link, logging the data and presenting the data to the user.

The application is intended to be executed at the server computer equipped with two monitors and two LAN cards. Each of the LAN cards is used for the direct crossover low-latency connection with one of the Haption Virtuose 6D controllers.

Figure 2-10 shows the global partition of the program into two threads. The duty of the *SVThread* is to handle the data from all the devices and execute the data logging. The errand of the *GUIThread* is to provide the user interface for the application, along with the graphical presentation of the virtual environment for the experimental task on two monitors.

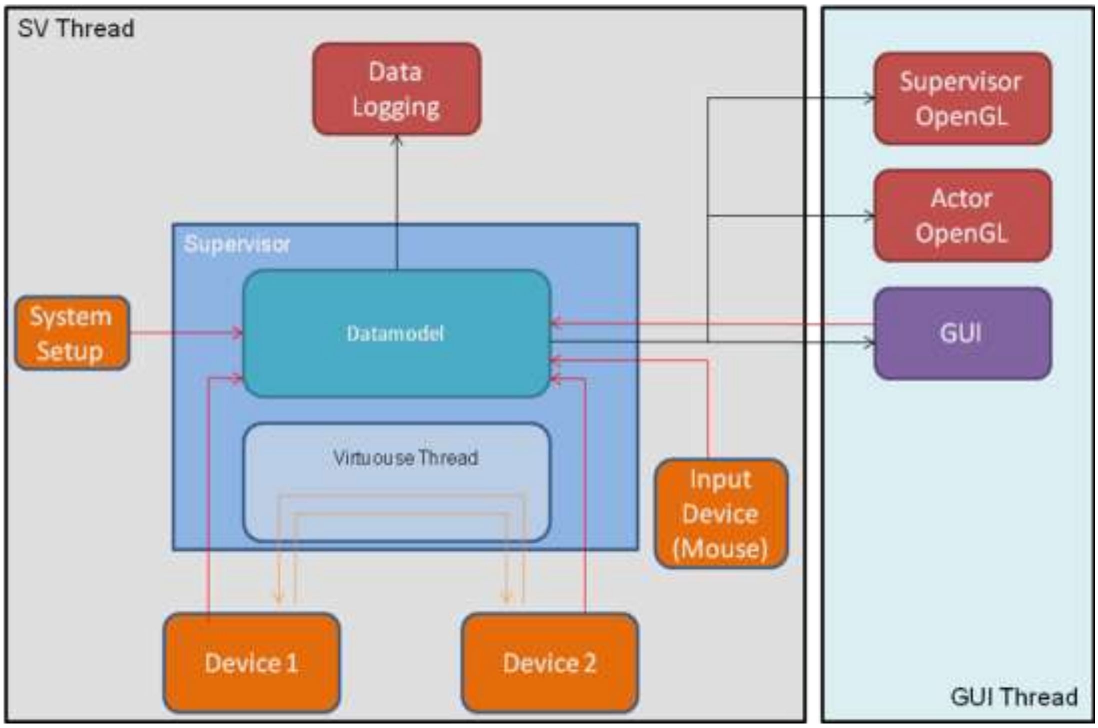


Figure 2-10. Application architecture model.

The main class of the application is the *Supervisor* class. This class is specific for two reasons, the first of which is the application data model. The variables declared in this class are used to hold the current state of the whole application. For example, if there is a click on the *Connect* button at the graphical user interface presented by the GUI class, change in the connection state would be recorded in the variable of the *Supervisor* class and be sent as a notification to the whole application. Along with the application state data, the application data model holds buffers for *Dynamical data* variables listed in Table 2. Current *Dynamical data* values in these buffers can be read at request from any other class. The second specificity of the *Supervisor* class is the SuperviseConnection method which establishes and preserves the haptic link between two *Virtuose 6D Desktop* devices. When started, this method makes a new thread called *VirtuoseThread*, which performs continuous position, velocity and force copying between the haptic devices using VirtuoseAPI function calls.

Figure 2-10 gives the main indication of the data flow between the classes of the application. Red arrows designate the flow of the data into the data model, while black arrows designate the flow of the data from the data model. Orange colored classes are the classes that produce data. At the start of the execution of the application, initial data model is formed from the setup file through the *SystemSetup* class. Upon successful connection of the haptic devices on the server, the haptic link is established and *Dynamical data* of haptic devices becomes available in the data model. Red colored classes are the classes which consume *Dynamical data*. Black arrows indicate inter-class connections for which *Dynamical data* is read from the data model upon the notification messages.

The *GUI* class is rather specific. It has continuous bilateral communication with the *Supervisor* class in order to ensure that the application state represented in the data model stays in accordance with the user's intentions. Figure 2-11 gives the example of graphical user interface (GUI) used for the user input of the parameters for the experimental session.

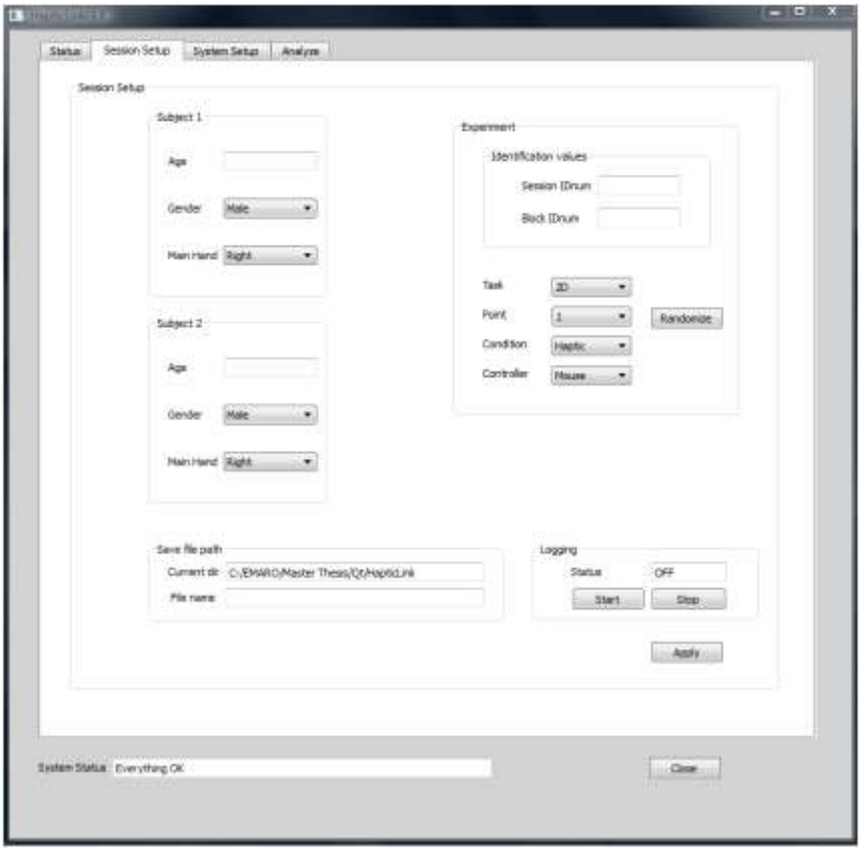


Figure 2-11. Screenshot of the application user interface.

2.4.5 System properties

Upon finishing the development of the software for the experimental system, it was necessary to test the system as the whole. The main goal of the system test was to check the properties of the haptic link.

The first features that had to be tested were physical properties of time delay and displacement errors between the devices. Also, with the physical properties test it was possible to check the functionality of the written software in terms of successful data logging. Additionally, another test of the haptic link had been done in order to find the map of relations between physical variables of the haptic link in the case when one device is guiding the other device. This map was foreseen to serve as the reference for later analysis of the experimental data through graphical plots of physical data.

To examine the physical properties of the haptic link we conducted a very simple step response test. *Supervisor*'s device (Device2) was used to as the input device, and the *Actor*'s device (Device1) was considered as the output device. To get the step response for a direction on one axis, the "step" input was given by the human operator on Device2 by a "quick as possible" motion in the desired direction. Device1 was without load during the step excitation and data was logged for both devices simultaneously with 300 Hz. The starting posture of the haptic devices for each step response test was:

a) position at the center of the workspace

b) vertical orientation along the haptic device's X-axis

The step response test was done for both positive and negative directions along each of the device axes. The reference frame for this test was the haptic device frame. The results of the step response test are given in Table 3.

Table 3. Times and displacements for the haptic link step response test.

		RiseTime [ms]	PeakTime [ms]	50%Time [ms]	Start [m]	SettlingMin [m]	SettlingMax [m]	Peak [m]	StepAmpl [m]	AbsDiff [m]
Xneg	**Device 1**	186	519	748	0,0399	0,0137	0,0172	0,0137	-0,0262	
	Device2	188	522	738	0,0400	0,0134	0,0172	0,0134	-0,0266	
	Diff(d2-d1)	2	3	-10	0,0001	-0,0003	0,0000	-0,0003	-0,0004	0,0004
Xpos	**Device 1**	131	1483	1393	0,0356	0,0609	0,0638	0,0638	0,0282	
	Device 2	140	1533	1384	0,0355	0,0623	0,0649	0,0649	0,0294	
	Diff(d2-d1)	9	50	-9	-0,0001	0,0014	0,0011	0,0011	0,0012	0,0012
Yneg	**Device 1**	136	1274	973	-0,0043	-0,0351	-0,0306	-0,0351	-0,0308	
	Device 2	147	1256	967	-0,0042	-0,0355	-0,0307	-0,0355	-0,0313	
	Diff(d2-d1)	11	-18	-6	0,0001	-0,0004	-0,0001	-0,0004	-0,0005	0,0002
Ypos	**Device 1**	121	1709	1434	-0,0028	0,0228	0,0274	0,0274	0,0302	
	Device 2	126	1706	1425	-0,0028	0,0229	0,0279	0,0279	0,0307	
	Diff(d2-d1)	5	-3	-9	0,0000	0,0001	0,0005	0,0005	0,0005	0,0005
Zneg	**Device 1**	117	1194	981	0,0014	-0,0330	-0,0273	-0,0330	-0,0344	
	Device 2	118	1197	973	0,0015	-0,0339	-0,0270	-0,0339	-0,0354	
	Diff(d2-d1)	1	3	-8	0,0001	-0,0009	0,0003	-0,0009	-0,0010	0,0010
Zpos	**Device 1**	108	837	239	0,0054	0,0317	0,0383	0,0383	0,0329	
	Device 2	113	837	236	0,0054	0,0321	0,0388	0,0388	0,0334	
	Diff(d2-d1)	5	0	-3	0,0000	0,0004	0,0005	0,0005	0,0005	0,0005
Avg				-8						0,0007

The majority of step response characteristics (RiseTime, PeakTime, SettlingMin, etc.) expressed in Table 3 can be obtained directly from MATLAB using the *stepinfo* function. When examining the haptic link in each axis direction (Xpos, Xneg, etc.), two response curves are obtained; each of them for one of the devices (Figure 2-12).

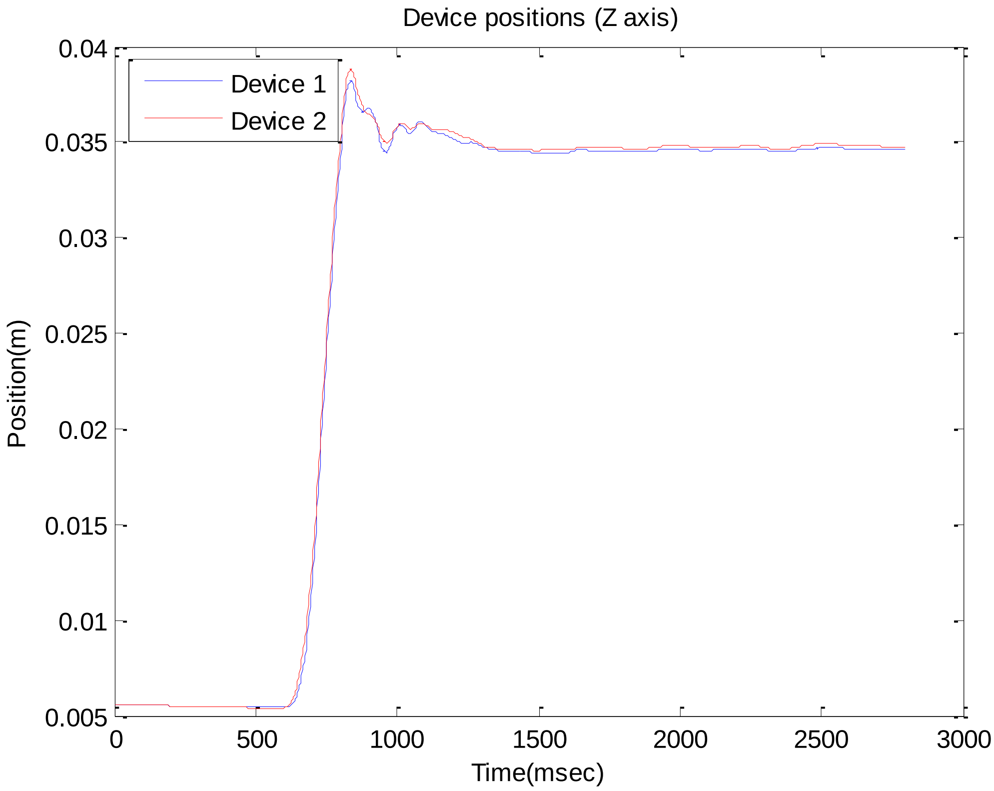


Figure 2-12. Example of the step response test along the positive Z-axis of the haptic device.

The characteristic called *50%Time* is obtained additionally from the numerical data for each of these step responses by finding the time when the device was aproximatively in the middle of the ascending (or descending) slope. By calculating the difference of the *50%Time* of both devices, it is possible to find the approximate time delay between the two devices under dynamic load. To get the single representative value with somewhat more statistical accuracy, we calculated the average time delay for all six tests (one fore each direction). The obtained result shows that under test conditions Device1 averaged a delay of 8 ms after Device2.

Before starting the experimental sessions with dyads, it was important to confirm that the time delay between the devices would not negatively influence the execution of the experimental control task. It is stated in the literature [22], that for humans the effect of time delay for a control task is noticeable around 200 ms. With the time delay of around 10 ms, we verified that the haptic link has acceptable time properties for the proposed control task.

To calculate the displacement error between the two devices, we checked the difference in the step amplitude. Step amplitude was taken as the difference between the start and peak value for each curve. Average absolute difference between the step amplitudes (Device2 - Device1) was calculated to be 0.7 mm for the average 3 cm displacement.

When two people use a haptic link actively, in each moment there is always one who is inputting force into his device and leading, and the other who is opposing that force and following. When devices are connected with a haptic link and moved around, each device measures its own values and both devices have very similar, but not identical positional and velocity profiles. On the other hand, forces measured in the haptic link are differential forces between the two devices. In this case, each device measures the same forces but with different signs, giving mutually inverted force profiles.

In order to enable an easier post-analysis of the experimental data through graphic plot inspection, we found it necessary to map the relations between the position, velocity and force of the linked devices.

A simple test to collect the necessary data to describe the mapping relations was conducted. Device2 was again the leading device, and Device1 was the following device. The haptic link was tested along the three main axes (X,Y,Z). Input produced by the operator on Device2 was similar to a trapezoidal function, with linear translations along the chosen axis, first in one and then in the other direction. During the movements, reaction forces were produced by the operator on the Device1.

