Haptic communication to enhance collaboration in virtual environments

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ABSTRACT

Motivation – To study haptic communication in collaborative virtual environments.

Research approach – An experimental study was conducted, in which 60 students were asked to perform in dyads a shared manual task after a training period.

Findings/Design – The results show that haptic communication can influence the common frame of reference development in a shared manual task.

Research limitations/Implications – Deeper verbalization analyses are needed to evaluate the common frame of reference development.

Originality/Value – This study highlights haptic interactions importance when designing virtual environment that support shared manual tasks.

Take away message – Haptic communication, combined with visual and verbal communication, enriches interactions in collaborative virtual environments.

Keywords

Collaborative virtual environments, human interactions, common frame of reference, haptic communication.

INTRODUCTION

Collaborative Virtual Environments (CVEs) are digital spaces that allow remote users to work together sharing virtual objects (Snowdon & Churchill, 1998). They are used in many applications such as surgery, CAD and architecture. They offer new interaction possibilities by allowing users to share virtual workspaces. However, the design of virtual environments that support collaboration remains an open issue. Indeed, Navarro (2001) argue that computer mediated communication introduced changes in the interactions between partners in synchronous collaborative activities. This implies that the virtual environments characteristics have an influence on collaboration between distant partners. Hence, a deep understanding of human-human interactions is requires to design CVE that allow distant users to work together.

In this paper, we focus on remote haptic interactions between human operators that perform a spatial manipulation task in a CVE. The goal is to investigate the influence of haptic communication on the collaborative performance and on the CFR development when the users perform together a synchronous manual task.

Collaboration and Common Frame of Reference

Collaboration is defined as a synchronous common work in which partners share resources and problems to accomplish a common task (Dillenbourg, 1999). When two operators collaborate, they construct a common mental representation of the situation. This is referred to by Loiselet and Hoc (2001) as the Common Frame of Reference (CFR). The CFR allows the partners to understand each other and to organize their common work. Thus, they can perform different but complementary actions. The CFR is constructed and updated by the *Grounding Process* (Clark & Brennan, 1991). During the grounding process, the partners exchange information and share understanding signs to develop their CFR. Depending on the task, the partners can use different communication channels (voice, vision and haptics) to develop their CFR.

In this paper, we focus on the haptic communication channel. Hence, human haptic interactions in CVEs are investigated. The goal is to understand how partners exchange haptic information to develop the CFR when performing common manual tasks in a CVE.

Haptic Communication

Unlike other nonverbal communication forms such as facial expressions and eye contacts, little attention has been focused on haptic communication. Haptic interactions can be observed when two operators collaborate to accomplish a common manual task such as lifting a table together or guiding the partner’s hand to teach a motor skill (Reed et al., 2001). Haptic communication permits to exchange information about the forces and the movements performed by the operators to accomplish the common manual task. Hence, the contacts enable the partners to synchronize their actions towards a common goal. To design haptic collaborative systems, it is important to understand how the virtual environments influence the haptic communication.

Haptic Communication in Virtual Environments

Haptic devices are widely used in motor skills learning systems based on virtual environments (Gillespie, et al., 1998, Morris et al. 2007, Yoshikawa & Henmi, 2000). However, few studies addressed haptic communication in CVE. Indeed, compared to other modalities, haptic communication requires physical contacts to transmit information. However, physical contacts are difficult to reproduce faithfully at a distance. With the advent of new haptic devices, haptic communication becomes feasible, even remotely. Researches in this area focus mainly on the effects of haptic communication on the users' performance in various tasks (Basdogan et al., 2000, Sallnäs et al., 2000). These studies suggest that haptic communication can improve the users' performance in manual collaborative tasks. They suggest also that haptic interactions have positive effects on the sense of copresence with a remote partner within the CVE. The partners enjoy the communication experience through the haptic sense and feel more confident when interacting with each other. However, the nature of information being exchanged through the haptic channel and its effects on collaboration had not been investigated yet in CVE.

