WYFIWIF: A Haptic Communication Paradigm For Collaborative Motor Skills Learning

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WYFIWIF: A HAPTIC COMMUNICATION PARADIGM FOR COLLABORATIVE MOTOR SKILLS LEARNING

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ABSTRACT

Motor skills transfer is a challenging issue for many applications such as surgery, design and industry. In order to design virtual environments that support motor skills learning, a deep understanding of humans' haptic interactions is required. To ensure skills transfer, experts and novices need to collaborate. This requires the construction of the common frame of reference between the teacher and the learner in order to understand each other. In this paper, human-human haptic collaboration is investigated in order to understand how haptic information is exchanged. Furthermore, WYFIWIF (What You Feel Is What I Feel), a haptic communication paradigm is introduced. This paradigm is based on a hand guidance metaphor. The paradigm helps operators to construct an efficient common frame of reference by allowing a direct haptic communication. A learning virtual environment is used to evaluate this haptic communication paradigm. Hence, 60 volunteer students performed a needle insertion learning task. The results of this experiment show that, compared to conventional methods, the learning method based on haptic communication improves the novices' performance in such a task. We conclude that the WYFIWIF paradigm facilitate expert-novice haptic collaboration to teach motor skills.

KEYWORDS

Common frame of reference, haptic communication, collaborative virtual environments, motor skills learning.

1. INTRODUCTION

Learning requires collaboration between an expert that masters a skill and a novice that wants to learn this skill. Collaboration is defined as a synchronous common work in which partners share resources and problems to reach a common goal (Dillenbourg, 1999). To collaborate efficiently, the partners must construct a common representation of the shared situation called the Common Frame of Reference (CFR; Loiselet & Hoc, 2001). The CFR helps the partners to understand each other and to organize their individual actions, taking into account their partner's actions. In a learning context, the CFR is used to transfer knowledge from an expert to a novice. To ensure skills transfer, the expert uses different means of communication to update the CFR. For example, to teach a motor skill, the expert must be able to describe accurately his gestures. This includes information about his hand movements (position, speed) and about the forces. The VR technologies offer a promising mean to transmit accurate information about motor skills. Indeed, virtual environments with haptics provide a safe and versatile practice medium to teach these skills.

In this paper we introduce a theoretic framework based on human haptic communication to show that haptic information is important to learn motor skills. Hence, a haptic communication paradigm: What You Feel Is What I Feel (WYFIWIF) is proposed as a solution to teach motor skills. The WYFIWIF allows visual, verbal and haptic real-time communication between an expert and a novice. To show the WYFIWIF efficiency for haptic collaboration, a biopsy learning system is evaluated through an experimental study.

2. LITERATURE REVIEW

2.1 Collaboration and communication

The CFR is constructed and updated through the Grounding process (Clark and Brennan, 1991). The grounding process consists of a continuous exchange of information and signs of mutual comprehension between the partners (Figure 1). In a learning situation, the grounding helps the expert to complete the novice's individual representation by teaching new skills. Moreover, it allows the novice to ask questions and express his understanding and misunderstanding. Hence, they both use different communication channels (voice, vision, and haptics). The choice of the appropriate communication channel depends on the skill to be taught and on the available communication mediums. In this context, virtual environments have been getting a considerable attention recently as a learning medium. For example, motor skills are difficult to describe linguistically and involve invisible elements such as haptic sensations that require consideration of the haptic communication channel. Therefore, the design of VR systems that support the learning of motor skills requires taking into account the characteristics of haptic communication in virtual environments.

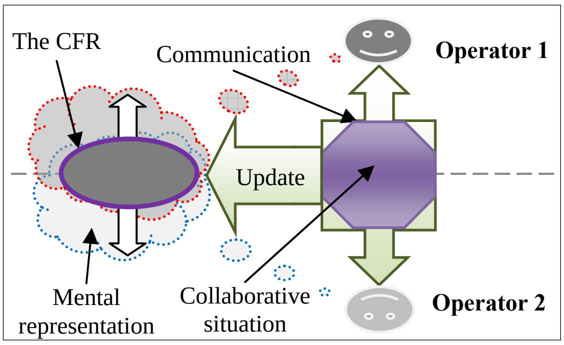

Figure 1. The grounding process

2.2 Haptic communication and motor skills learning

The role of haptic information in motor skills learning is still an open issue (Blavier, 2006). While some authors show the importance of haptic information for teaching motor skills (Bluteau et al., 2008, Solis et al., 2003), others question the necessity of this information (Willingham, 1998). Our objective is to show how haptic communication can be used to transmit motor skills in a collaborative activity.