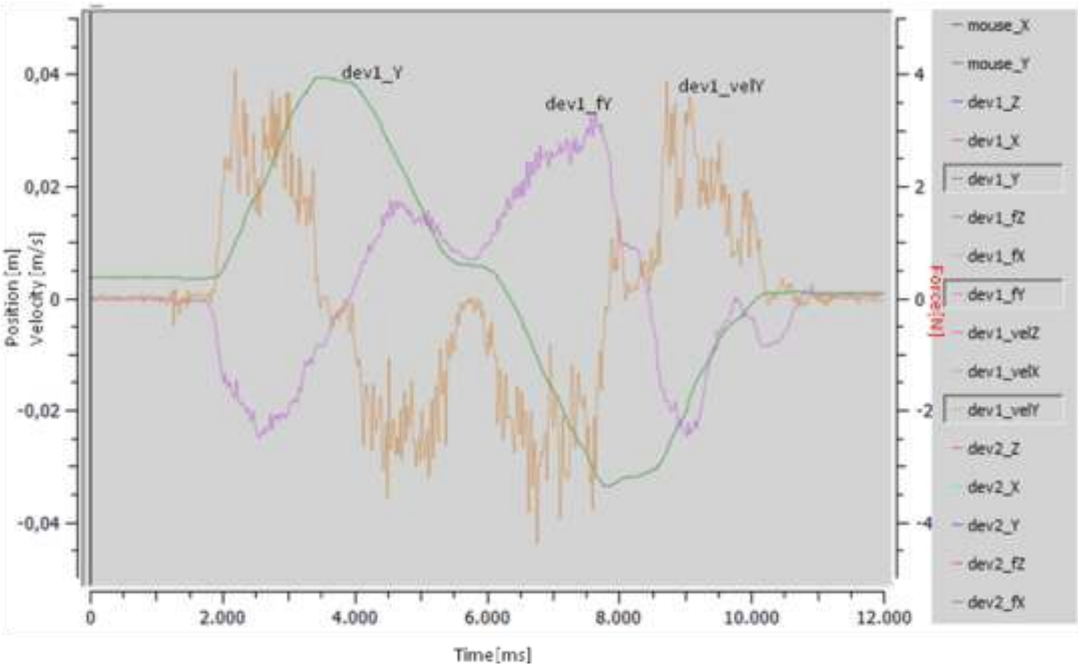


Figure 2-13. Device1 following Device2. Position, velocity and force profiles for Z-axis of the haptic device frame.

Figure 2-13 was taken from the Analyzer tool developed within the GUI part of the haptic link software. Previously, in the section 2.4.2, different frames used in the experimental system were explained. In the Analyzer tool there is only one reference frame used, and that is the Task frame. The haptic device axes names have been renamed in the Analyzer to alleviate the analysis based on the comparison with the mouse trajectories and to avoid confusion. The X-axis of the Task frame refers to the Y-axis (left-right) of the haptic device frame, and the Y-axis of the Task frame refers to the Z-axis (forward-backward) of the haptic device frame. Up-down movements along the X-axis of the haptic device are denominated as Z-axis movements on the presentation graphs.

Figure 2-13 shows the physical values along the Y-axis of the Task frame of the Device1 in the case when Device1 is following the movement induced on Device2. After the observation of similar plots for all axes of the device, it is possible to come up with the following table.

Table 4. Algebraic signs of physical values during trapezoidal movement.

Position	Velocity	Force
no change	no change	no change
positive	positive	negative
positive	negative	positive
negative	negative	positive
negative	positive	negative

From Table 4 it can be concluded that when one device is following another, the forces measured by this device are negative if there is a movement in the positive direction along a particular axis, and positive when the movement is in the negative direction. This applies anywhere along any axis, irrespective of the position.

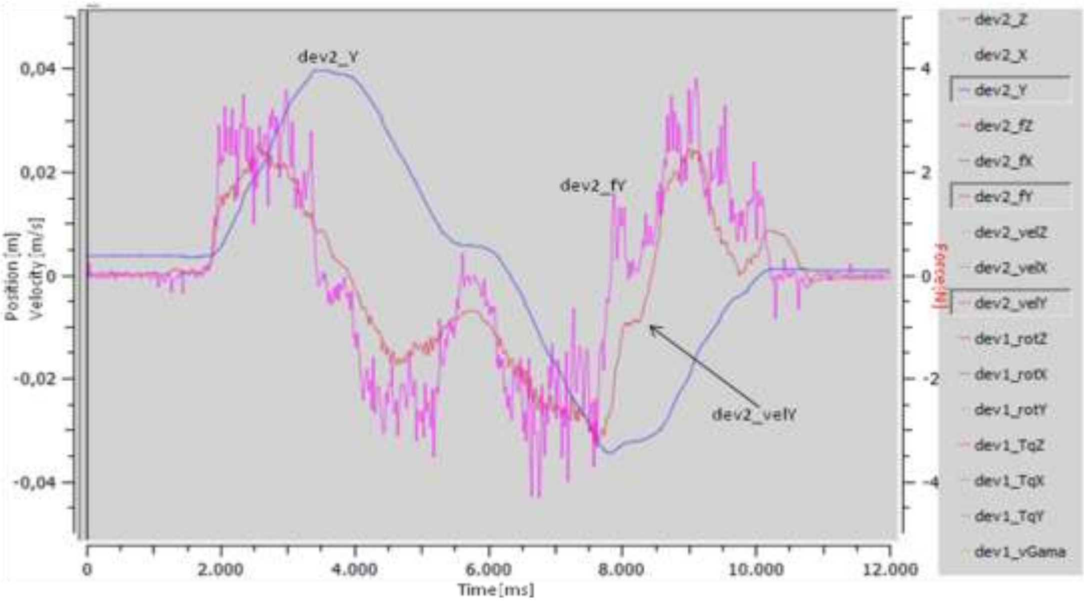


Figure 2-14. Device 2 leading Device1. Position, velocity and force profiles in Z-axis.

Figure 2-14 shows the physical value profiles of Device2 for the same measurement test given in Figure 2-13. With quick inspection it can be observed that when one device is leading the other device, the force measured by the leading device is positive when the velocity is positive and negative when the velocity is negative. The forces profiles for the two linked devices are mirror images between themselves and they always cross each other at the zero value. The points of mutual crossings of the two force curves are indicative points, since they occur only when one device changes the direction along the axis while in the same role (leader, follower), or when the devices change roles while keeping the same direction.

The change of the role can be deducted from the comparison of position curves for both devices. Usually the leading device position curve is moved somewhat to the left compared to the following device. If the force goes through zero and the position curves change their relative positions on the time axis, then a change of roles occurs.

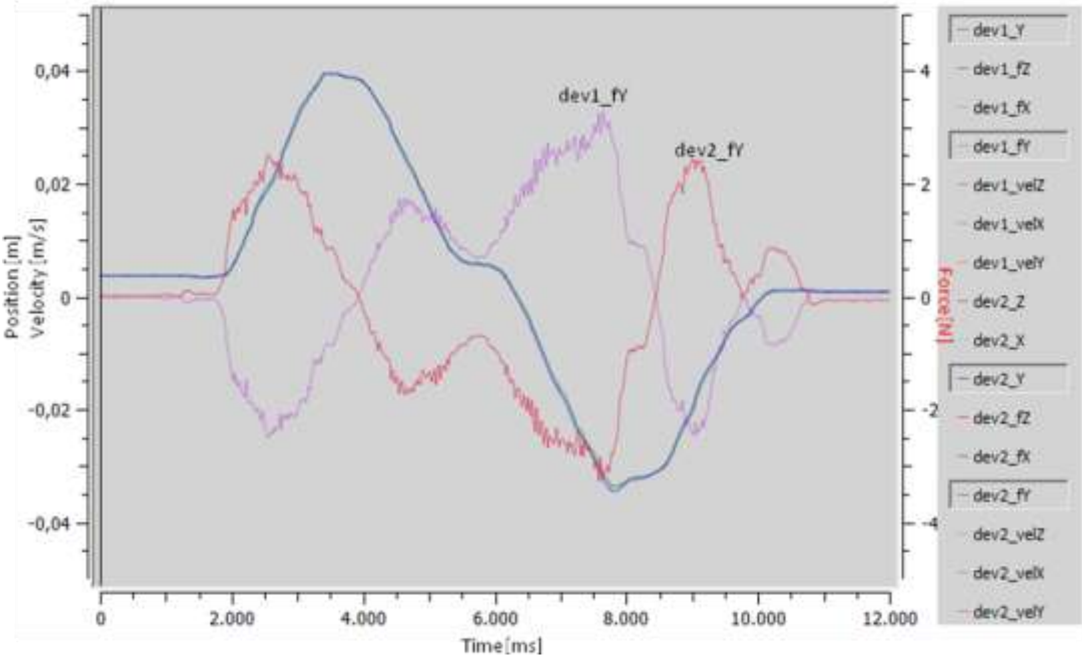


Figure 2-15. Device 2 leading Device1. Forces and positions for both devices.

3 DATA ANALYSIS AND RESULTS

In this chapter we will present the methods that we have used to analyze the experimental data in order to prove our hypotheses. Section 3.1 is focused on the statistical analysis of the dyad performance under different experimental conditions used in the experiments. The purpose of the performance analysis is to investigate the efficiency of haptic modality as a communication channel. In section 3.2, we will thoroughly analyze haptic communication strategies occurring for each dyad. In the end of the chapter, the verbalization analysis resulting in verbal strategies for each dyad will be presented.

3.1 Performance analysis

In the chapter 2.3.1, when describing the choice of the experimental task, it was mentioned that the use of the task modeled after Fitts's law gives easily applicable metrics to prove haptic communication efficiency afterwards. How so?

The performance of Fitts's type task is measured directly by the completion time of the trial for each target point. Fitts's law says that the time required to rapidly move a cursor to a target area is a function of distance and target size. The law is proven to be valid for one person carrying out the simple 2D positioning task described by Figure 2-1. When this simple 2D task is transformed into a collaborative task, it can be expected that Fitts's law will still hold if the communication between collaborators is efficient. Since verbal communication is a very efficient form of communication, statistical analysis of the performance in the experiments with the verbal modality is expected to confirm that the used collaborative task indeed conforms to Fitts's law. If similar results are obtained for experiments done with the haptic modality, it will prove that haptic modality is an efficient communication channel.

3.1.1 Haptic modality efficiency

During the experimental sessions three fixed factors were manipulated:

a) Communication with two modalities: Haptic (H), Verbal (V)

b) Order of modalities in the experiment: Haptic>>Verbal (H>>V), Verbal>>Haptic (H>>V)

c) Index of difficulty of target points (ID) with values: 1.8 (ID1), 2.8 (ID2), 3.3 (ID3), 3.8 (ID4).

The time (T) to complete one trial was used as a direct measure of the task performance for each trial.

Table 5. Fixed factors in the experiment.

	Haptic		Verbal	
H->V	ID1	ID2	ID1	ID2
	ID3	ID4	ID3	ID4
V->H	ID1	ID2	ID1	ID2
	ID3	ID4	ID3	ID4

The statistical data we had was taken from all the trials done by 10 dyads. This gives an overall number of 640 trials. The first thing that we wanted to check was if the collaborative task is a Fitts's type task as we expected.

First, we calculated the average performance times for each ID under two different modalities of communication. Putting the ID on the horizontal axis, and performance times on the vertical axis, we obtained the graphical representation usually used for Fitts's law. Graphs are shown on Figure 3-1.

On Figure 3-1 it can be seen that the resulting trend for verbal modality conforms to Fitts's law. This proves that the collaborative task is a Fitts's type task as it was anticipated.

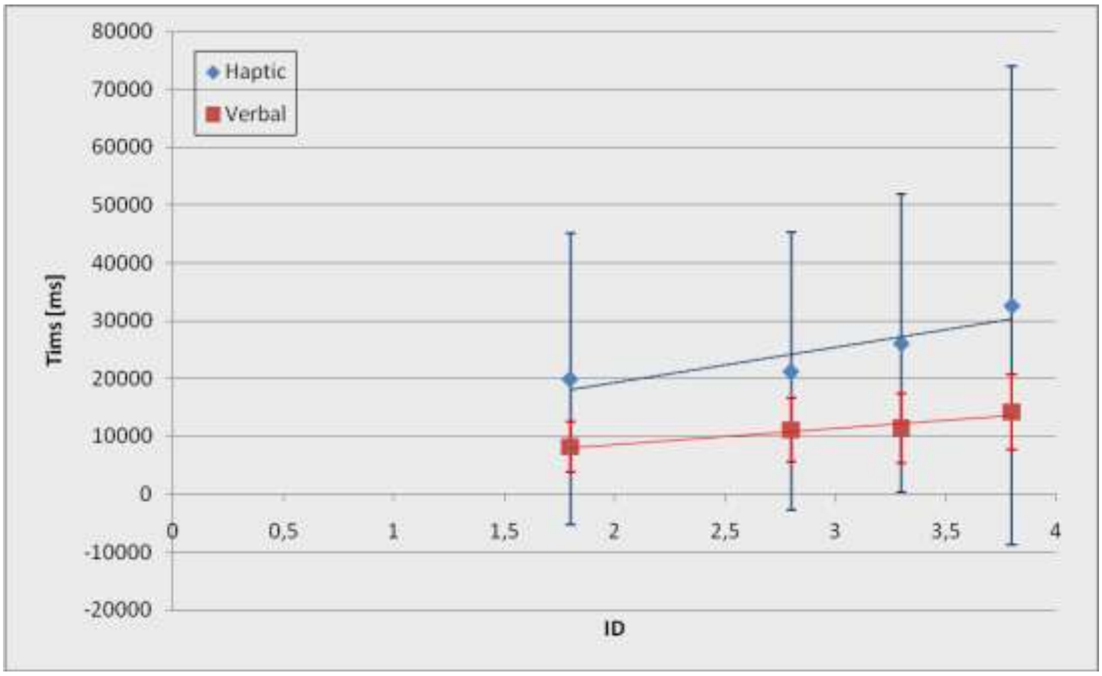


Figure 3-1. Performance with haptic modality compared to verbal modality. Overall experimental data.

The haptic modality data fits to a rising linear trend similar to the trend for verbal modality. This proves that haptic collaboration on average was efficient to use in the collaborative task. However, its average efficiency is around two times less than when using verbal modality. Furthermore, there are larger standard deviations for haptic modality data. The reason for this could be that for haptic modality each dyad had to develop their own communication model, which is not the case for verbal modality. There were big individual differences because some subjects were able to start with efficient haptic communication right away, and others needed more time to become effective.

In order to check the performance in the case with the developed efficient communication via haptic modality, we will consider the data from the 10 session blocks (with haptic modality) for which the overall time needed to solve all 16 trial points was the fastest. Furthermore, we will estimate that the learning phase for each block of trials with haptic data was the first 6 points. We will eliminate the first 6 points from each of the chosen 10 best blocks, and then calculate the averages and standard deviations. The resulting graph is shown in Figure 3-2.