In this paper, we present a user centred design for a haptic collaborative virtual environment. We believe that direct haptic interactions between two users will enhance CFR construction when performing a shared manual task. To support haptic communication, we developed a system based on the WYFIWIF (What You Feel Is What I Feel) paradigm (Chellali et al., 2010). The system (Cf. Figure1) allows two users to exchange haptic information (forces and movements) even remotely. It supports also other communication forms (visual and verbal).

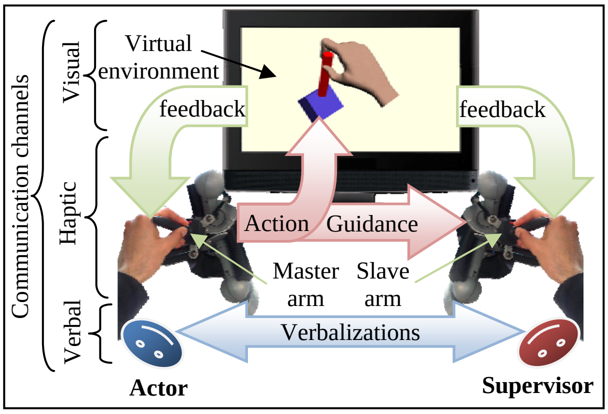


Figure 1: the collaborative system based on the WYFIWIF paradigm

By using the haptic communication paradigm, we hypothesize that a CVE that supports different interactions channels will help partners to exchange more accurate information about their common manual tasks and will enhance the collaborative performance.

Hypotheses

A medical biopsy training system is developed to assess the impact of haptic interactions on the collaborative performance and on the CFR development (the system is described in the following section).

By using this collaborative system to perform a biopsy procedure we hypothesize that:

- **H1. Learning a motor skill through haptic communication combined with verbal and visual communications will help the users to better perform the manual task when collaborating with a partner**. Hence, we expect to have faster gestures and a better management of the environment haptic feedback after learning a biopsy procedure through haptic communication combined with verbal and visual communications.

- **H2. The way the partners learn a motor skill has an influence on their verbal communications when they collaborate to perform the task**: According to the grounding process definition, the partners exchange information and signs of comprehension about their common activity in order to develop their CFR. Hence, study the verbal communications during a collaborative manual task is a way to investigate the contents of the CFR. We hypothesize that learning to use the haptic communication channel will have an influence on the CFR development during the collaborative activity. This influence will be investigated through the study of the verbal communications contents.

These two hypotheses are tested in the following experimental study.

EXPERIMENTAL STUDY

60 novice students (19-29 years old; 30 males, 30 females; 6 left-handed), from the *Medicine Faculty of Nantes* and from ONIRIS (Nantes Vet School), participated in the study. None of the participants had prior knowledge of the biopsy procedure. All the participants had no experience either with the CVE or with the haptic devices. All students received 30 € for their participation.

The biopsy procedure

For this study, a biopsy performing task is chosen because of its dependency on haptic information. To better understand the biopsy procedure, a 6-months activity analysis was conducted. This observation phase permits to make a detailed description of the task characteristics and the motor skill characteristics: the procedure consists of inserting a needle inside the body to remove cells or tissues for examination. To perform the task, the radiologists perform very accurate movements by manipulating a specific tool (a biopsy needle). Prior to the needle insertion, the radiologists use CT-scan (Computed Tomography scanner) images to plan their operation. During the operation, the radiologists have no real-time visual feedback of the needle position inside the body. Hence, they rely mainly on the haptic feedback and on the memorisation of the offline images to perform the gesture. Actually, the speed of movements, accuracy, sharpness of the touch and safety are still learned by "doing" through the observation of the experts in real situations. Studying the procedure through virtual environments can be useful to understand how this kind of motor skills are transmitted between human operators. It can also highlight haptic communication importance for motor skills transfer and can help to design training tools for such procedures.