Unlike other forms of nonverbal communication such as facial expressions and eye contacts, little attention has been focused on haptic communication (Sallnäs et al., 2000). Haptic interactions can be observed when common manual tasks (such as lifting a table together or as passing the baton in a relay race) are performed (Reed et al., 2005). The physical contacts enable the partners to synchronize their actions towards a common goal. But how can haptic communication influence motor skills transfer?

Many existing learning systems for motor skills are based on a hand guidance paradigm (Feygin et al, 2002). This paradigm requires recording and modeling an expert's reference gesture. This reference gesture is then transmitted to the learner through a haptic interface. The paradigm was used in many applications such as calligraphy learning (Yoshikawa & Henmi, 2000), moving a virtual crane (Gillespie et al. 1998) or memorizing a sequence of forces (Morris et al. 2007). The results of these studies show that haptic guidance combined with visual guidance allows novices to learn effectively some motor skills characteristics.

However, the use of an automatic system for teaching presents some restrictions. Indeed, while the guidance is based on the recording of an *optimal* gesture, it is difficult to define a *unique* optimal gesture for must motor tasks. Therefore, this can prevent a novice from defining his own optimal gesture. Furthermore, a haptic guidance system can transmit information about positions or forces, but not both at once. Finally, a direct interaction with a human expert can be richer than interaction with a haptic robot. Indeed, it permits to combine several communication channels at once: verbal, visual and haptic. This allows the novice to question the expert and the expert to provide further explanations. Hence, this interactive situation allows both sides to develop a more efficient CFR around the motor skills characteristics.

In this context, Nudehi et al. (2003) present a shared control paradigm for training in minimally invasive surgery. The system allows an expert surgeon to interact with a trainee by sharing the control of a robot when performing a surgical procedure. However, no human subject studies were reported to support this paradigm.

This paper presents an experimental study in which a human haptic collaboration system is evaluated.

2.4 Characteristics of haptic communication in virtual environments

Compared to other modalities, haptic communication requires physical contact to transmit information. However, physical contacts are difficult to reproduce faithfully at a distance. This can restrict haptic interactions through collaborative virtual environment between remote partners. With the advent of new haptic devices, haptic communication becomes more feasible, even remotely.

Despite the use of VR technologies for motor skills learning systems, little research addresses haptic communication in virtual environments. The main issues addressed in this area concerns the effects of haptic communication on the users' performance in various comanipulation tasks (Basdogan et al., 2000, Sallnäs et al. 2000). These studies suggest that haptic communication improves users' performance in manual collaborative tasks. They suggest also that users enjoy the communication experience through the haptic sense and feel confident when interacting with each other through this modality. However, the nature of information being exchanged through the haptic channel and its effects on collaboration has not been investigated yet.

In this paper, we present a user centered design for a motor skill learning system. Therefore, we propose a haptic communication paradigm based on hand guidance and direct interactions. We hypothesize that compared to record and replay systems, a learning system that permits direct interactions between an expert and a novice can help them to develop a more efficient CFR and to exchange more accurate information about motor skills. Furthermore, virtual environments can be used to support interactions and to improve communication by providing a shared visual workspace.

3. THE WYFIWIF PARADIGM

In the real world, the hand guidance metaphor can be observed when a teacher guides a child's hand to teach writing. This method seems to be effective to learn handwriting and is used to teach many other motor skills. However, it presents some restrictions; first, an expert can only work with one novice at a time. Furthermore, as the expert and the novice handle the same tool, one of them has no direct contact with this tool. This constrains the operator's perception of the movement being performed.

To overcome these problems, we formalize the guidance metaphor into a new interaction paradigm: What You Feel Is What I Feel (WYFIWIF). The paradigm supports multiple communication channels through virtual environments and is used to teach motor skills.