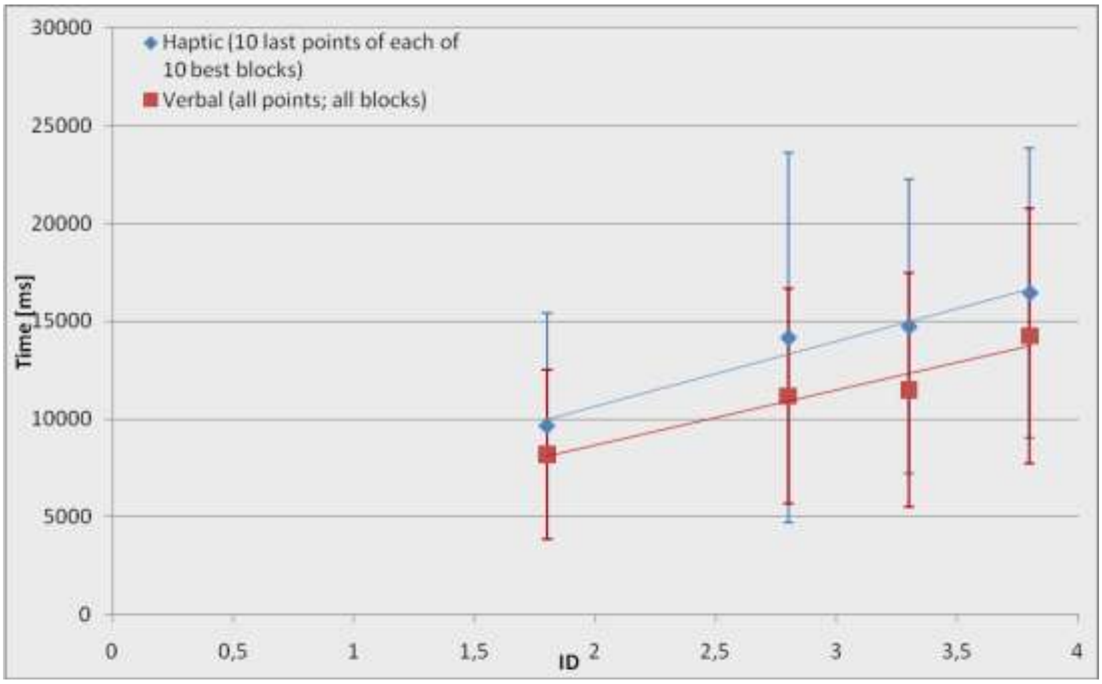


Figure 3-2. Performance with haptic modality compared to verbal modality. The data for haptic modality is from trials for which it is presumed that dyads have had already established common grounds for communication.

In Figure 3-2 it is visible that when there is an established common ground between the members of the dyad, the efficiency of the haptic modality is almost on par with the efficiency of the verbal modality. The plots for both conditions have similar slopes, and the average time difference is around 3 seconds in favor of the verbal modality. It also can be noticed that the standard deviations for haptic modality are now on the same level that is comparable to the verbal modality.

3.1.2 ANOVA

With further analysis of performance, we wanted to investigate the possible influence of experimental factors on the results. The data we have contains interrelated factors, so we used an ANOVA. The dependent variable is time, and the fixed factors are communication, order and ID. This leads to the univariate three-way ANOVA. The spread of all trial points (N=640) between the different experimental factors and their modalities is given in Table 6.

Table 6. The spread of number of trials among fixed factors.

Between-Subjects Factors

		N
Communication	Haptic	320
	Verbal	320
Order	H - V	320
	V - H	320
ID	ID1	160
	ID2	160
	ID3	160
	ID4	160

Table 7. ANOVA results.

Tests of Between-Subjects Effects

Dependent Variable:Time

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5,148E10	15	3,432E9	7,397	,000
Intercept	2,144E11	1	2,144E11	462,080	,000
Communication	3,170E10	1	3,170E10	68,333	,000
Order	5,160E9	1	5,160E9	11,121	,001
ID	8,004E9	3	2,668E9	5,750	,001
Communication * Order	3,798E9	1	3,798E9	8,186	,004
Communication * ID	1,736E9	3	5,785E8	1,247	,292
Order * ID	2,347E8	3	7,823E7	,169	,918
Communication * Order * ID	8,463E8	3	2,821E8	,608	,610
Error	2,895E11	624	4,640E8		
Total	5,554E11	640			
Corrected Total	3,410E11	639			

a. R Squared = ,151 (Adjusted R Squared = ,131)

The results of ANOVA are shown in Table 7. The statistically significant differences are noticeable for each of the fixed factors, which was to be expected. By examining dependent relations between factors, it can be observed that the only statistically significant difference is present for the combination of communication and order.

Figure 3-3 shows the general performance of the dyads for the different combinations of communication and order.

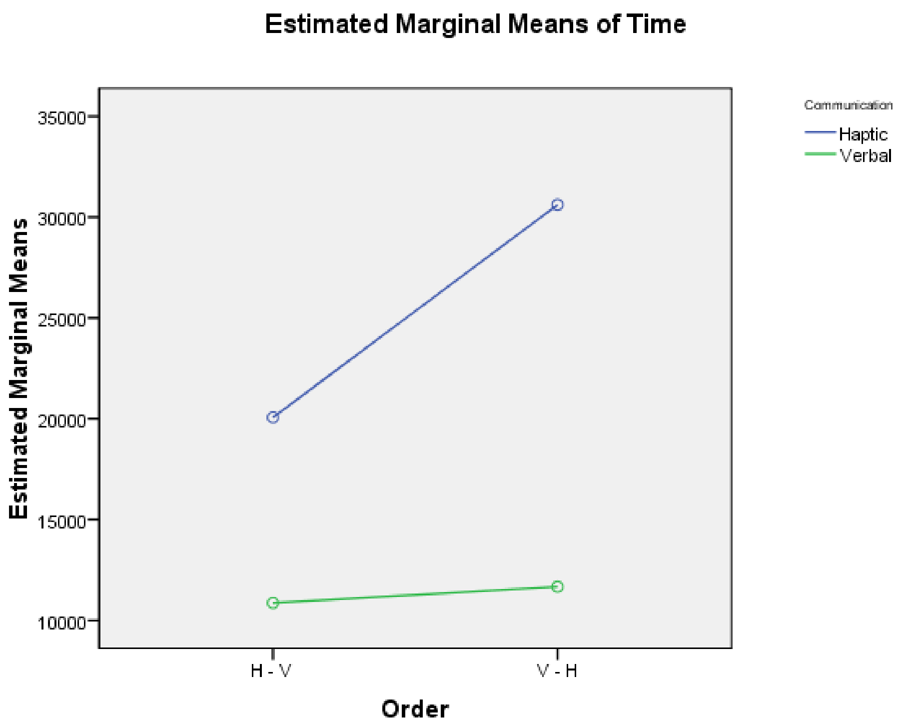


Figure 3-3. Dependency between communication modality and the order of the introduction of modality during experimental session.

In the verbal communication there is a small influence of the order of the introduction of modalities into the experiment. Whether the experiment started with the verbal modality or with the haptic modality, for the efficiency of performance using the verbal communication, it seems to be non-essential. The explanation can be found in the fact that people are very adept in using verbal communication. There might be a present influence of the haptic modality on the choice of words used in verbal communication (which will be investigated later), but since people in general are very proficient with verbal communication they can adapt very quickly to the used vocabulary. On the other hand, the dyads did not previously know any haptic vocabulary when starting to work with the haptic modality. They needed to develop one in order to become more successful in solving the task. Figure 3-3 shows that the performance of the dyads was better when they started the experimental session with the haptic modality first. This is a very interesting result. A possible reason for this could be that when starting with the haptic modality, subjects learned the experimental task together with the handling of the haptic device. Whereas, when starting with the verbal modality, subjects first learned the task and developed verbal strategy, and afterwards they learned how to use haptic device. Then, when the haptic modality was introduced, subjects had to unlearn the previous strategy and develop a new one. A more complete way to present how exactly each fixed factor combination influenced measured performances is given in the Figure 3-4.

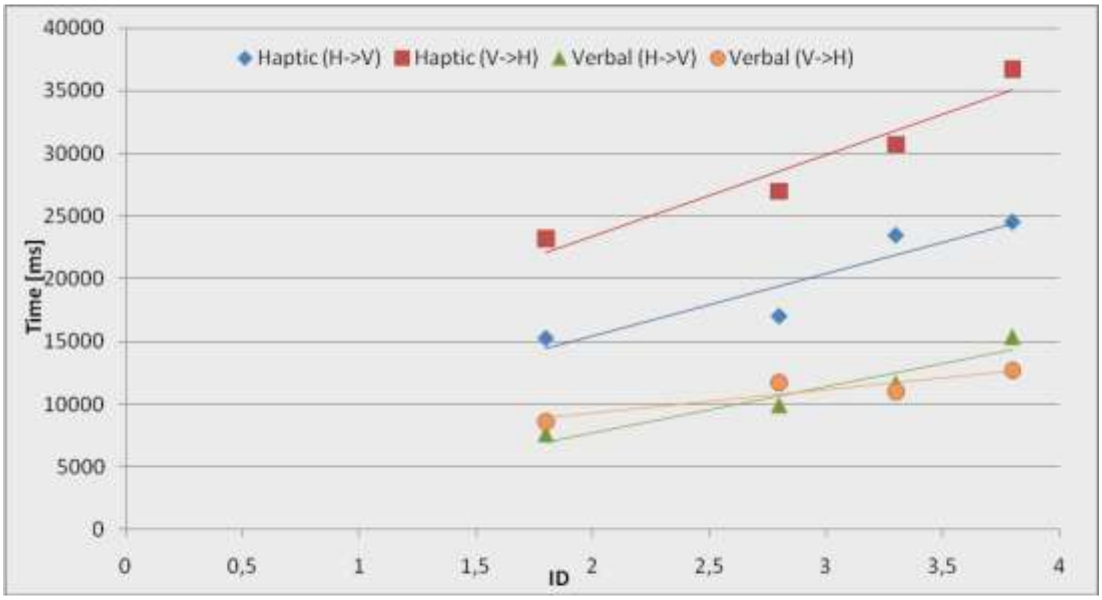


Figure 3-4. Performance for different combinations of communication and order of introduction of modalities.

3.2 Haptic communication analysis

In H2 and H3 (Chapter 2.2) we hypothesized about the expected behavior of dyads in the given collaborative task. We propose that the haptic communication can be categorized into two main categories, depending on whether the movements used by dyad members have specific meanings assigned to them or not. We want to confirm these categories, and find a way to describe them using physical properties of the haptic link system.

Our initial approach to the analysis was visual inspection of the haptic link data together with the captured videos of the sessions. We inspected the graphs with the physical data of all the trials for all the dyads. During the data inspection we developed our own taxonomy for the characteristics we could observe. We will present these observed characteristics here, and show how they differentiate for each of the proposed haptic communication strategies.

3.2.1 Collaborative task and control theory

During the visual inspection, the majority of the terms that we used to describe what was seen originated in the field of control. If we look back at the collaborative task, these terms had to be expected, since the experimental task we used was essentially a control task. The position of the target point can be seen as a reference and the position of the cursor on the screen can be considered as the system output. Using visual feedback the *Supervisor* was able to detect the error, and act by applying his control strategy. The *Actor* can be seen as a controlled subsystem, with two tasks; interpreting the communication and controlling the cursor. Between them was the haptic link which can be seen as the element having attenuation, delay and saturation. The whole idea is presented at Figure 3-5.

The haptic link supports bilateral communication. The observations of trials showed that this property was not utilized by dyads. Only in one trial out of more than 300 with the haptic modality, there was a case in which the *Actor* took over the initiative on the haptic link for a brief moment. On all other occasions, the haptic link was used as the unilateral communication channel with the direction of transmission from

Supervisor to *Actor*. The communication in direction from *Actor* to *Supervisor* was realized only through visual feedback of the cursor on the screen. The *Actor* had the full freedom to choose how to control the mouse device. In some cases the *Actor* initialized the random search, which showed to the *Supervisor* that his current strategy is not efficient and that the change in control is needed. If *Supervisor* had seen that his current strategy is effective he would hold onto it. After establishing stable communication on the haptic link, it was not unusual for the *Actor* to continue evolving his control strategy to include the prediction of position desired by the *Supervisor*.

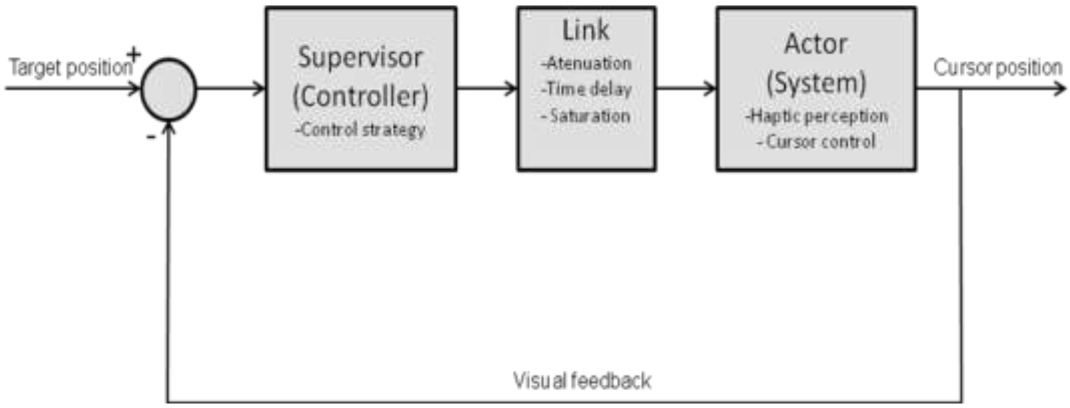


Figure 3-5. Experimental setup with haptic modality viewed as a control system.

3.2.2 Control characteristics

The control characteristics are features that we noticed during the observation of the physical data of the trials. We use these features to describe control strategies used by dyad members.

For the haptic link we identified:

a) sequential axis control

b) dominant DoF

c) device workspace

and for the mouse:

d) movement type

e) control type.

Sequential axis control

This characteristic is very simple to observe. It tells us whether the *Supervisor* is trying to control the cursor along both axes of the task workspace simultaneously or sequentially, one after the other. Using sequential control simplifies the control problem for the dyad. This control mode is the easiest to observe through the mouse position variable. An example of the plots of mouse position in both axes for sequential control is given on Figure 3-6.

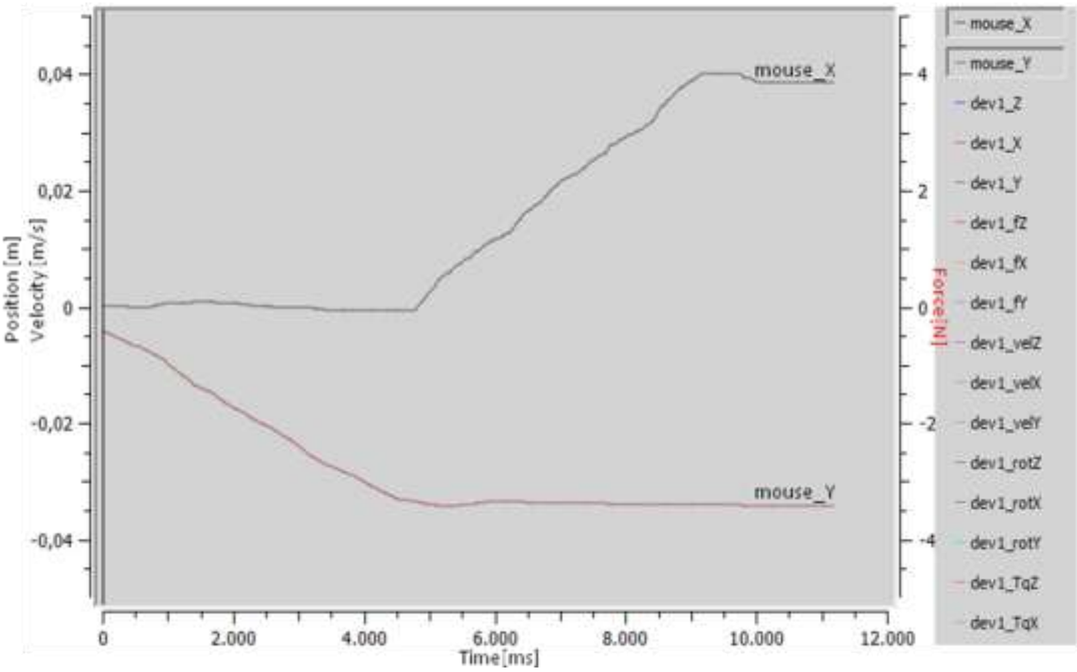


Figure 3-6. Mouse positions for strict sequential control.