The task analyses permits to divide the activity into two main phases:

- **The planning phase:** the goal of this step is to analyze the CT-scan images in order to localize the tumor. After that, the radiologist defines the needle insertion path to reach the target respecting some constrains.
- **The manipulation phase:** the goal of this step is to insert the needle inside the body to remove a sample of the tumor cells. The radiologist follows then, the defined path in order to reach the target. Since he has no real-time visual feedback, he relies mainly on the path memorization and on the haptic sensations.

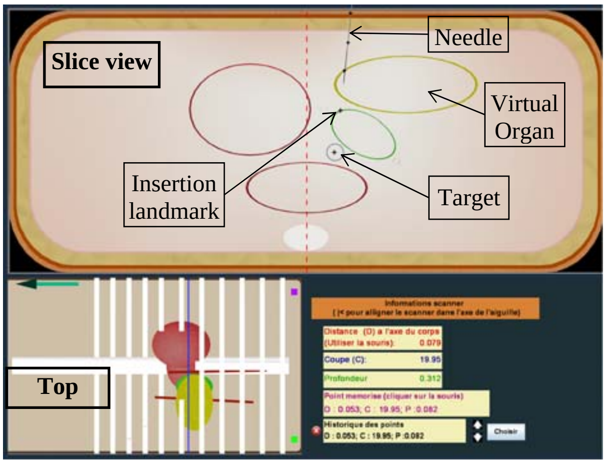
System Description

To support haptic communication when teaching or performing a manual task, the WYFIWIF (What You Feel Is What I Feel) paradigm is used (Chellali et al., 2010). In this paradigm, one user (the actor) moves a tool while his partner (the supervisor) follows the movements handling an identical tool as shown in Figure 1. Hence, the actor can act freely, while his partner follows and feels his actions.

To illustrate the paradigm, two *Virtuose 6D desktop* haptic arms from *Haption* are linked in a master-slave setup (Figure 1). Thus, while the master is moved to act in the CVE, the slave reproduces the same movements. This allows the partners to exchange haptic information.

The virtual environment graphics, created using *Virtools* from *Dassault system*, consists of two main views:

- **Planning interface:** it provides a slice view of the body (cf. Figure 2) that permits to localize the target. The user can define the insertion path by positioning landmarks on the slice view using a mouse,
- **Manipulation interface:** it provides a three-dimensional view that allows the user to manipulate the virtual needle using the haptic arm (cf. Figure 3). The user's action point is represented by a virtual hand handling a biopsy needle. In addition to the haptic feedback, information about the 3D position of the needle is displayed on the screen.



Informations scanner
(|< pour alligner le scanner dans l'axe de l'aiguille)

Distance (D) a l'axe du corps (Utiliser la souris): 0.079

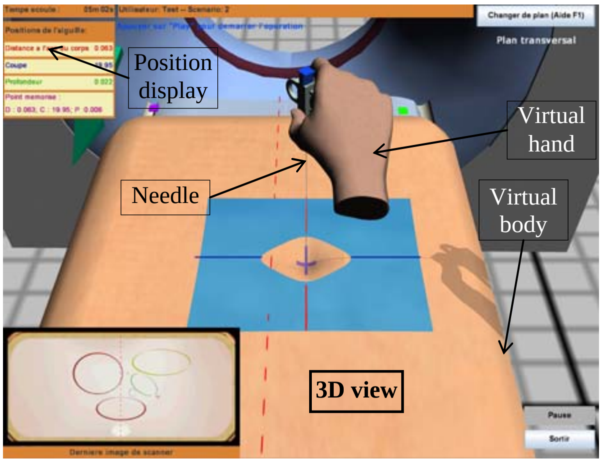
Coupe (C): 19.95

Profondeur 0.312

Point memorise (cliquer sur la souris)
D : 0.053; C : 19.95; P :0.082

Historique des points
D : 0.053; C : 19.95; P :0.082

Figure 2: the planning Graphic User Interface



Temps ecoule : 05m 02s

Utilisateur: Test -- Scenario: 2

Positions de l'aiguille

Coupe 19.95

Point memorise :
D : 0.063; C : 19.95; P : 0.006

Figure 3: the needle manipulation Graphic User Interface

Task

All the volunteer students participated successively to the three following sessions:

Starting session

Prior to the task, the participants were allowed to perform a simple insertion scenario. The objective of this session was to familiarize them with the manipulation of the haptic device and with the use of the virtual environment. At the end of the session, all the participants were observed to feel comfortable with the experimental setup.

