A web-based collaborative virtual reality environment for distance learning

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Abstract- Recent years have seen the emergence of virtual reality environments intended for learning activities. This situation gives rise to new innovative teaching practices and tools which exploit the possibilities offered by immersion, 3D interaction, sense of presence and virtual reality flow. The advantages for using these environments have been demonstrated in several scientific studies for general learning activities. We present the specifications of a web-based virtual reality environment designed specifically for collaborative learning situations in a distance learning context. The environment makes it possible to address the issue of learner isolation caused by spatial and temporal distance, and to improve the user experience of distance learners. Our framework is based on a 3-tier architecture and recent web technologies (A-Frame, WebRTC) to ensure stable connections between users and a greater flexibility.

Index Terms- Hardware - Networked Systems, Interaction - User Studies, Methods and Applications - WWW Applications, Virtual Environments - Immersive VR

I. Introduction

Distance Learning (DL) is a form of education in which the participants in educational process, teacher and learners are physically separated and communicate by different means and at different time [1]. Since its creation, DL has experienced various forms of innovation. The advent of digital and mobile technologies has contributed to the creation of new educational tools in this field. Some of these tools help to promote interactions between learners and teachers, e.g. synchronous collaborative tools that can be used to carry out group activities in real time. The most common ones are videoconferencing tools such as Adobe Connect, Zoom, Skype or BigBlueButton, often used to transmit courses at a distance [2]. These software allow a teacher to be linked to one or more groups of learners, or learners among themselves, even though they are located in different geographic places.

Virtual reality (VR) is another novel technology which offers new opportunities in many sectors, and education is one of them. VR applications are gradually entering the classrooms to increase collaboration between participants, making the learning process more effective [3]. Authoring systems also become available and provide more and more content creation tools for virtual environments [4].

Our work focuses on the creation of a new virtual collaborative platform designed for the DL context, with a double objective. First, we seek to define a set of features and virtual behavioral primitives (VBP) in order to create collaborative VR environments specifically targeted at DL. The goal is to strengthen the feeling of co-presence between the learners in a DL context and address such problems as isolation, commitment and motivation of learners linked to distance training. These features and VBP are identified through existing works on collaborative VR environments, and user feedbacks collected from the users of a collaborative VR environment produced as part of our work. We also present our technical solution, based on a 3-tier architecture and recent technologies (A-Frame, WebRTC). Here the goal is to address various problems and technological constraints related either to collaborative VR or distance learning. To sum up, we seek to offer a novel approach to the network side of virtual classrooms and an evaluation of design decisions for a virtual classroom implementation. A test version of our VR environment is accessible here: https://vdlearning.fr/vrclassroom/5fad94fd0a9bf5fcfe0d8d34.

This paper is organized as follows. In Section II, we present the associated concepts and the state of the art in collaborative VR environments for distance learning. Section III presents the goals and design methodology of our approach, based on the human operator-centered design methodology for interactive systems. Section IV describes the GUI features and virtual behavioral primitives designed for our collaborative VR environment, and also gives more details on future functionalities. In Section V, we present the technical architecture of our system based on WebRTC peer to peer communication. Section VI describes the first results we observed from our initial experiments with a group of distant learners assigned to perform a simple task on the system.

II. Related works

The purpose of VR is to allow one or several persons to engage in a sensorimotor and cognitive activity in an artificial world which can be imaginary, symbolic or a simulation of the real world [5]. Technically, VR can be seen as a scientific and technical domain exploiting computer science and behavioral interfaces in order to simulate in a virtual world the behavior of 3D entities. In any VR application, the user perceives, decides and acts in the virtual environment, which implies that he/she is fully engaged in the activity. This is what Fuchs calls the "perception, decision, action" loop. Several other concepts linked to VR, such as immersion, interaction and presence, are presented below.