3.1 Principal:

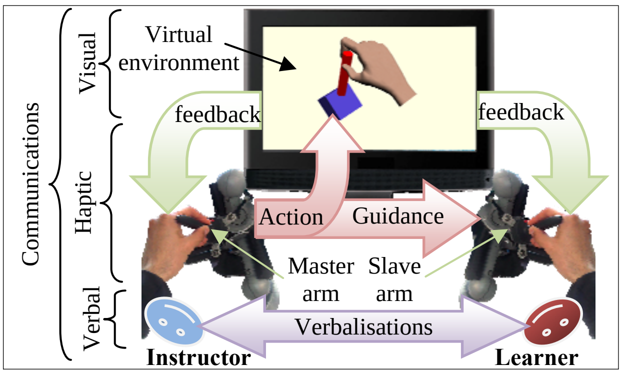

Figure 2. The WYFIWIF paradigm

The WYFIWIF paradigm is schematically explained in Figure 2 and consists of:

- Two linked haptic arms through a network connection in a master-slave setup.
- Two collaborating users: One participant (the instructor) moves a tool, while the partner (the learner) follows the movements handling a linked identical tool.
- The slave arm reproduces exactly the same behavior than the master arm.
- The coupling permits a direct interaction between the instructor and the learner through the haptic arms.

3.2 Advantages

- The instructor can perform the manual task freely while guiding the leaner's hand.
- The learner follows passively the instructor's movements and understands much better the actions.
- The learner can feel the environment feedback.
- Haptic communication is combined with verbal and visual communication (in the virtual environment).
- WYFIWIF enrich the CFR development in a joined manual task: the expert provides to the novice (through haptic communication) the necessary information to perform the correct gesture.

To evaluate the WYFIWIF efficiency for learning motor skills, we develop a learning prototype.

3.3 Learning task: biopsy procedure

For the study, a biopsy performing task is chosen because of its dependency on haptic information and the lack of learning tools. The task consists of performing very accurate movements by manipulating a tool: inserting a needle inside a body to reach a target. During the operation, radiologists have no real-time visual feedback of the needle position inside the body. Hence, they rely mainly on the haptic feedback 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 this kind of gestures in virtual environments will help us to understand how such information can be transmitted between human operators. It can also highlight haptic communication importance and help to design training tools for biopsy procedures. An observation of real situations permits to make a task description: the procedure is divided into two main phases: (i) **Planning** i.e. tumor localization using CT scanner images and (ii) **Manipulation** i.e. needle insertion inside the body to reach the target. The task description is used to design the learning system.

3.4 Hypothesis

A collaborative virtual environment is used to test a first learning scenario through an experimental study. The goal of the experiment is to investigate efficacy of the WYFIWIF paradigm to learn a needle insertion task. By using this system to teach the biopsy gesture we hypothesize that:

- Learning the gesture via haptic communication combined with visual and verbal communication may help novices to perform the gesture faster and more accurately than via a conventional learning (by observation, or through theoretical learning). Indeed, haptic communication can help the novices to better master the characteristics of the gesture by developing a more efficient CFR with the instructor.

4. EVALUATION OF THE WYFIWIF PARADIGM

4.1 Participants

60 volunteer students aged 19-29 (30 male and 30 female) participated to the study (6 left handed). None of the participants had prior knowledge of the biopsy procedure. All the participants had no experience either with virtual environments or with haptic devices. We presented the learning system to the participants at the beginning of the experimental sessions to familiarize them with the manipulation of the haptic device and with the use of the virtual environment. We also allow them to perform a simple biopsy scenario. After this initial training period, all the participants were observed to feel comfortable with the experimental setup.

4.2 Task

Each participant performed with an instructor a training session (4 exercises) that consists of learning to perform a biopsy. The procedure consists of a (i) **planning** phase: locating the target and positioning landmarks in the sectional view of the virtual body to define an insertion path and a (ii) **manipulation** phase: inserting the needle in the body to reach the target according to the defined path.

Participants learnt the procedure according to 3 conditions (Details of the 3 experimental conditions are schematically represented on Figure 3):

- **Paper instructions leaning condition (PIL)**: the instructor taught the gesture to the participants through verbal instructions and with support pictures.
- **Visual learning condition (VL):** the instructor taught the gesture to the participants through visual feedback combined with verbal explanations. The novices observed directly the expert's hand manipulating the haptic device and saw the feedback on the virtual needle on the screen.
- **Visual-haptic learning condition (VHL):** in addition to the visual feedback and verbal explanations, the expert used the haptic feedback to guide the novice's hand through the second haptic device.