Training session

After the starting session, the participants performed an individual training period (4 different exercises) with an expert instructor. It consists of learning the biopsy procedure which is divided into two steps:

- **Planning:** positioning landmarks in the slice view to define the insertion path with respect to the planning constraints,
- **Manipulation**: inserting the needle in the body to reach the target with respect to the defined path.

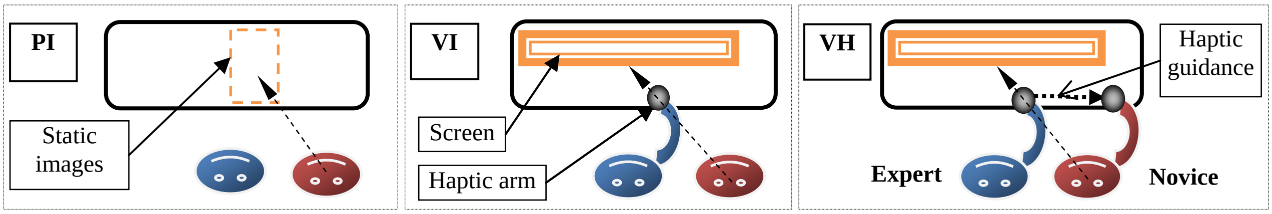


Figure 4: the learning conditions: (left) Paper Instructions condition (PI); (center) Visual condition (VI); (right) Visual-Haptic condition (VH)

For this session, the participants were divided into three learning groups (details of the three experimental conditions are schematically represented on Figure 4):

- **Paper Instructions learning group (PI).** The instructor teaches the procedure and the motor skill to the participants through verbal instructions and with support of static images,
- **Visual learning group (VI).** The instructor teaches the procedure and the motor skill through visual feedback combined with verbal explanations. The novices observe directly the expert's hand manipulating the haptic device and see the feedback on the virtual needle on the screen,
- **Visual-haptic learning group (VH).** In addition to the visual feedback and to the verbal explanations, the instructor uses haptic communication to guide the novice's hand when he manipulates the needle.

Collaborative practice session

After the training session, participants were regrouped in 30 dyads. Each dyad was composed of two participants from the same learning group. They were asked to perform together four new exercises. For each exercise, partners were asked to plan the operation together. During the manipulation phase, one participant (the actor) was asked to insert the needle, while the other (the supervisor) had to follow and supervise the actor's movements. The partners' roles were reversed after each exercise.

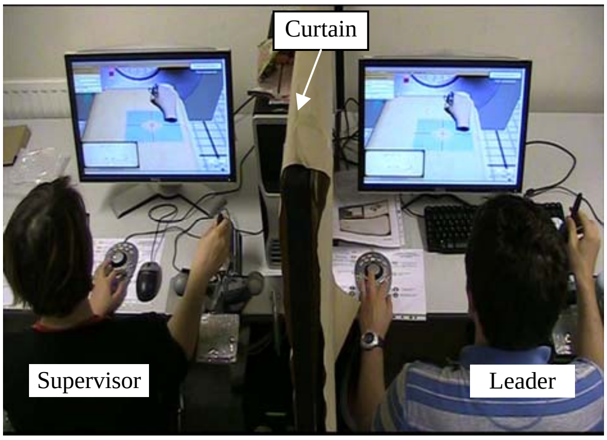


Figure 5: the collaborative practice session

Each participant was seated in front of a 21 inches screen. The partners were asked to perform the task in collaboration. Moreover, they were separated by a curtain to prevent them to see each other (cf. Figure 5). Hence, the partners could only communicate using: (i) the haptic channel, (ii) verbal communication or (iii) through the shared visual workspace.