Dominant degrees of freedom

By this characteristic we want to describe which DoFs of the haptic device are used to transmit information. The main classification is based upon whether the *Supervisor* is using translational (T) or rotational (R) motions. As explained previously our haptic device is a parallel robot with a base, three legs and a mobile platform. Joystick held by the user during utilization of the device is attached to the mobile platform. Measured position of the haptic device is defined as the position of the center of the mobile platform. When the device is translated inside the workspace, this is measured by the positional variables for X,Y and Z axis (dev_X, dev_Y, dev_Z). The rotation of the mobile platform in the space is measured with quaternion, which is subsequently transformed into angles around each of the frame axis (dev_rotX, dev_rotY, dev_rotZ).

Dominant translational movements are specified by the noticeable change in position, while the rotational angle stays the same. This change is observed easiest through translational velocity. Each axis is observed independently. On Figure 3-7 an example for the X-axis is shown. We can see that there is a displacement (posX) in the positive direction at about 0.01 m for duration of 500 ms. This displacement is accompanied by the velocity spike. Rotation along the X-axis is defined by the rotY variable. This is the outcome of the Task frame definition. Positive rotation around the Y-axis means that the device is rotated in the positive X direction.

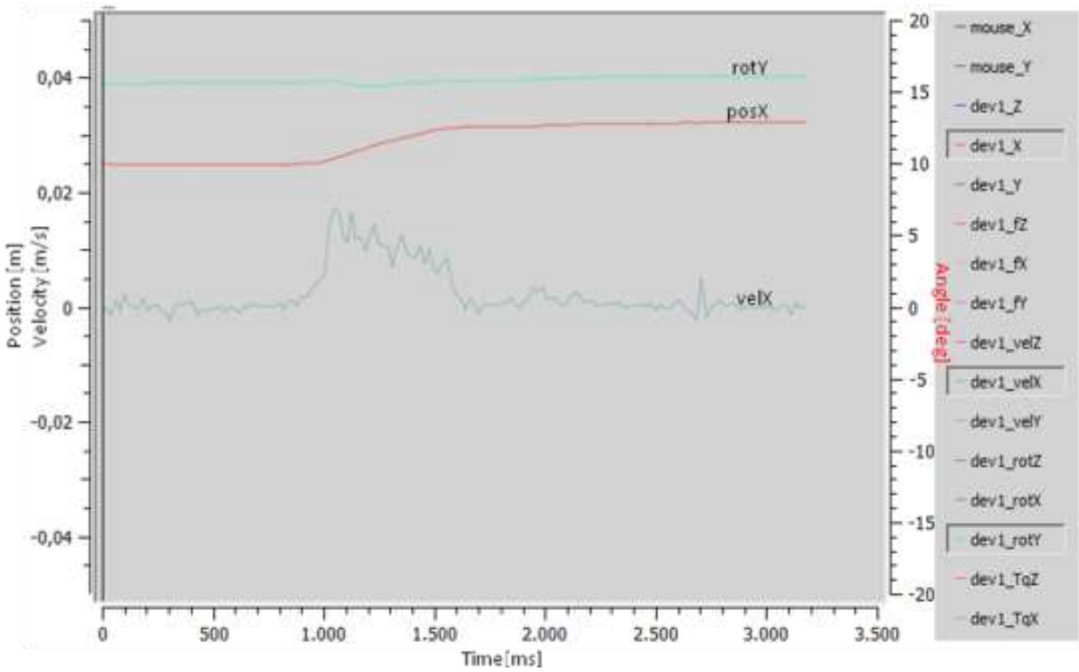


Figure 3-7. Position, velocity and rotation along X-axis for dominant translational movement. Rotation angle of the device stays unchanged.

For the dominant rotational movements, the relation between the displacement and rotation angle is inverse, as can be seen in Figure 3-8. Angle changes are noticeable and they yield at least 10 degrees or more, while position along the same axis stays the same. The severity of the rotational movement can also be observed through angular velocity variables (vAlfa, vBeta,vGama). vAlfa corresponds to the angular velocity along the X-axis. The angular velocity, vAlfa, is positive when the rotation about the Y-axis (rotY) is in the positive X direction. vBeta corresponds to the Y-axis and it is negative for the rotation along positive Y direction.

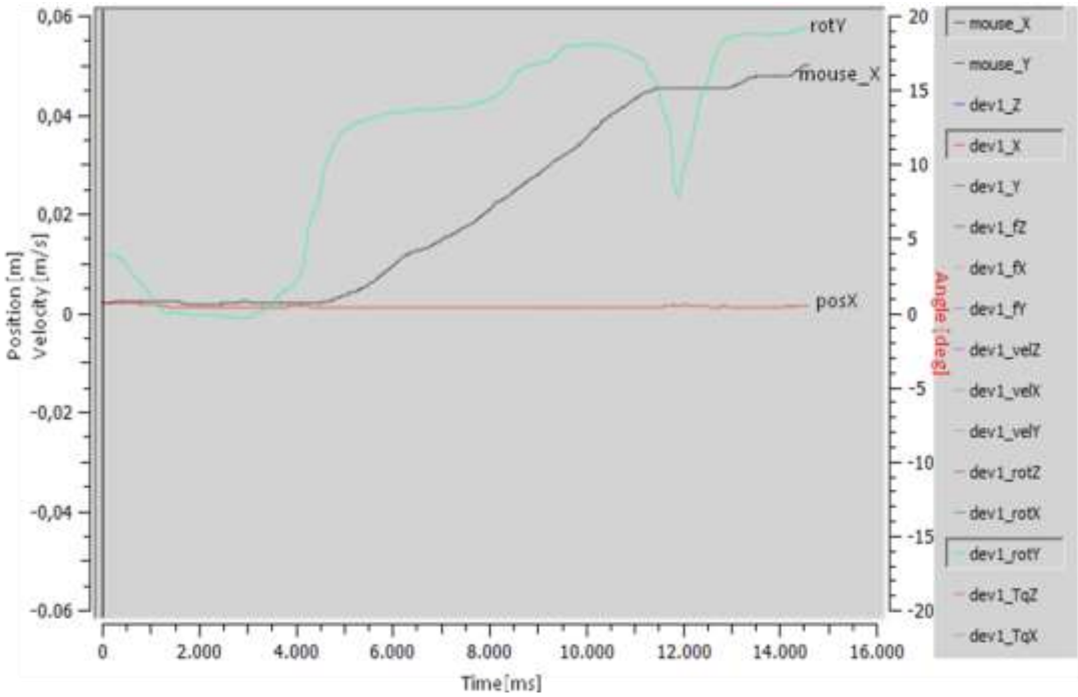


Figure 3-8. Position and rotation on the haptic device for dominant rotational movement along X-axis. *Actor*'s response to the movement is represented by mouse displacement.

Further classifications of movements include different combinations of translation and rotation. The most used one was proportional translational-rotational movement of the device (PTR). For PTR movement, the translation of the device farther from the center in a particular direction is accompanied by a proportionally bigger rotation in that direction. The example is showed in Figure 3-9.

Furthermore, we have temporal combinations of dominant movements, where for example translational movements are used first for approximating the position, and then a rotation is used for fine positioning around the target (T>>R). At last, there are motions for which it is impossible to figure out if there is any dominant DoF present (T+R).

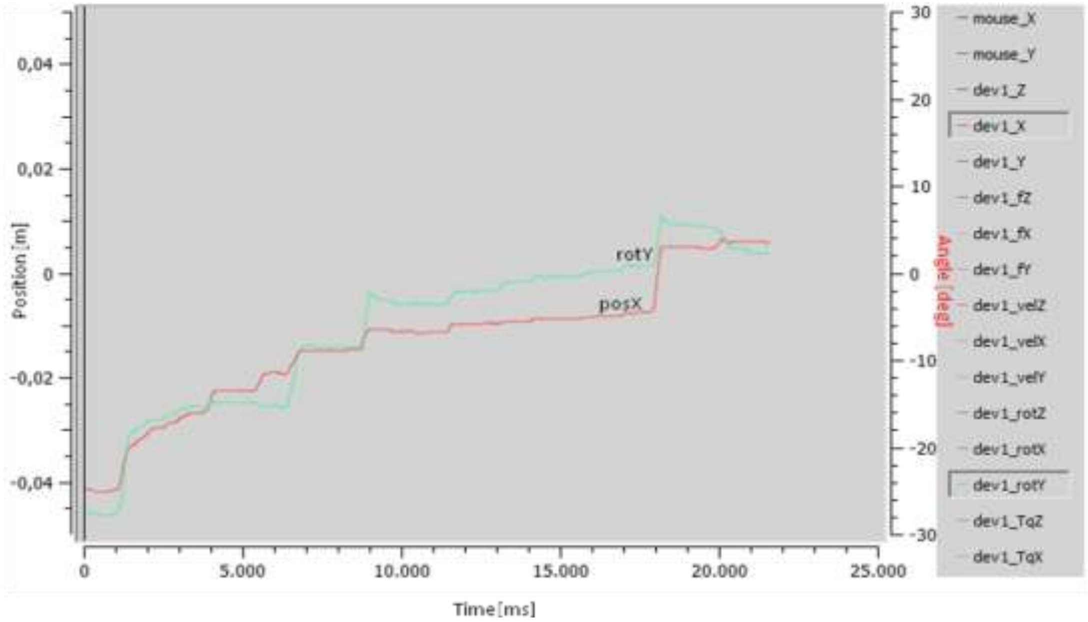


Figure 3-9. An example of proportional translational-rotational movement along X-axis.

Device workspace

With this characteristic we try to describe the way in which the *Supervisor* utilizes the workspace of the haptic device. The first observation is about the main used plane of the haptic device frame. For our experiment, we predicted that the horizontal plane would be the obvious choice, because it was positioned in the same way as the mouse work plane. However, we left the haptic device unconstrained and didn't give any particular instructions about the specific work plane to be used. We wanted to observe the natural human mapping between the visual workspace and haptic device workspace for the given task. Experiments with dyads showed that the vast majority of subjects used the horizontal haptic device plane (X-Y), as was expected. There was one dyad in which both members used the vertical plane (X-Z). Also, there was one subject that used the diagonal plane; with the diagonal plane as the indication for moving the cursor vertically on the screen. An up-and-forward movement of the haptic device was used to indicate an up motion on the mouse plane, and a down-and-backward movement was used to indicate a down motion on the mouse plane.

A second observation about the work plane is whether applied strategies use the full active workspace, just the zone near the center, or just limits of the workspace. As it will be presented later, the effectiveness of the haptic control strategy depends heavily on the way in which the *Supervisor* uses available workspace.

Mouse movement type

We classified mouse movements executed by the *Actor* into three particular classes; considering the regularity and continuity of the movement. The first class consisted of irregular mouse movements. This is a general class for mouse movements that don't have any specific axis direction during their execution. These movements might be continuous or they can contain pauses, which transforms them into a series of short discrete displacements. Depending on the success of the dyad's communication strategy, a pause in the mouse movement along the axis can mean that there is a recognized direction change instructed by the *Supervisor*, or that the *Actor* is indecisive whether to continue in the same direction.

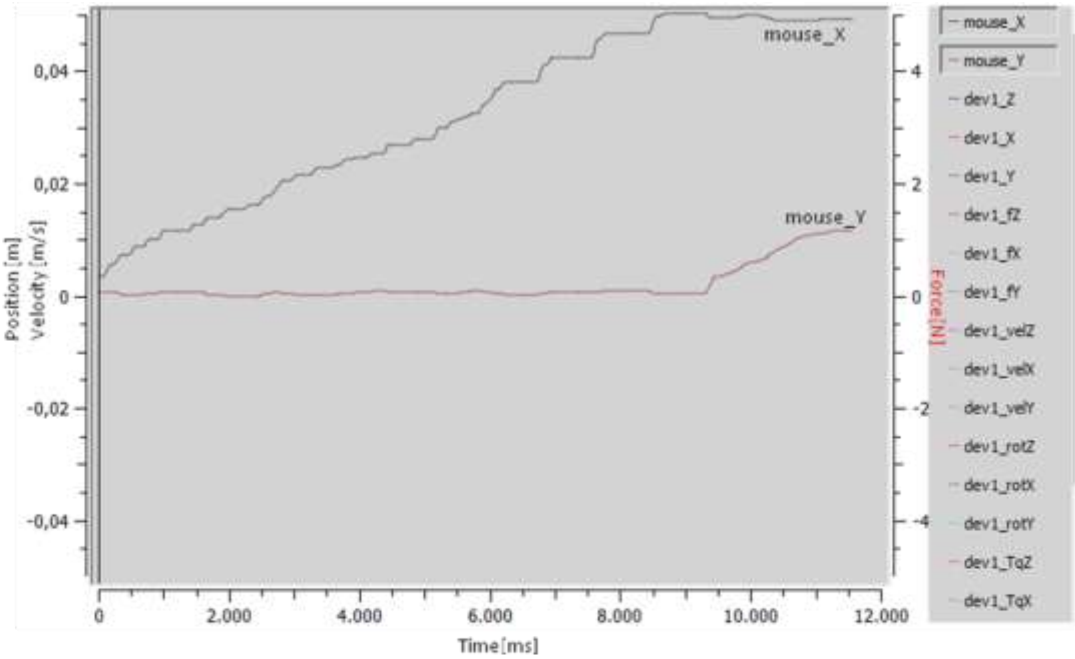


Figure 3-10. An example of the directed step movement.

The second class is directed step movement. The mouse movement is characterized by a series of discrete positional steps in one direction, as seen in Figure 3-10.

The third possible class is directed continuous movement. In this class we considered mouse movements which have longer continuous segments along the same axis.

Mouse control type

This characteristic describes the behavior of the Actor in terms of how he controls the mouse based on inputs from the haptic device. From the control theory, two basic control types are known; feedback and feed-forward. The idea was to characterize the *Actor's* mouse control strategy in a similar manner. In the case when it is obvious that mouse movements are the delayed responses of the input value from the haptic device, we classify the control type as feedback. Feedback control of the mouse can be mostly expected in the given experimental system. This control was applied in the big majority of the trials observed.

It was noticed that if a dyad develops effective haptic communication, so that the *Actor* knows for sure which is the intended direction of the movement, the *Actor* will try to improve his performance. After realizing the desired direction of the movement, the *Actor* will usually make big initial movements in that direction, and then wait for the next input from the haptic device to see whether to go on more or not. In subsequent movements, always knowing the desired direction, the *Actor* will vary the mouse displacement based on his prediction about where the target position could be. We called this mouse control type predictive control. This mouse control type is used for discrete mouse movements, and it is an indicator of very good haptic communication inside the dyad.