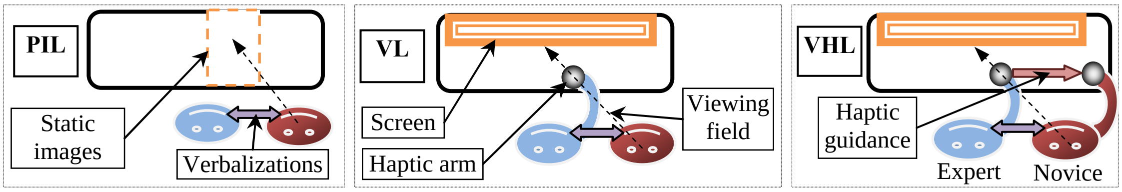

Figure 3. Learning conditions: (left) paper instruction condition; (center) visual condition; (right) visual-haptic condition

After reading the instructions, participants were installed differently depending on the learning condition (Figure 3). In the VL and the VHL conditions, participants were installed slightly behind the expert. This allowed them to observe the expert's hand while he was handling the haptic arm. Moreover, in the VHL condition, learners held a haptic arm through which they were able to follow passively the expert's gesture. In the PIL condition, the expert taught the procedure using static pictures. The pictures contained necessary information to solve the different exercises (they included screenshots of the different needle positions during the procedure). Finally, the expert gave the same verbal instructions to all participants in the 3 conditions.

In order to assess the learning efficacy, participants performed a practice session. In this session, they were asked to perform individually 3 new exercises (Table 1 summarizes the details of the two sessions).

Table 1. Experimental sessions

Conditions / Sessions	PIL group	VL group	VHL group	Total
Training session: 4 exercises with an expert (duration≈90mn)	20 participants (10 male, 10 female)	20 participants (10 male, 10 female)	20 participants (10 male, 10 female)	60 participants
Individual practice session: 3 exercises (duration≈90mn)	20 participants (10 male, 10 female)	20 participants (10 male, 10 female)	20 participants(10 male, 10 female)	

4.3 Description of the leaning system

The haptic interaction system consisted of two identical *Virtuose 6D desktop* haptic arms from *Haption* (Figure 4). The two devices were linked using the *Virtuose API* from *Haption* through a high speed network connection. The *Virtuose API* was used to calculate in real time the master arm position and then to move the slave arm so that it reaches the same (relative) position. This allowed the 2 devices to get the same behavior.

The virtual environment was created using *Virtools* from *Dassault system* on an *Intel Dual-core* based PC with *Windows XP* operating system. The virtual environment consisted of two main views: a planning GUI and a needle GUI (Figure 4). The planning GUI provided a slice view that represented a CT-scanner image. It allowed target localization and path definition. It allowed also the user to visualize any cut plane of the body. The needle insertion GUI provided a 3D display that permitted the manipulation of the needle. Additional information (such as needle position display) was provided. The virtual body is represented by a large 3D box. The body lies down on a CT-scanner table. The user's action point was represented by a virtual hand holding a biopsy needle. Therefore, the needle displacements matched those of the haptic arm. Furthermore, the haptic arm design was adjusted to fit the virtual needles characteristics (workspace, DoF…etc,).

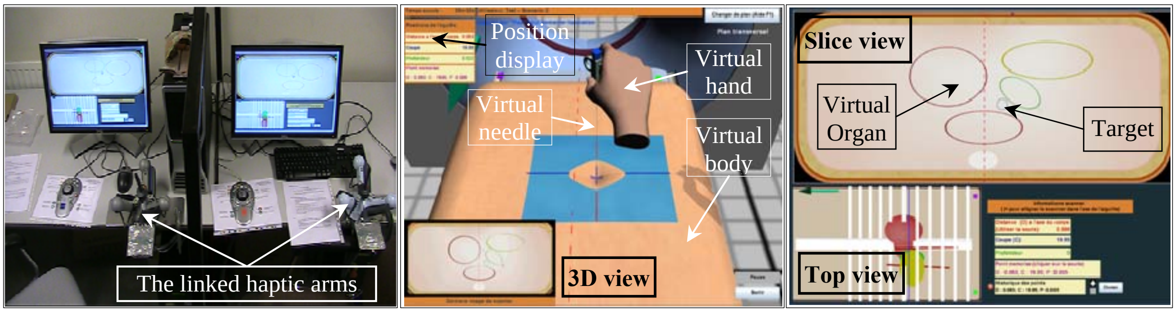

Figure 4. (Left) the experimental setup, (center) the manipulation GUI, (right) the planning GUI