The following table summarizes the composition of the participants' groups and the estimated completion time for each experimental session:

Table 1: the three experimental sessions

	PI	**VI**	**VH**
Starting session (~20 minutes)	60 subjects		
Training session (~30 minutes)	20 subjects	20 subjects	20 subjects
Practice session (~90 minutes)	10 dyads	10 dyads	10 dyads

Measurements

Verbalisations

All the conversations between the partners were recorded and faithfully transcribed for verbalization analysis. The verbalisations analyses are used to explore the development of the CFR during the collaboration.

Performance

The participants' performances during the collaborative session were compared regarding different measures (a distinction was made between the planning phase performance and the manipulation phase performance):

- **Planning phase performance.** The planning time (participants were asked to perform the task as fast as possible. However, no time limit was fixed); the number of landmarks used to define the path; the amount of the needle penetration inside the organs (participants were asked to minimize the organs damages by penetrating an organ across the thinnest part); the distance to the target center, the number of slice views displayed (participants were asked to minimize the number of displayed scanner images. In the real situations, the radiologists try to reduce the patient's exposition to the x-rays),
- **Manipulation phase performance.** The needle insertion time (participants were asked to perform the biopsy gesture as fast as possible); the number of contacts with the organs (participants were asked to

minimize the organs damages by minimizing the contacts with these organs); the number of gestures (experts split the needle insertion task into small insertion movements. This measure is used to explore the participants' insertion strategy).

RESULTS

Verbalizations

A first verbalizations analysis was conducted using the *Tropes software (from SoftConcept)*[1]. This analysis gave some indications concerning the conversations contents between the partners. The main significant differences observed among groups are summarized below. The collected data were subjected to an analysis of variance (ANOVA). Moreover, pair-wise t-test comparisons were performed (F, mean values and standard deviation are provided on Table 2; t values are provided on Table 3):

Table 2: data analyses for verbalizations (the * symbol represents the significant values with $p<0.05$)

***=p<0.05**	**PI: mean (sd)**	**VI: mean (sd)**	**VH: mean (sd)**	**F-values (2,27)**
References to the perception	0.8 (1.9)	2.4 (2.6)	5.8 (4.4)	_4.5*_
References to haptic sensations	0.0 (0)	0.0 (0)	2.0 (2.4)	_4.8*_
References to places	26.6 (3.7)	28.5 (4.3)	24.0 (1.9)	_3.5*_
References to the space/dimensions	13.9 (12.7)	0.0 (0)	0.0 (0)	_8.3*_

Table 3: the t-values for the pair-wise comparisons for the verbalizations analyses (the * symbol represents the significant values with $p<0.05$)

***=p<0.05; DoF=18**	**PI/VI**	**PI/VH**	**VI/VH**
References to the perception	-1.3	-2.7*	-1.7
References to haptic sensations	0.0	2.2*	2.2*
References to places	-0.9	1.7	2.7*
References to the space/dimensions	2.8*	2.8*	0

- The partners made more references to perception ("touch the vain", "the view", "the red",…etc.) and to haptic sensations ("I feel", "I touch",…etc.) in the VH condition compared to the partners in the PI and VI conditions,
- The partners made fewer references to places (up to, down to,…etc.) in the VH condition compared to the partners in the PI and VI conditions,
- The partners made more references to the space and the dimensions (depth, length, height,…etc.) in the PI condition compared to the partners in the VH and VI conditions.

Performance

The collected data were subjected to an analysis of variance (ANOVA). Moreover, pair-wise t-test comparisons were performed (mean values, standard deviation, F-values and t-values are provided in the tables below).

Planning phase

The ANOVA shows that there is an effect of the learning condition on the planning time, on the distance to the target center, on the number of used landmarks, on the number of scan images and on the amount of penetration of the organs (Table 4).