The final mouse control type that we classified is random search control. As in the previous case, this way of control is based on predictions, but unlike the previous one there is no knowledge about the desired direction of the movement by the *Supervisor*. This control type is an indicator of failure in the haptic communication. Input coming from the haptic device is not well perceived by the *Actor*, and he is trying to guess the target position, or to provoke the *Supervisor* to give him new instructions.

3.2.3 Haptic communication strategies

Classification of the haptic communication strategies used by the dyads is the final result of the observation of the experimental data. The basic factor for assessment of the dyad haptic strategy was the type of the motion used on the haptic device. We observed that three types of motions are used by subjects on the haptic device:

a) continuous motion

b) impulse motion

c) pointing

A continuous motion is a movement in which the position and orientation of the device is changed gradually, without notable changes in the linear and angular velocity of the device.

Impulse motions are the series of fast jerks of the device in the desired direction. Impulse motions are characterized by distinctive spikes in the linear and angular velocity.

Pointing is the movement in which the device is held in a certain posture for a given amount of time, without a change in rotation or position. The purpose of pointing is to signal the desired direction of the movement of the cursor. Depending on how the pointing state is developed, we were able to classify pointing into two subcategories. The first one is pointing which evolves through continuous movement. Since the used device is kinesthetic, subjects who try to guess the desired direction are not able to feel the absolute position and orientation of the device. That can often lead to misinterpretation of the wanted direction. The second category is pointing evolved through impulse direction change (IDC). With the IDC, the haptic device is put into the pointing state through a fast and resolute translational or rotational motion observable by a spike of velocity or force/torque.

For each trial of each dyad, haptic communication was described using the basic movement type used on the haptic link, together with all the other previously introduced characteristics. Then, the descriptions were classified into a few main categories. To each category we assigned a descriptive name.

Motion copying

Motion copying seems to be the most natural and the most obvious way to transmit spatial information through the haptic link. The recordings showed that each dyad started their haptic portion of the session by using this method. The subjects were considered to be using motion copying if:

a) The *Supervisor* used continuous (T or PTR) movements inside the active workspace of the haptic device

b) Haptic device movements were changing concurrently along both axes of the work plane

c) The *Actor* responded with mouse movements that tried to copy the trajectory of the haptic device

d) The mouse trajectory was continuous and was changing concurrently along both axes

This strategy showed to be effective only if the haptic devices were operated inside the active workspace. This means that the strategy usually worked for target points with ID 1.8 and 2.8. Still, the proximity of the point was not an assurance of an easy completion of the task, since the trajectory could have been easily misinterpreted by the *Actor* at any moment.

The available workspace for the translational movement on the haptic device was a crucial factor. It often happened that the *Supervisor* wanted to continue the movement in a certain direction, but was not able to, because of the workspace limitations. If there wasn't more space for translational movements, the position of the device was set to the limit of the workspace and the passive pointing in the desired direction would occur. The lack of movement was not well interpreted by the *Actor*, who either completely stopped moving the mouse, or just applied random mouse displacements. If the random mouse displacements occurred, the *Supervisor* would try to direct them by changing the rotation of the device, while still being positioned at the limit.

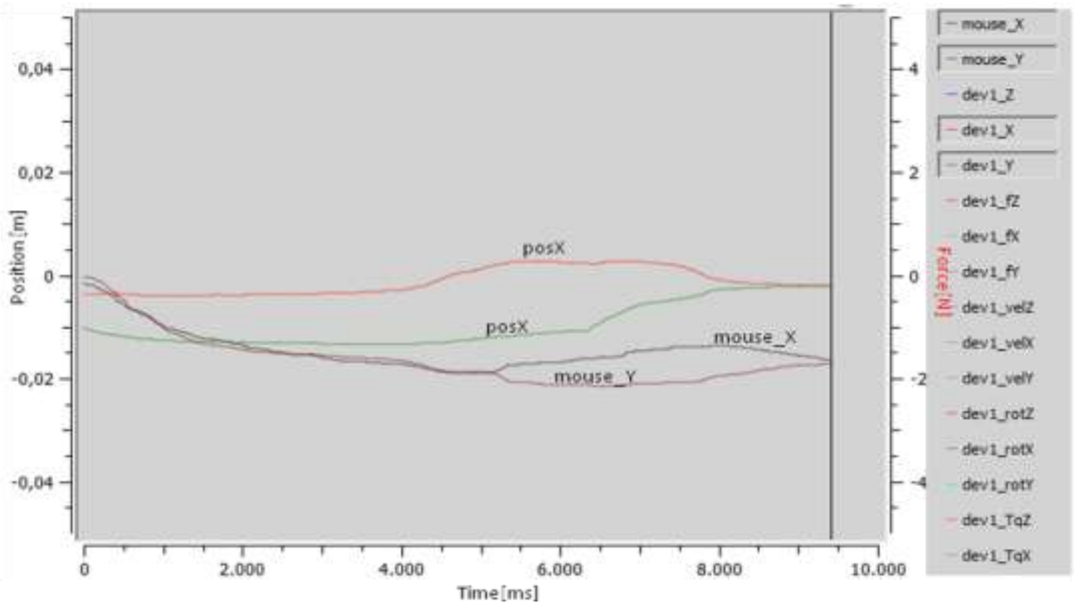


Figure 3-11. Motion copying strategy. Positions of the haptic device and mouse device as the function of time.

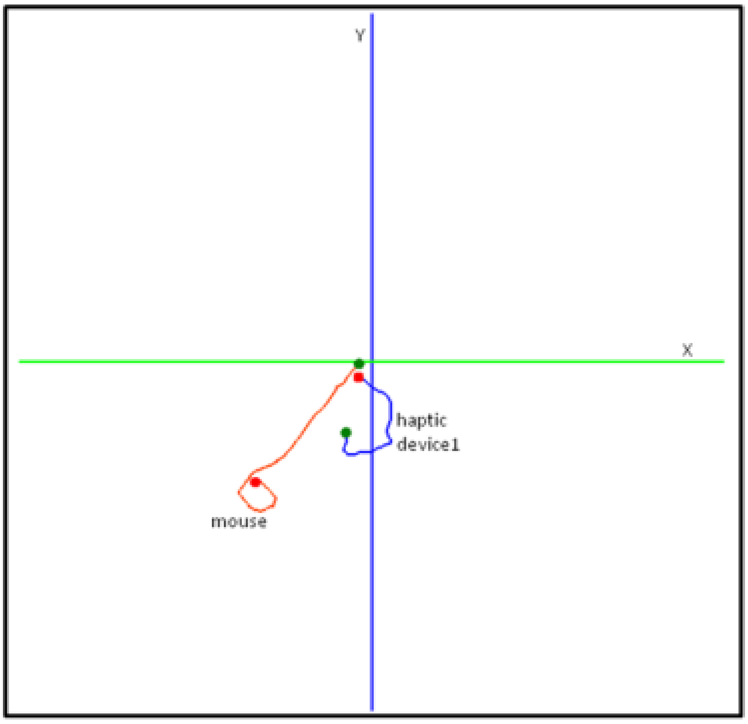


Figure 3-12. Motion copying strategy. 2D trajectories of the mouse and the haptic device for the same trial as in Figure 3-11. Target point has ID=2.8. The green point is the starting position.

Attempts to recentralize the haptic device were also registered. The haptic device would be returned to the center of the workspace, but the usual response of the *Actor* subject was to follow the movement or just not to react in any way. Motion copying with the recentralization of the haptic device never evolved to be a working strategy.

The task can eventually be solved by using a motion copying strategy, but the overall performance times are very inconsistent. For example, for the points with the same ID of 1.8, minimum and maximum times of 5 seconds and 341 seconds were recorded respectively.

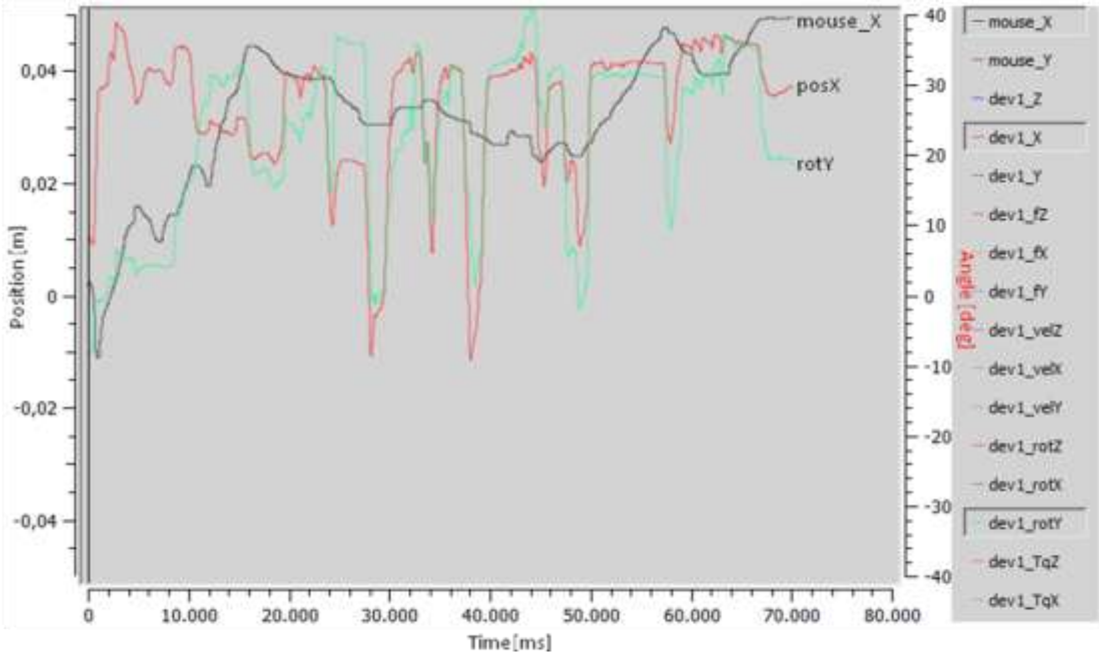


Figure 3-13. An example of the motion copying strategy for a case when haptic device goes at the limit of the workspace along the X-axis. The *Supervisor* used PTR movements. The device was recentralized two times, but there was no adequate response from the *Actor*.

Steering

Steering is the type of communication strategy that evolves from motion copying as a way to bypass the constraints of the limited workspace of the haptic device. After realizing that it was not very effective to use slow movements of the haptic device for the points with bigger distances from the center, the *Supervisor* would usually start to make bigger translational or PTR movements in the desired direction and then just stop and keep the device still. Swift directional movement was done with the intention to compel the *Actor* to use faster mouse movements in order to cover more distance towards the target point. If the response mouse movement was too strong and it overshot the target point in the direction of a movement, a sharp motion in the opposite direction would have been applied in order to signal a need for stopping. After stopping, a swift directional movement along the other, orthogonal axis would be made in a similar manner.

By using this strategy, dyads were able to reach the target point area very quickly. When being in an area near the target point, the communication strategy was usually switched to motion copying for fine tuning of the cursor position.

The dyad members were said to be using the steering strategy if:

a) The work plane of the haptic device was split into two distinct orthogonal axes, and the haptic device was pointed along the axes in a sequential order.

b) They used translational or PTR pointing motion inside the active workspace of the haptic device, or used rotational pointing motion in the center of the device workspace.

c) The beginning phase of the swift device motion in one direction had very high velocity, recognizable through a velocity spike.

d) The stopping phase of the pointing was also recognizable through a velocity spike, this time in the opposite direction than the starting one. If the strategy uses the stopping impulse when switching between the axes, the motion was labeled as IDC-S pointing, where S stands for the stop message.

e) Sometimes it was possible to make a direct change of axes, without using the stopping impulse, but instead, to just initiate the pointing in the other direction. This kind of motion is labeled as IDC-D, where D stands for direct.

f) The pointing movement of the *Supervisor* in a certain direction was responded to by the *Actor*'s movement of the mouse along the same direction. Mouse movements were usually continuous for the first direction, and might have been continuous or discrete for subsequent directions, after the first direction change.

g) If the cursor didn't reach the target point by the straightforward use of this strategy, subjects would still know that they were in the area quite close to the target. For fine tuning, the *Supervisor* usually switched to continuous motions of the haptic device and the motion copying strategy.

Figure 3-14 displays a nice example of the steering strategy use. It can be noticed that when there was a movement of the mouse along one of the axes, the position didn't change in the other axis. Velocity spikes are clearly visible. The lag between a velocity impulse for the direction and the mouse movement response is around 600 ms. The mouse was always moved continuously between the two velocity impulses of the opposite directions.

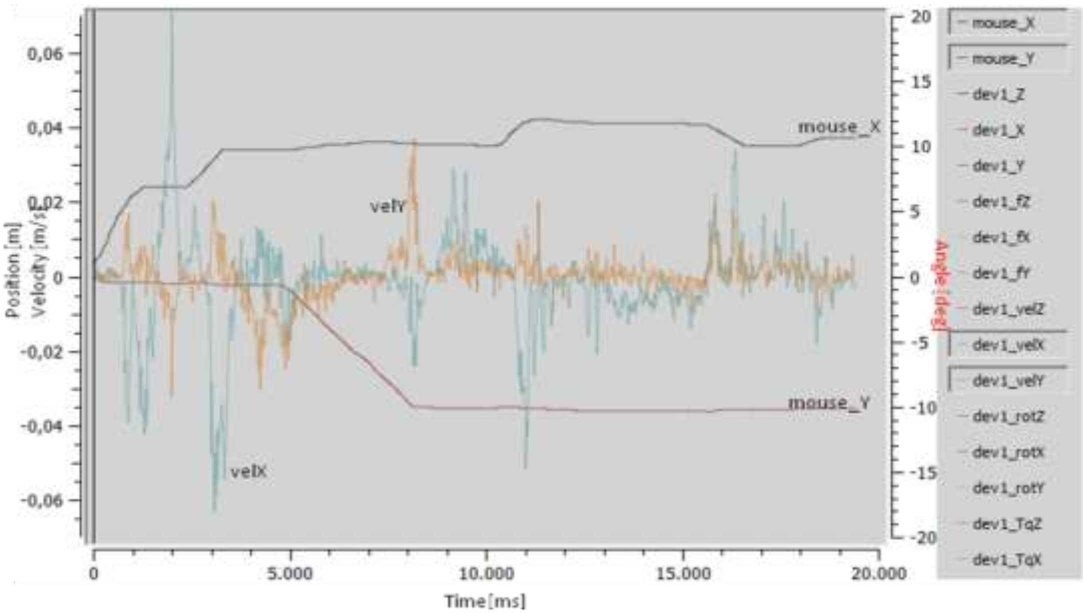


Figure 3-14. Steering strategy. Mouse positions and linear velocities of the haptic device in X and Y axis as functions of time.

Impulse control

Instead of using single impulses to control the movement in a certain direction, it is possible to use a continuous series of discrete impulse motions for the same task. Impulse motions happened when the haptic device was displaced or rotated from the center of the workspace with a very high velocity in the desired direction, and then returned back into the center with a somewhat lesser velocity. Usually, one impulse would be responded to by the *Actor* with a discrete displacement of the cursor for a few millimeters in the given direction. In order to designate the necessity for the prolongation of the already started cursor movement, directional impulses were repeated continuously in a series. The lack of impulses meant that the cursor movement should be stopped.