To simulate the haptic feedback sensations, a multi layer tissue model was used. The model corresponded to the one used by Barbé et al. (2006): a model of a needle insertion inside a pig liver at a constant speed. Different model coefficients were assigned to reflect differences in tissue densities (skin, fat, organs and tumor). Finally, the bone was considered as a solid structure through which no puncture can occur.

5. RESULTS

Participants' performance in the practice session was compared over the 3 learning conditions regarding different measures:

- Completion time: in order to evaluate the influence of the learning condition on the participants' performance, the necessary time to perform the task was measured for each participant.
- Contact with organs: when performing a biopsy, the radiologist tries to limit the contacts with the organs to avoid lesions. Hence participants were asked to minimize contacts with organs when performing the gesture. The number of contacts with organs was measured for each participant.
- Number of landmarks: Before inserting the needle, the radiologist uses landmarks to plan the insertion path. When he uses fewer landmarks, this indicates that he relies more on haptic feedback than on visual feedback to reach the target. The number of the used landmarks was measured for each participant.
- Number of insertion gestures: When performing biopsy, surgeons split their gestures into several small insertion movements. The gestures number must be minimized. It was measured for each participant.
- Gestures average amplitudes: Insertion movements' amplitudes can help us to characterize the learner's gesture. Hence, gestures average amplitude was measured for each participant.

The statistical significance of the data was evaluated by pair-wise t-tests (t values are provided) and ANOVA (F values are provided) as shown in Table 2 and Table 3. The results can be summarized as follow:

- **Total completion time:** the results show that the participants performed the task faster in the VHL condition compared to participants in the PIL and VL conditions.
- **Planning time:** no significant differences were observed among the three groups.
- **Manipulation time:** Participants performed the gesture faster in the VHL condition compared to participants in the PIL and VL conditions.
- **Contact with virtual organs:** Participants reduces the contacts with organs in the VHL condition compared to participants in the PIL and VL conditions.
- **Number of landmarks:** Participants used fewer landmarks to plan the insertion path in the VHL condition compared to participants in the PIL and VL conditions.
- **Number of insertion gestures:** Participants increased the number of insertion gestures in the VL condition compared to participants in the PIL and VHL conditions.
- **Gestures average amplitudes:** Participants increased the average amplitudes of their gestures in the PIL condition compared to participants in the VHL condition.

Table 2. Data analyses

	PIL	VL	VHL	F values
Total completion time	2243.2 (639.5)	2628.5 (579.4)	**↘ 1876.1 (343.7)***	$F_{2,57}$= 7.938; p<0.05
Manipulation time	673.5 (201.5)	743.9 (271.8)	**↘ 491.3 (156.8) ***	$F_{2,57}$= 6.963; p<0.05
Planning time	904.8 (323.1)	1037.3 (789.5)	789.5 (252.3)	$F_{2,57}$= 2.590; p>0.05
Contacts with the organs	32.9 (29.0)	31.9 (28.8)	**↘ 15.7 (15.2) ***	$F_{2,57}$= 2.799; p>0.05
Total landmarks used	12.1 (6.3)	15.3 (10.4)	**↘ 8.5 (4.3) ***	$F_{2,57}$= 4.054; p<0.05
Total of insertion gestures	69.4 (28.2)	**↗ 96.1 (30.0) ***	62.2 (18.4)	$F_{2,57}$= 8.990; p<0.05
Gestures average amplitude	**↗ 7.6 (1.0) ***	6.9 (1.0)	**↘ 6.6 (0.8) ***	$F_{2,57}$= 4.565; p<0.05