Table 4: data analyses for the planning performances (the * symbol represents the significant values with $p<0.05$)

***=p<0.05**	**PI : mean (SD)**	**VI: mean (SD)**	**VH: mean (SD)**	**F-values (2,27)**
Planning time (seconds)	1422.0 (306.8)	2121.0 (399.7)	2054.1 (384.5)	9.9*
Distance to target (cm)	0.6 (0.1)	0.8 (0.1)	0.8 (0.1)	5.4*
Used landmarks (points)	24.0 (6.7)	32.8 (8.0)	34.7 (9.6)	3.5*
Used slice views (displayed images)	56.1 (10.7)	89.5 (27.12)	83.0 (13.16)	4.7*
Amount of organs penetration (cm)	4.8 (0.8)	6.1 (0.4)	4.9 (1.1)	7.9*

Table 5: the t-values for the pair-wise comparisons for the planning performances (the * symbol represents the significant values with $p<0.05$)

***=p<0.05; DoF=18**	**PI/VI**	**PI/VH**	**VI/VH**
Planning time	_4.1*_	_3.8*_	_0.3_
Distance to target	_3.0*_	_2.6*_	_0.2_
Used landmarks	_2.1*_	_2.7*_	_0.2_
Used slice views	_2.5*_	_2.8*_	_0.6_
Amount of organs penetration	_4.5*_	_0.31_	_3.2*_

The pair-wise comparisons indicate that the participants planned the operation path faster, minimized the distance between the center of the target and the needle tip, used fewer landmarks and used less slice views

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[1] *Tropes* is a program dedicated to speech analyses. http://www.semantic-knowledge.com/

(scanner images) to plan the path in the PI condition compared to participants in the VI and VH conditions (Table 5).

The pair-wise comparisons indicate also that the participants minimized the amount of organs penetration in the PI and in the VH condition compared to participants in the VI condition (Table 5).

No significant differences were observed between the participants in the PI condition and the participants in the VH condition concerning the amount of organs penetration (Table 5).

Manipulation phase

The ANOVA shows that there is an effect of the learning condition on the manipulation time, on the number of contacts with the organs and on the number of insertion gestures (Table 6).

The pair-wise comparisons indicate that the participants performed the needle insertion gesture faster, minimized the contacts with the organs and minimized the number of insertion gestures in the VH condition compared to the participants in the PI and in the VI conditions (Table 7).

Table 6: data analyses for manipulation performances (the * symbol represents the significant values with p<0.05)

*=p<0.05	PI : mean (SD)	VI: mean (SD)	VH: mean (SD)	F-values (2,27)
Manipulation time (seconds)	1163.0 (429)	1090.0 (294)	692.8 (80)	5.5*
Organs contacts (contact)	11.2 (3.1)	22.4 (20.1)	5.7 (2.9)	4.6*
Insertion gestures (gestures)	113.4 (40.2)	130.8 (55.8)	82.1 (17.2)	3.2*

Table 7: the t-values for the pair-wise comparisons for the manipulation performances (the * symbol represents the significant values with p<0.05)

*=p<0.05; DoF=18	PI/VI	PI/VH	VI/VH
Manipulation time	0.4	2.9*	3.3*
Organs contacts	1.6	3.9*	2.4*
Insertion gestures	0.7	2.1*	2.5*

No significant differences were observed between the participants in the PI condition and the participants in the VI condition concerning the manipulation performances (Table 7).

DISCUSSION

For this experimental study, we were expecting an effect of the visual-haptic learning on the users' performance when performing in pairs a collaborative manual task **(H1)**.

The results of the experiment show that partners performed the needle insertion gesture faster in the visual-haptic learning groups. The results show also that the partners limited the collisions with the organs and decreased the number of insertion gestures. These results indicate that the partners learnt to better manage the needle manipulation after a visual-haptic learning. Indeed, they respected much better the constraints of the manipulation phase by minimising the operation duration and by minimising the damage of the organs. As shown in the task analysis, these constraints are mainly dependent on the haptic feedback. Hence, we can argue that the participants manage better the environment haptic feedback after the visual-haptic learning. During collaboration, the haptic communications helps the partners to better understand the needle movements and the haptic feedback. Hence, they perform the insertion task better than the participants in the two other groups. This confirms our first hypothesis.

Furthermore, we were expecting an influence of the visual-haptic learning on the verbal communications between the partners during the collaborative execution of the task **(H2)**.