Impulse control communication strategy is described by the following characteristics:

a) work plane of the haptic device is split into two distinct orthogonal axes, and the haptic device was moved along axis in a sequential order.

b) Impulses can be produced by device translations, rotations or a mixture of both types of movements. Impulse motions are best observed through linear or angular velocity.

c) Usually the center of the haptic device workspace is used for translational and rotational impulses. Active workspace is used if big PTR impulses are being applied.

d) The frequency of movement impulses is between 0.5 Hz and 2.5 Hz.

e) The mouse response is usually a series of discrete movements along the desired direction, although, there were also some cases when the mouse movement was continuous.

f) The mouse movements are generally a response to an impulse. Instead of using displacements of aproximatively the same length, sometimes, the Actor used displacements of variable length in order to guess a position closer to the target. This is the indication of a predictive type of mouse control. Predictive types of mouse control showed up only in the impulse control strategy.

An example of impulse control with translational motions is given in Figure 3-15. The plane used on the haptic device was X-Z plane (vertical). The alteration between the axes controlled is clearly visible. Impulses on the haptic device were responded to with continuous mouse movements. The frequency of the impulses was around 2 Hz.

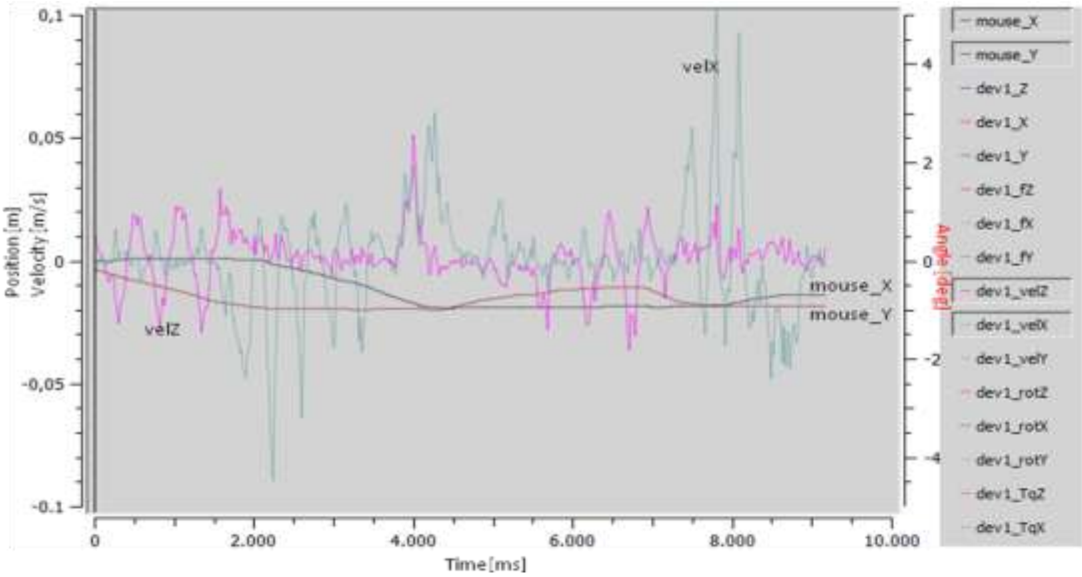


Figure 3-15. Impulse control with 2 Hz frequency and continuous mouse movement response. Mouse positions in X and Y axis, and haptic device linear velocities in X and Z axis are showed as the functions of time.

The impulse control communication strategy yielded the best results in terms of task trial completion times. The efficiency level of haptic communication with this strategy is directly comparable with the efficiency of communication with the verbal modality.

An interesting observation was the evolution of this strategy inside a dyad. In our experiments, the impulse control strategy was always developed during the first trial in a block directly from the motion copying strategy. After realizing that motion copying is not effective, the *Supervisor* would try out directional impulses and the strategy was accepted right away from the *Actor*. If the impulses were tried out in some later stage of the session block, when the motion copying strategy or steering strategy was already used, the *Actor* would not accept the impulse strategy.

3.2.4 Results

For each trial of each of the experimental blocks with haptic modality, we tried to designate the used haptic strategy. Knowing the different haptic strategies used for each point in the block, we were able to identify the dominant strategy for the whole block. Identified dominant haptic strategies of the dyads, along with their performance times, are given in Table 8.

Table 8. Identified haptic strategies for each dyad.

	Block	HAPTIC STRATEGY	Block time [ms]
Haptic -> Verbal	**S1B1**	Impulse control	201464
	S1B2	Impulse control	162203
	S2B1	Motion copying/Steering	406071
	S2B2	Steering	248155
	S3B1	Motion copying	255119
	S3B2	Motion copying	215839
	S4B1	Steering	1008629
	S4B2	Steering	334760
	S5B1	Impulse control	275924
	S5B2	Impulse control	384673
Verbal->Haptic	**S6B3**	Motion copying	644310
	S6B4	Motion copying/Steering	329223
	S7B3	Motion copying	326267
	S7B4	Steering	615906
	S8B3	Motion copying	1484577
	S8B4	Steeering/Impulse control	244071
	S9B3	Steering	266507
	S9B4	Steering	338990
	S10B3	Motion copying	800609
	S10B4	Impulse control	233069

3.3 Verbal communication analysis

The goal of the verbal analysis was classification of the verbal strategies that dyads used when solving the positioning task. Conversations between dyad members in sessions with verbal modality were transcript and the transcripts were checked for regular patterns. For each observed pattern, we analyzed verbal commands for moving and stopping, and mouse movement responses. Based on these characteristics we defined several types of verbal communication strategies

3.3.1 Control system model

The experimental system with verbal modality can be modeled as a control system, similarly to the control system model for haptic modality previously presented in section 3.2.1.

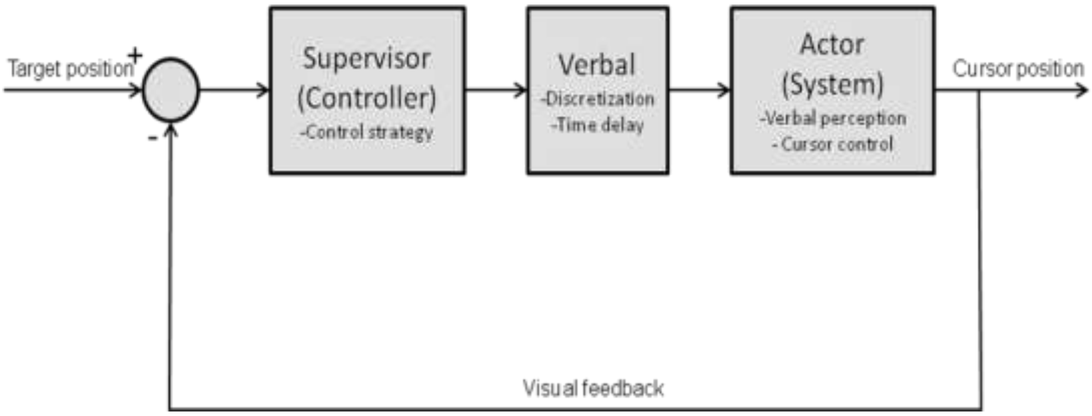


Figure 3-16. Experimental system with verbal modality viewed as a control system.

The majority of the initially introduced control model stays unchanged. The *Supervisor* still has to develop a control strategy based on the visual information about the current cursor position, and the *Actor* still needs to perceive the commands of the *Supervisor* and execute a control of the mouse that he finds to be most appropriate. The only difference is verbal modality which is used for communication inside the system. Communication through verbal modality is always discrete in its nature, which means that there is no way to directly transmit spatial information in the way that it can be done when using haptic modality. However, this is easily compensated by the good mutual understanding, which comes from the experience that people have in using this modality.

An interesting note about the experimental system setup is that the communication during the trials with a verbal modality was unilateral, the same way as it was with haptic modality. Verbal control strategies were imposed by the *Supervisor*, and never questioned by the *Actor* during the trials. There are only three cases noted in which different dyads tried to establish a strategy by mutual talking. The talk was always done in downtime between trials.

3.3.2 Control characteristics

Control characteristics observed in order to analyze verbal strategies were:

a) verbal directional commands

b) verbal stopping commands

c) mouse movement types

Verbal directional commands

The hardest part of the verbalization analysis was the proper systematization of verbal directional commands. Based on the transcripts, we concluded that there were two big groups of these commands.

The first, and the most obvious group of directional commands, are those which use the common relative directions as a reference. Words used as the basis of commands are *left* (L), *right* (R), *up* (U) and *down* (D). This group of commands can be further divided. Relative directional commands can be used separately as they are, or they can be augmented with quantification information.

The quantification information that is added to the relative directional command can have two different forms. The first form is numerical quantification, and the second form is semantical quantification. Numerical quantification is the one in which subjects use numerical quantities of some spatial measurement unit that they found appropriate. Examples of numerical quantification of space that were used by participants are: *1 centimeter*, *2 inches*, *1 finger*, *half of the screen*.

Semantical quantifications are portrayed with an adverb or an adjective common in languages and are used to give the information about the desired quantity of the cursor movement in the already established direction. We noted the following expressions that were used in this context: *slow*, *big*, *small*, *very small*, *not too much*, *just little*, *little*, *little bit*, *little bit more*, *slightly*, *slowly*. As it can be seen, the majority of these expressions try to inform about the need for a small movement in the certain direction, and it is used for a precise control of the cursor.

The second big group of verbal commands were commands that operated with absolute frames of reference which is in the space of the monitor screen. These commands are usually used for the first movement of the trial and their intentions were to put the cursor as close as possible to the target right away. Examples of noted expressions for this type of verbal commands are: *down almost 'till the end*, *all the way to the top*, *corner south-east*, *close south-east*, *north-east far*, *north-east very close*, *diagonal down and left*, *close to the centre*, *down 5 cm from the end of the screen*.

Verbal stopping commands

Verbal stopping commands are the ones that stop the cursor's movement that is going in a certain direction in order to change the direction of the movement with a subsequent command or to just stop on the target. The main observed property observed for this command was whether it was existent or not in the vocabulary of the dyad when the change of the mouse movement direction was completed. Words used for stopping commands were: *stop*, *good*, *OK*, *yes*. Word "stop" was used the most.

Special cases of stopping commands were words "back" and "almost", which were sometimes used. "Back" was used to signal the need for an immediate correction in cases when the target was overshot with a fast mouse movement. "Almost" was used in the opposite case, when a mouse movement undershot the target and an additional small movement was needed.

Mouse movement type

Noted types of the mouse movements are similar as the ones in the experiments with haptic modality. We have:

a) directed continuous movements along one axis

b) directed step movements along one axis

c) irregular movements (synchronous on both axes or small discrete movements which change directions each time)

3.3.3 Verbal communication strategies

We were able to deduce several strategies for verbal communication. Some of them are directly comparable to the previously proposed haptic communication strategies.

Verbal impulses

This strategy uses only relative directional commands. Directional commands are repeated with a certain frequency, which usually depends on the rate of movement of the cursor. If the cursor movement was slow and continuous, the frequency of verbal commands was high, and if the cursor movement was discrete with bigger steps, then the rate of verbal commands was smaller.

The approach to the target was always sequential along the axes of the workspace. Directional commands were always non-quantitative in the beginning of the movement along the axis, and towards the end of the movement, relative directional commands with semantical quantification were sometimes used. Direction changes were usually signaled by a stopping command. Sometimes, instead of using the same directional command (e.g. *left*) in a series, some other word was used with the same meaning. The replacement word was always used only after the direction of the movement was already established. Noted replacement words are: *more*, *go* and *continue*.

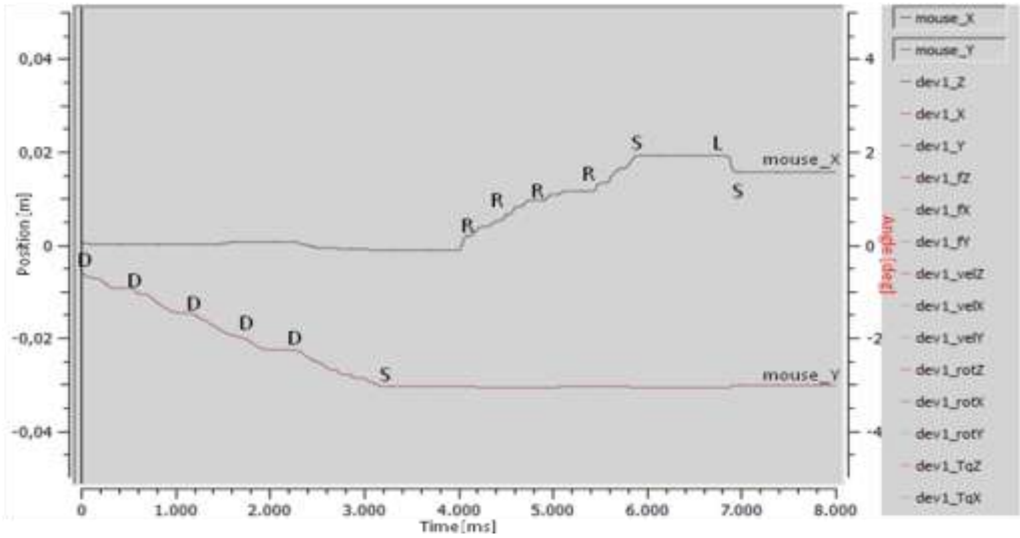


Figure 3-17. Verbal impulse control. Control is responded with directed step mouse movements.

An example of a mouse response for straightforward impulse control is given in Figure 3-17. First, the Y-axis is controlled and then after correcting the Y position, the X-axis was controlled. The sequence of commands used was:

➔ D,D,D,D,D,S; R,R,R,R,S; L,S.

Verbal steering

This strategy uses relative directional commands. The movement is sequential along the axes of the workspace. Only one directional command is given for the movement in a certain direction. This command is responded to by continuous mouse movements until the stopping command is announced. Then, the command for the next direction is given.

An example of a successful use of this strategy is given in Figure 3-18. The control of the movement along the axis was sequential. Verbal commands given are:

➔ U,S; R,S; D,S; L,S; L,S.

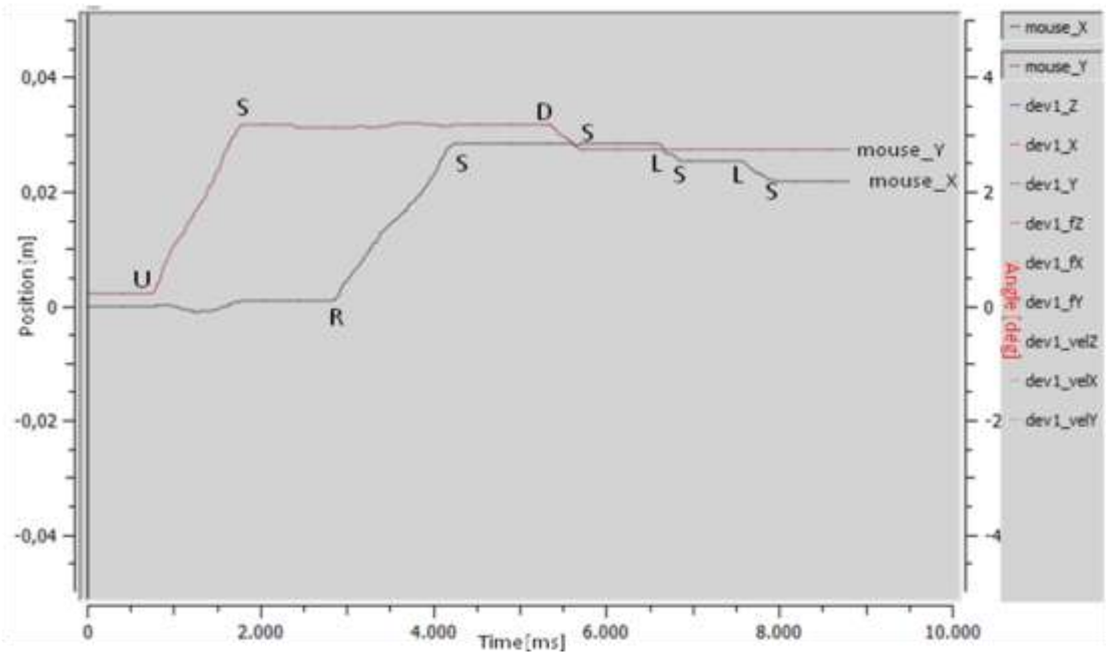


Figure 3-18. Verbal steering. Commands are responded with directed continuous mouse movements.