A. Immersion and interaction in VR

Immersion represents the user's exposure to a virtual environment which uses devices that partially conceal his surrounding environment's perception, and display an image of the virtual world [6]. The degree of immersion depends on the environment characteristics and the equipment used, which can include VR headsets, motion controllers and haptic devices.

Interaction is a common language between humans and the virtual environment. This language corresponds to the set of reciprocal actions/reactions between humans and computers through sensory interfaces, motor interfaces and sensorimotor interfaces. They can be characterized as "behavioral" interfaces, because they rely on human behavior [5]. The sensory interfaces (visual, tactile, sound) inform the user through his senses of the evolution of the virtual world, the motor interfaces (controllers, gloves, treadmills, etc) inform the computer of human motor actions in the virtual environment and sensorimotor interfaces (force feedback) provide information in both directions. Several 3D VR interaction techniques, such as navigation, selection and manipulation, allow users to perform different tasks within the virtual world.

B. Virtual presence in VR environments

Virtual presence is the feeling of being physically present in a computer-generated environment, using visual, auditory or force devices [7]. Scientific research suggests three dimensions for evaluating presence in a virtual environment [8], [9], [10]. First, the environmental or physical presence occurs when the user is brought to perceive the objects of the virtual world as being real during his experience. It is reflected in the reaction of the environment to the presence of a user and its actions. Self-presence or personal presence occurs when the user perceives his self as part of the virtual world. This presence is very similar to the physical presence, because the feeling of being physically present in a real place presupposes that oneself is also there. Finally, social presence occurs when the user can interact with other users who are also present in the virtual environment.

C. Collaborative VR environments for distance learning

Although the use of VR for distance learning is recent, there is nevertheless some scientific research on the subject specifically related to the creation of collaborative virtual environments. Most of these projects are based on client-server architectures, where the server takes charge of connecting users to the environment and synchronizing changes for all users [11], [12]. They use the standard ISO VRML language, which makes it possible to design virtual environments, 3D models and animations [13]. Existing projects integrate features that are sometimes different from each other. For example CLEV-R (Collaborative Learning Environment with Virtual Reality) [11] contains: (i) a graphical interface allowing users to register and connect, manage communication (gestural, textual and vocal) between learners, communication recording, group administration etc; (ii) virtual rooms management (the conference room, group rooms, corridors, private space or personal space); (iii) graphics optimizations to deal with network problems and display graphics in a reasonable amount of time. The Vrmed system [14] for medical education offers: (i) a virtual classroom that plays a significant role in the learning process and reproduces conditions developed in a real university classroom. Students have direct access to the educational material (images and text) through their interaction with a virtual board; (ii) a virtual laboratory allowing learners to participate in virtual conferences and to connect the physical learning environment to the simulation part of the application; (iii) a simulation library connected to external resources to learn the conditions of a specific pathology and the human cellular structure.

Other works have described the various problems associated with the creation of VR learning environments [15]. This includes the choice of the architecture for user communications and interfacing protocols, how the data will be stored (data architecture), how to minimize network traffic and compensate for the influence of latency, how to maintain a consistent state of the environment for all users, or how to analyze the interactions in the virtual environment (e.g. collision detection).

Collaborative VR environments help to stimulate the learning process [16], and avatars personification has been found to have an impact on the motivation of learners [17]. The free interactions through body movement and speaking engage the communication and stimulate motivation, but on the other hand gratification functions in an immersive environment do not seem to have a significant impact.

III. Goals and design methodology of our approach

Despite the multiple uses of VR in learning activities in general, the application in the specific field of distance learning remains very little explored. This situation makes the design and realization of collaborative VR environments for DL a complex task, because of the lack of information allowing to anticipate the behavior and user-experience of learners in these environments. There is indeed a strong risk that a virtual environment is not useful and usable and therefore does not meet pedagogical and didactic objectives.