The preliminary verbalizations analyses indicate that the discussions between the partners involved more references to haptic information (touch and perception) in visual-haptic learning groups. This suggests that haptic communication influences the CFR development: the visual-haptic learning helps the participants to better understand the haptic information when following the expert. Hence, in a collaborative situation, haptic communication is used to support the discussions about the needle insertion and to explain the haptic sensations when performing the task. The haptic interactions through the WYFIWIF system, combined with verbal communication about the haptic sensations were useful in that case, to develop a CFR about the needle manipulation sub-task.

On the other hand, the partners made fewer references to the haptic sensations after the two other learning conditions (The Paper Instructions learning and the Visual learning conditions). This indicates that they were less likely to share information on the haptic sensations in these conditions. This suggests that they did not develop a CFR around haptic sensations. These results confirm our second hypothesis (**H2**).

Additional findings

The results of the experiment show also that partners planned the operation faster with more respect to the planning constraints: they decreased the distance to the target by using fewer landmarks and by using fewer slice views) after the paper instructions learning. This indicates that the verbal instructions are more useful to learn how to manage the planning constraints. This suggests that the participants are more involved in learning the planning constraints when no additional devices or environments are used. In fact, the Visual and visual-haptic learning participants were disturbed by the virtual environment and the haptic devices during the learning of the planning constraints. However, more investigations must be made to determine the effects of the devices and the virtual environments on learning.

On the other hand, the manipulation phase was more complicated for the paper instructions learning groups. Indeed, their manipulation performances were worse than the performances of the visual-haptic groups. This suggests that they did not learn to manage well the haptic information. In fact, during the training period, the expert taught the motor skill through static images using only spatial information to describe the movements of the needle. Hence, the novices learnt only how to move the needle without learning to manage the haptic feedback. This can be confirmed by the verbalization analysis: the results indicate that the discussions between the partners after the paper instructions learning, involved more references to the needle and to the space. On the other hand, the discussions involved fewer references to the perception and to the sense of touch compared to the partners from the visual-haptic learning groups. This suggests that they used more the spatial information than the haptic information to describe the needle movements to their partners.

Furthermore, the paper instructions and the visual learning groups got the worse performances in the manipulation phase. In fact, only spatial information about the motor skill was taught by the expert in both groups. Hence, the partners did not share haptic information when performing the manual task. This is confirmed by the verbalizations analysis since they made more references to places and fewer references to the haptic information (perception and touch) in the visual learning condition.

The results suggest that the visual learning is less effective than the two other conditions to learn the biopsy procedure.

CONCLUSIONS AND FUTURE WORK

In this paper, we investigated human-human collaboration through haptic communication in collaborative virtual environments. A communication paradigm based on hand guidance was used to enhance users' haptic interactions. A virtual environment for performing a collaborative manual task has been developed to examine the effects of such a paradigm on humans' haptic collaboration. The results show that haptic guidance improves human's haptic interactions and enhance the collaborative performance.

The results show also that the common frame of reference construction is dependent on the communication channel being used. Hence, learning to use the haptic channel can incite the operators to exchange haptic information when this is made possible by the availability of a suitable system. Systems based on haptic communication can be useful to improve human collaboration for manual tasks performing in collaborative virtual environments.

In future, a deeper verbalization analysis is needed to explore more accurately the contents of the common frame of reference developed between the partners after each learning condition. This can be helpful to better understand the influence of haptic communication on collaboration in manual tasks.

We are continuing to study the haptic communication paradigm in collaborative virtual environments. This paradigm can be used in a system that helps two distant users to co-manipulate the same tool. This ongoing work will contribute to better understand collaboration using haptic interactions and how the common frame of reference is developed through the haptic channel.

The WYFIWIF paradigm can be used in other learning scenarios. One can image a learning system in which expert radiologist can supervise novices during the practice. This scenario can help the novices to be more active during the learning process. Furthermore, since the teacher feels the novices' actions, he can give more practical advices to the students. This can permit to design more efficient systems for learning motor skills.

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