Table 3. Pair-wise t-test comparisons

	PIL/VL	PIL/VHL	VL/VHL
Total completion time	t_{38}= 1.7049; p>0.05	**t_{38}= 2.8555; p<0.05**	t_{38}**= 4.8681; p<0.05**
Manipulation time	t_{38}= 0.9073; p>0.05	**t_{38}= 3.1093; p<0.05**	**t_{38}= 3.5090; p<0.05**
Planning time	t_{38}= 1.1017; p>0.05	t_{38}= 1.2262; p>0.05	t_{38}= 2.2339; p>0.05
Contacts with the organs	t_{38}= 0.1067; p>0.05	**t_{38}= 2.2904; p<0.05**	**t_{38}= 2.1719; p<0.05**
Total landmarks used	t_{38}= 1.1508; p>0.05	**t_{38}= 2.1011; p<0.05**	**t_{38}= 2.6594; p<0.05**
Total of insertion gestures	**t_{38}= 2.8313; p<0.05**	t_{38}= 0.9402; p>0.05	**t_{38}= 4.2121; p<0.05**
Gestures average amplitude	t_{38}= 1.8422; p>0.05	**t_{38}= 3.0476; p<0.05**	t_{38}= 1.0511; p>0.05

6. DISCUSSION AND FUTURE WORK

In this paper, we presented a haptic interaction paradigm WYFIWIF to teach motor skills in virtual environments. The paradigm permits to combine haptic communication with visual and verbal communication in order to help an expert to transfer his knowledge to a novice operator. A first prototype of the learning system was developed to teach a needle insertion task. The prototype was used to evaluate the WYFIWF paradigm through an experimental study. In this experiment, the WYFIWIF paradigm was compared to two other biopsy procedure learning conditions. We hypothesized that the WYFIWIF will help novices to perform a biopsy faster and to use haptic information better after a training phase with an expert.

The results show that participants performed the task faster after a visual-haptic learning with an expert. This total time can be divided into two main components: planning time and manipulation time. Looking at these two components separately, results show that the time difference is mainly due to the manipulation time decreasing in the VHL condition. This confirms that the WYFIWIF paradigm helps participants to learn the biopsy procedure faster. Furthermore, participants minimized the contacts with the organs and used fewer landmarks to plan the path after a visual-haptic learning. This indicates that participants increased the use of haptic information to perform individually the gesture. Indeed, the visual-haptic learning combined with verbal instructions helped them to better manage the environment haptic feedback. Hence, they tried as frequent as possible to avoid the organs when they felt the contacts. In addition, they used less often the visual information (landmarks) to reach the target compared to the two other conditions. This indicates that they preferred to use haptic feedback rather than visual feedback to locate the needle inside the body.

Regarding the gesture characteristics, results show that the participants had different strategies to perform the gestures. Hence, after the visual learning, participants increased the number of insertion gestures while they decreased the gestures average amplitudes. On the other hand, after the paper instructions learning, participants decreased the number of insertion gestures while they increased the gestures average amplitude. Hence, whereas no performance differences were observed between these two conditions, these results indicate that they performed the gestures differently. Furthermore, participants reduced the average gesture amplitudes and the total insertion gestures after a visual-haptic learning. By combining both metrics, we can observe that the participants minimized the distance traveled by the needle inside the body in the visual-haptic learning condition. Hence, we can assume that they chose the best strategy in this case. However, further investigations are needed to confirm this result. Indeed, more measures must be used to describe more accurately the gestures profiles and the insertion paths. Furthermore, investigations on the CFR developments between the expert and the novices are needed.

To summarize, the experimental study confirms that the WYFIWIF is useful for learning motor skills. Indeed, it allows learners to perform the gestures faster and to use haptic information more efficiently after a training period with an expert operator. However, more investigations are needed in order to evaluation more accurately this paradigm. One option could be to study verbal communications between the instructor and the leaner. This can help us to understand better the nature of the exchanged information when using the system and to study the CFR development in this situation.

We are currently investigating other collaboration scenarios based on the WYFIWIF. The paradigm is used in a collaborative virtual environment that allows two distant users to communicate when performing a joined manual task. This can help us to understand whether haptic communication allows operators to better perform manual tasks in dyads. This ongoing wok will permit to study how haptic collaboration works and how partners construct a CFR at a distance through the haptic communication channel.

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