Metric based guidance

Metric based guidance uses exclusively relative directional commands with numerical quantification. The appropriate metric system (cm, inch, finger) is introduced by the *Supervisor* in the beginning. The *Actor* responds to a given metric as precisely as he can with a displacement that he evaluates to be appropriate. The movements are sequential by axes, and there is no use of a stopping command.

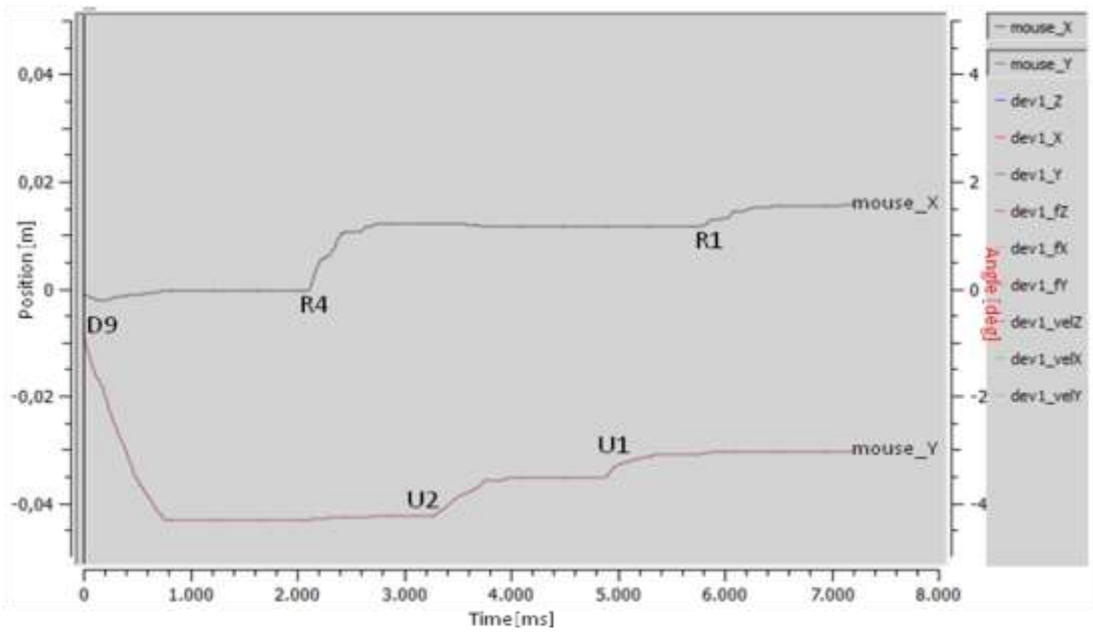


Figure 3-19. Metric based guidance. Commands are responded with displacements which are aproximatively proportional to numerical values.

In the example in Figure 3-19, centimeters were chosen as units by the *Supervisor*. In subsequent trials, after the metrics were established, a notion of the unit was excluded and only direction and numerical values were used. The sequence of verbal commands issued is:

➔ D9; R4; U2; U1; R1.

Accurate positioning

This is the strategy that is always used in combination with other verbal strategies to control the cursor in the area around the target point, or at the end of the long continuous movements along the axis. Relative directions with semantical quantification are dominantly used (i.e. *little more left*, *little bit*). Commands are responded to with the small discrete movements of the mouse. Stopping command is not strictly used.

General positioning

This is a strategy that is always used in combination with other verbal strategies. Verbal commands are based on the description of the position of the target point in the reference frame of the screen. Descriptive verbal commands can be responded to with slow continuous mouse movement in the desired direction, or with big discrete steps. Usually, big movements of the cursor are terminated with the stopping command, after which verbal impulses or accurate positioning are applied.

Figure 3-20 shows an example in which the general positioning strategy was mixed with accurate positioning. The exact transcript of command sequence is:

- ➔ go directly to the corner of the right down; go up diagonally, little bit, little bit, little bit, little bit; Stop.

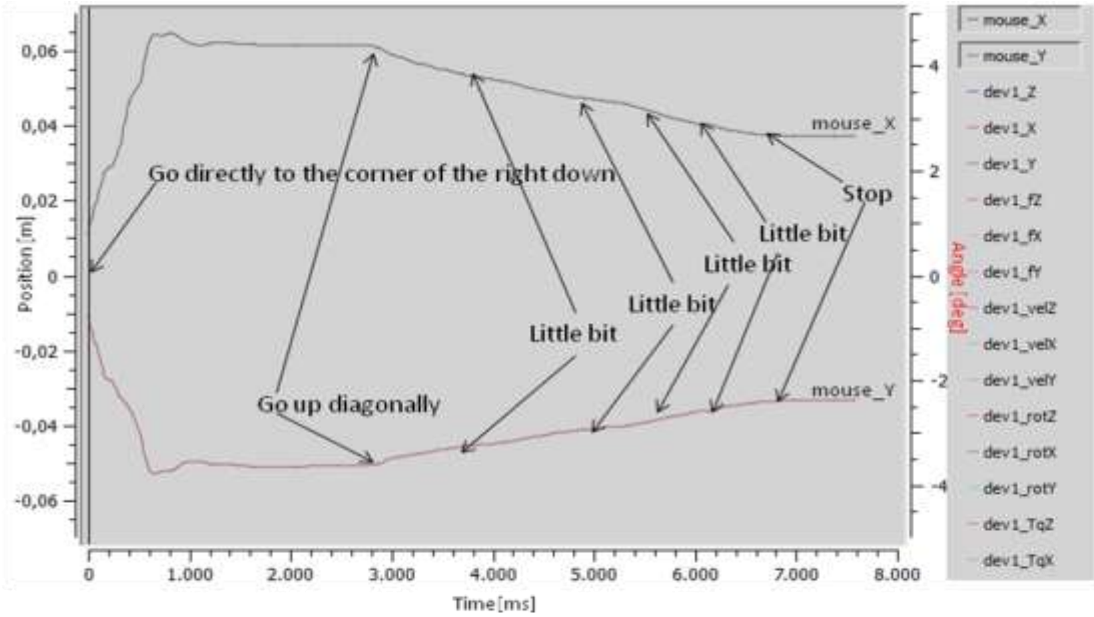


Figure 3-20. General positioning strategy followed by the accurate positioning.

3.3.4 Results

For each trial of each of the experimental blocks with verbal modality, we tried to designate the used verbal strategies. Knowing the verbal strategies used for each point in the block, we were able to identify the dominant strategies of the whole block. Identified dominant verbal strategies of the dyads, along with the performance times are given in Table 9.

Table 9. Identified verbal strategies for each dyad.

Block	VERBAL STRATEGY	Block time	Natural speaker
S1B3	Verbal impulses	144502	N
S1B4	Verbal impulses	116978	N
S2B3	Verbal steering	137385	N
S2B4	Verbal steering	137410	N
S3B3	Verbal impulses	181372	N
S3B4	Metric guidance/Accurate positioning	233051	N
S4B3	Metric guidance	145655	N
S4B4	Metric guidance	106375	N
S5B3	Verbal impulses/Accurate positioning	298369	N
S5B4	Verbal impulses	236653	N
S6B1	Metric guidance/Accurate positioning	287356	N
S6B2	Verbal impulses/Metric guidance/Accurate positioning	172258	N
S7B1	General positioning/Accurate positioning	176844	N
S7B2	General positioning/Accurate positioning	155371	N
S8B1	General positioning/Verbal impulses	160736	Y
S8B2	Metric guidance/General positioning/Accurate positioning	152629	Y
S9B1	Verbal impulses/Accurate positioning	260345	N
S9B2	Verbal steering	174820	N
S10B1	Verbal impulses/General positioning/Accurate positioning	172224	Y
S10B2	Metric guidance	154253	Y

4 CONCLUSIONS

In this thesis, we wanted to examine the properties of haptic communication in the case when two humans use kinesthetic haptic devices in a collaborative task in virtual environment. Our goal was to find out how haptic communication is used to transmit data about the collaborative task at hand between two task participants, and to see if there is any resemblance to the verbal communication.

We built experimental system, found appropriate collaborative task and designed experimental protocol in order to gather the data for analysis. Our experiment was done with haptic and verbal modality of communication by 20 participants divided in 10 dyads.

For experiments we used 2D positioning task in which one participant had to move the cursor on the screen onto the target point without being able to see the position of the target (*Acting agent*), while the other participant knew the target position and used haptic (or verbal) communication for guidance (*Supervisor*). We measured positions, velocities and forces of each haptic device and positions of the mouse which was used as the input device.

We analyzed the haptic and verbal data in two ways. The first was dyad performance based on completion times of task trials, while the second was communication strategy used by the dyad. These results are briefly discussed below.

4.1 Performance

The time to complete one trial was used as a direct measure of the task performance for each trial. We used the time data from all the trials done by 10 dyads. Each dyad did 32 trial points with haptic modality and 32 trial points with verbal modality which gives an overall number of 640 trial points.

We divided 320 points for haptic modality into 4 groups of 80 points according to the index of difficulty and calculated the mean and standard deviation for each of four IDs. The same was repeated for verbal modality data. The results for both modalities were presented on the graph of time dependency to ID. Plots for verbal and for haptic modality, both had rising linear trend fit characteristic for Fitts's law.

When designing our experiment we chose a collaborative task for which we believed that trial times would comply to Fitts's law if the communication between the members of the dyad was meaningful and efficient. If the communication was not efficient the times would not be dependent on the index of difficulty, and instead they would be just random. For verbal communication we know that it is efficient form of communication and we expected the graph for it to comply with the Fitts's law. According to resulting graph this was a good expectation. Haptic modality data fits to a rising linear trend similar to the trend for verbal modality. This proves that haptic collaboration on average was efficient to use in the collaborative task, which is the confirmation of our hypothesis H1.

Average performance time of haptic modality was found to be around two times less than when using verbal modality. Furthermore, there were larger standard deviations for haptic modality data. The reason for this could be that for haptic modality each dyad had to develop their own communication model of use of haptic devices, which is not the case for verbal modality for which people already know how to communicate using language. There were big individual differences because some participants were able to start with efficient haptic communication right away, and others needed more time to become effective.

In order to see up to what degree the learning of haptic communication influenced overall performance with haptic modality, we found a subset of trial points for which we believed that it could approximate haptic communication with the already established communication model. The results showed that the level of performance under haptic modality could be close to the level of performance under verbal modality, with the difference in time of about 3 seconds. To be completely sure additional experiments should be done in which the dyads would use already established haptic communication models in all the trials.

ANOVA of the influence of the experimental factors on the results of the experiment showed that the only statistically significant difference is present for the combination of communication and order of introduction of modality into the experiment. Results showed that for verbal communication performance it is the same whether the experiment was done with the verbal or haptic modality first. On the other hand, for haptic modality twice better performance times were obtained by the group of dyads who did the haptic modality trials before verbal modality trials. This is directly opposite to our expectations in H4, where we expected the verbal modality to have a positive influence if introduced in the experiment before haptic modality.

We suppose that a possible reason for this phenomenon could be the task learning process. It seems that it is better to associate the learning of the haptic device handling together with the learning of the experimental task, because the participants are unhindered with previous experience and they can start developing their haptic strategy right away. In the other case, when the experimental task and verbal modality are introduced first and haptic modality later, participants need to unlearn first their verbal strategy and then start learning the haptic strategy.

4.2 Communication strategies

4.2.1 Haptic communication

The classification of the haptic communication strategies was our attempt to answer the question of possible ways to transmit the data in collaborative task when using kinesthetic haptic devices. Strategies were classified using measured physical data and visual observation of the video recordings of experiments.

In order to enable the classification of strategies in a systematic manner we introduced a set of 6 observable parameters of the experimental system. *Type of motion*, *sequential axis control*, *dominant degrees of freedom* and used *device workspace* were measured and observed on haptic link, while on input device (mouse) we followed *movement type* and *control type*.

Type of motion used on the haptic device by the *Supervisor* was recognized as the basic characteristic for classification of haptic communication strategies. We were able to generalize observed haptic communication strategies into following three categories:

a) Motion copying

b) Steering

c) Impulse control

Motion copying is a strategy based on continuous movements of the haptic device in which the motions used by Supervisor don't follow a specific message logic clearly understood by both participants. Instead, the movements of the haptic device are just copied by the *Actor*.

Steering and *impulse control* strategies, both incorporate usage of fast movements of the haptic device. We called this movements *impulses*. Impulses are always performed in the directions of the coordinate system of the workspace. *Steering* uses only singular impulses to signal the need starting and stopping along certain direction, while in *impulse control* series of impulses is used to signal the need for the prolonged movement in one direction.

All three observed strategies are in concordance with the two categories proposed in H2, with *motion copying* going under the first category and the other two strategies going under the second category.

For each dyad on its own we observed the evolution of the communication strategy. *Motion copying* strategy was always used first in each block of trials. Impulse control strategy was usually developed in the first few trials of a block, after the *Supervisor* realized that it could be more efficient to use impulses. *Steering* strategy was usually developed later in the block of trials, as a way to avoid the problem of the limited haptic device workspace. There was no observed direct transition between the two strategies which use impulses. The described evolution of the haptic strategies is in concordance with the hypothesis H3.

4.2.2 Verbal communication

The analysis of the verbal communication was done in the similar manner as the analysis of haptic strategies. First, the three main characteristics for analysis were recognized and described: *verbal directional commands*, *verbal stopping commands* and *mouse movement types*. We made the transcripts of all the conversations and classified observed verbal strategies into five categories:

a) Verbal impulses

b) Verbal steering

c) Metric based guidance

d) Accurate positioning

e) General positioning

Verbal impulses and *verbal steering* are verbal strategies which have their direct counterpart among the classified haptic strategies. The last two verbal strategies can be seen as the ways to make direct spatial guidance using the discrete medium of speech instead of the analogous haptic device. Metric based guidance could be interpreted as the special, improved case of verbal steering which is possible because with the verbal communication numbers can be expressed directly through speech.

4.2.3 Modality order influence

Experimental session for each dyad consisted of four blocks of trials. Between the second and the third block in each session the change of communication modality was done, while participants stayed in the same roles as before. Comparing strategies used in these two blocks of trials (B2 and B3), we analyzed the influence that change of modality has on the used strategies.

By observing Table 10, it can be seen that in the case when haptic modality was introduced first into experiment, the strategy of the dyad was kept in its verbal counterpart in 3 out of 5 cases. If the verbal modality was used prior to haptic modality, the direct influence is noted only in 1 of 5 observed cases.

Table 10. Dyad strategies in trial blocks for which the change of modality occurs.

	B2	B3
H-->V	Impulse control	Verbal impulses
	Steering	Verbal steering
	Motion copying	Verbal impulses
	Steering	Metric guidance
	Impulse control	Verbal impulses/Accurate positioning
V-->H	Verbal impulses/Metric guidance/Accurate positioning	Motion copying
	General positioning/Accurate positioning	Motion copying
	Metric guidance/General positioning/Accurate positioning	Motion copying
	Verbal steering	Steering
	Metric guidance	Motion copying

Based on the results, it can be summarized that if effective haptic strategy was established first and then the change to verbal modality occured, there was a direct influence of haptic strategy on the used verbal strategy. On the other hand, there was no strong positive influence of the verbal strategy on the haptic strategy following it.

4.3 Future work

During the work on this thesis we have come up with a short list of future experiments that could be done with none or minor modifications to the current setup.

In the current experimental design, we could add the third experimental condition in which haptic and verbal modality are used together at the same time. It would be interesting to see which modality is preferred when both of them can be used, and if having both modalities has significant positive influence on performance times and haptic strategy development.

Our experiment is designed to encourage unilateral communication through haptic link, from the *Supervisor* to the *Actor*. This is the consequence of the choice of the experimental task. Bilateral communication through haptic link could be accomplished in the experiment in which each of the members of the dyad would have partial information about the collaborative task and partial control in the virtual environment. This means that additional input device would have to be included in the current experimental setup, along with the new collaborative task which puts participants into symmetric roles.

In order to gather more information about natural haptic communication, current experimental task could be repeated with the condition in which two members of the dyad have their hands directly hand in hand, or hold ends of some real world object like a short stick. We could see which of the strategies used with haptic devices would be repeated, and which new strategies would emerge in the case when there are no limitations of haptic device workspace.

Research on haptic communication is still in its beginning. This thesis has shown that pairs of people are able to develop haptic communication strategies for information transmit ion in collaborative task and use these strategies to communicate effectively. Comparison with the verbal communication strategies for the same spatial positioning task, showed that observed haptic and verbal strategies that showed up in the experiments resemble. The work in this thesis showed a new approach to the research of haptic communication in which hand movements on the haptic device were analyzed into detail along with measured physical values. In the thesis we opened discussion about several topics like performance, communication strategy and mutual influence of communication modalities. Each of these topics deserves further investigation on its own.

REFERENCES

[1] A. Chellali, I. Milleville-Pennel, C. Dumas et E. Nouri, “Common Frame of References in Collaborative Virtual Environments and their Impact on Presence“, *The 10th Annual International Workshop on Presence*, Barcelona, Spain, October 2007, pp. 371-372.

[2] A. Chellali, I. Milleville-Pennel, C. Dumas, “Elaboration of common frame of reference in Collaborative Virtual Environment“, *ECCE 2008 European Conference on Cognitive Ergonomics*, Madeira, Spain, September 16-19, 2008.

[3] A. Chellali , C. Dumas, I. Milleville-Pennel, “Haptic communication to enhance collaboration in virtual environments“, *Proceedings of the European Conference on Cognitive Ergonomics ECCE2010*, Delft, Pays-Bas, August 25-27, 2010.

[4] A. Chellali, C. Dumas, I. Milleville-Pennel, “WYFIWIF: A Haptic Communication Paradigm for Collaborative Motor Skills Learning*“, Proceedings of the Web Virtual Reality and Three-Dimensional Worlds 2010*, Freiburg, Germany, July 27-29, 2010.

[5] S. J. Lederman, R. L. Klatzky, “Haptic perception: A tutorial“, *Attention, Perception & Psychophysics,* vol. 71, pp. 1439-1459., 2009.

[6] L. Ming, M. Otaduy, “Haptic rendering: foundations, algorithms and applications“, Wellesley, MA,USA: A K Peters Limited, 2008., pp. 1-3

[7] M.A. Srinivasan, C. Basdogan, “Haptics in Virtual Environments: Taxonomy, Research Status, and Challenges“, *Computers and Graphics*, Vol. 21, No. 4, pp. 393-404., 1997.

[8] C. Ho, C. Basdogan, M. Slater, N. Durlach, M.A. Srinivasan, “An Experiment on The Influence of Haptic Communication on the Sense of Being Together“, *British Telecom Workshop on Presence in Shared Virtual Environments*, Ipswich, June 10-11, 1998.

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

[10] J. Jordan, J. Mortensen, M. Oliveira, M. Slater, B.K. Tay, J. Kim, and M.A. Srinivasan, "Collaboration in a Mediated Haptic Environment", *Presence 2002: The 5th Annual International Workshop on Presence*, University Fernando Pessoa, 2002.

[11] K. Reed, M. Peshkin, J. Colgate, and J. Patton, "Initial Studies in Human-Robot-Human Interaction: Fitts' Law for Two People", *Proc. of IEEE International Conference on Robotics and Automation (ICRA)*, New Orleans, April 2004.

[12] K. Reed, M. Peshkin, M. J. Hartmann, J. E. Colgate, and J. Patton, "Kinesthetic Interaction," *Proc. of the 9th International Conference on Rehabilitation Robotics (ICORR)*, Chicago, June 2005.

[13] K. Reed M. Hartmann, J. Patton, P. Vishton, M. Grabowecky, and M. Peshkin, "Haptic cooperation between people, and between people and machines", *Proc. of IEEE International Conference on Intelligent Robots and Systems (IROS)*, Beijing, October 2006.

[14] D. Feth, R. Groten, A. Peer, S. Hirche, M. Buss, "Performance Related Energy Exchange in Haptic Human-Human Interaction in a Shared Virtual Object Manipulation Task" , *Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2009 .

[15] R. Groten, D. Feth, R. Klatzky, A. Peer, M. Buss, "Efficiency Analysis in a Collaborative Task with Reciprocal Haptic Feedback", *The 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2009 .

[16] R. Groten, D. Feth, H. Goshy, A. Peer, D. A. Kenny, M. Buss, "Experimental Analysis of Dominance in Haptic Collaboration", *The 18th International Symposium on Robot and Human Interactive Communication* , 2009 .

[17] D. Feth, R. Groten, A. Peer, M. Buss, "Control-theoretic Model of Haptic Human-Human Interaction in a Pursuit Tracking Task", *Proceedings of the 18th*

IEEE International Symposium on Robot and Human Interactive Communication (Ro-Man), 2009 .

[18] M. J. Enriquez, K.E. MacLean, “The Hapticon Editor: A Tool in Support of Haptic Communication Research“, *Proc. of the 11th Annual Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems, IEEE-VR2003*, Los Angeles, CA, 2003.

[19] A. Chan, K. E. MacLean, J. McGrenere, “Designing Haptic Icons to Support Collaborative Turn-Taking", *International Journal of Human-Computer Studies*, vol. 66, pages 333-355, January 2008.

[20] I. S. MacKenzie, “Fitts' law as a performance model in human-computer interaction“, Doctoral dissertation, University of Toronto: Toronto, Ontario, Canada, 1991.

[21] Virtuose API v2.60 Documentation, HAPTION S.A.

[22] T. N. Liukkonen, “*Human Reaction Times as a Response to Delays in Control Systems*”, Retrieved from: http://www.measurepolis.fi/alma/ALMA%20Human%20Reaction%20Times%20as%20a%20Response%20to%20Delays%20in%20Control%20Systems.pdf, Accessed: july 2010.

APPENDIX A: EXPERIMENT MATERIALS

A.1 Coordinates of target points

Table 11. Coordinates of target points given in haptic device frame and virtual enviroment frame.

		Haptic device coordinates		VE coordinates	
	Point	Y	Z	X	Y
ID1	1	-0,006	-0,008	-0,12	-0,16
	2	-0,004	0,009	-0,08	0,18
	3	0,008	-0,006	0,16	-0,12
	4	0,005	0,009	0,1	0,18
ID2	5	0,019	0,013	0,38	0,26
	6	-0,015	-0,017	-0,3	-0,34
	7	-0,009	0,021	-0,18	0,42
	8	0,010	-0,021	0,2	-0,42
ID3	9	-0,033	0,012	-0,66	0,24
	10	0,022	0,027	0,44	0,54
	11	0,015	-0,032	0,3	-0,64
	12	-0,007	-0,034	-0,14	-0,68
ID4	13	0,049	0,01	0,98	0,2
	14	0,037	-0,034	0,74	-0,68
	15	-0,047	-0,017	-0,94	-0,34
	16	-0,029	0,041	-0,58	0,82

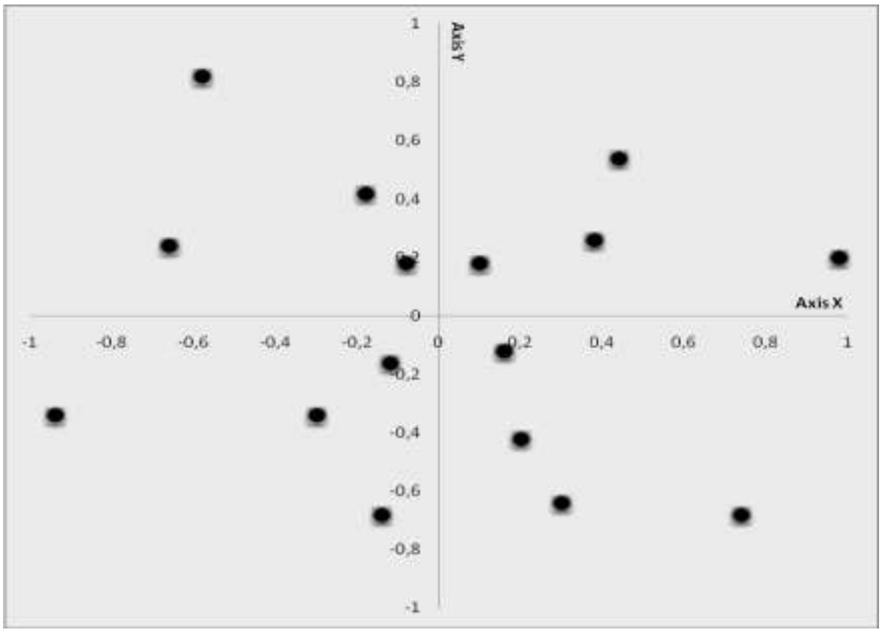
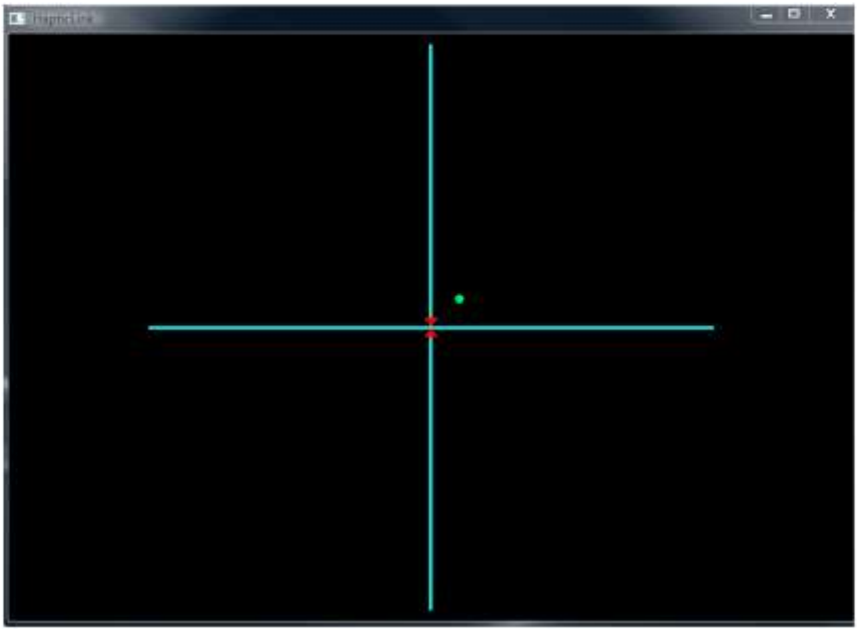


Figure A-1. X-Y plot of target points.

A.2 Instructions (Acting agent)



The goal is to position the red cursor inside the green target circle and keep it there for 1 second.

You **can** move the red cursor using the mouse. Your partner **can not** move the red cursor. Both of you can see on your display screens movement of the red cursor and its current position.

You don’t see where the green target circle is since that piece of information is not displayed on your screen. Your partner sees the green circle on his screen and knows its position.

In order to successfully complete the experiment you and your partner have to communicate. Allowed mode of communication (haptic, verbal) for the current experiment is given by the person monitoring the experiment, prior to the experiment start.

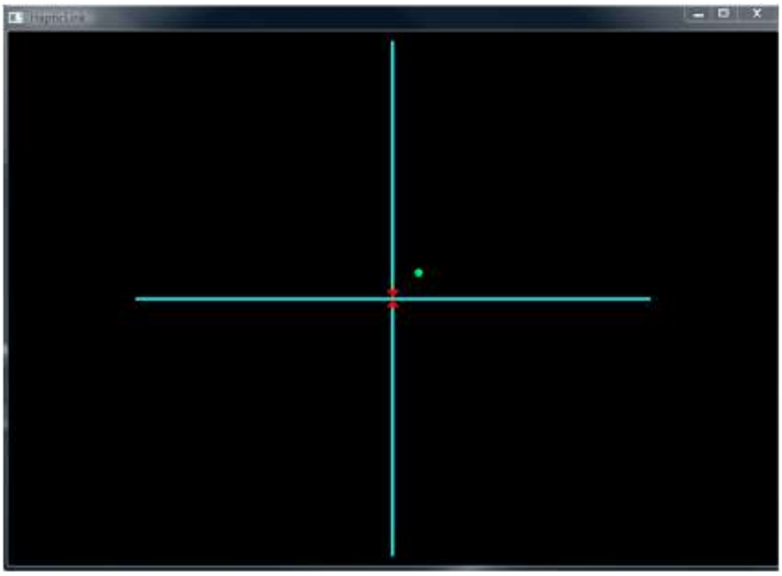
When you successfully reach the target you will hear a beep sound and your screen will become blue. After that, a new target point is automatically set and you can start with the new trial.

One experiment has 16 target points (trials) to be reached in succession.

You don't have any time limit for the trial completion.

In this experiment we are **not** evaluating you or your personal performance.

A.3 Instructions (Supervisor)



The goal is to position the red cursor inside the green target circle and keep it there for 1 second.

You **can not** move the red cursor. Your partner **can** move the red cursor using the mouse. Both of you can see on your display screens movement of the red cursor and its current position.

Your partner doesn’t see the green target circle on his screen and doesn’t know its position. You can see and know the position of the red cursor and the green target at all times.

In order to successfully complete the experiment you and your partner have to communicate. Allowed mode of communication (haptic, verbal) for the current experiment is given by the person monitoring the experiment, prior to the experiment start.

When the red cursor successfully reaches the target you will hear a beep sound and your screen will become blue. After that, a new target point is automatically set and presented in front of you, and you can start the new trial.

One experiment has 16 target points (trials) to be reached in succession.

You don't have any time limit for the trial completion.

In this experiment we are **not** evaluating you or your personal performance.