On the technical level, existing environments described in the literature mostly use aging technologies (e.g. VRML) and do not meet the specific constraints related to collaborative virtual environments for distance training nowadays. These constraints are linked to the real-time connection of users, the management of latency and refreshing time, etc. In addition, the choice of technological solutions can have a great impact on the complexity, the interoperability and the development cost, as well as the flexibility and the quality of the environment. From these problems, two questions emerge to which our work attempts to answer: (1) What are the main functional features and virtual behavioral primitives to consider in a web-based collaborative VR environments for DL ? (2) What technical architecture, based on recent technologies, may respond to these environment constraints listed above ?

Our approach is based on the human operator-centered design methodology for user-centered interactive systems, described in the international standard ISO 9241-210 [18]. End users (teacher and learners) are involved in the entire design process, which is carried out in several steps as shown on Figure 1. The design activity begins with the definition of pedagogical and didactic requirements. In our case, we focused on the co-presence, motivation and involvement of learners in achieving a group learning activity in the DL context. The second step is to identify basic features to meet these requirements: here we used feedbacks from existing virtual environments, recommendations related to the design of general graphical user interfaces, and a survey of user preferences carried out as part of the experiment presented in Section VI. At this stage, the identified features are in the assumption form. The third step is to design a prototype for each hypothetical feature identified. The designed prototypes are then submitted to end users for evaluation. Based on their observations and feedbacks, we can either create a new iteration (if the prototype does not meet expectations) or move on to the next increment (new prototype). In this way, we can reduce the risks associated with educational and didactic requirements on one side, and specific end-user requirements on the other.

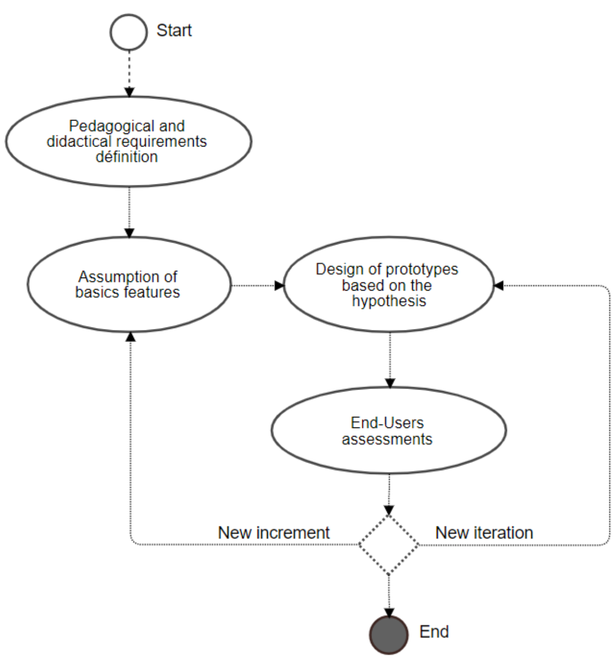

Fig. 1. Activity diagram for collaborative virtual environment design

IV. Description of our collaborative VR environment

A collaborative virtual environment is a 3D space that allows several users to work together on one or more common activities through "user-environment" interactions and "user-user" interactions [19]. The system implemented here is a web-based environment allowing to engage learners and teachers in collaborative learning activities. It is designed primarily for DL situations and can be used in several educational contexts. Multiple learning activities can be achieved in our virtual environment, such as:

- A teacher can give a live lesson to all connected learners in a virtual classroom using a virtual projection board (similar to a real classroom)
- Learners can manipulate virtual objects as part of a practical work
- Learners can carry out a group learning project

To address the issues mentioned above and generally related to DL (isolation, lack of motivation, etc), our system meets a number of characteristics that we recommend for any collaborative VR environment intended for DL:

- **A high degree of immersion**: several features of our environment contribute to the sense of immersion, e.g. 360 degrees gaze perception, first person-perception (FFP), maintenance of spatial and temporal coherence between the different elements in the environment, etc. Among other things, for total immersion we also recommend the use of a a headset with 6 degrees of freedom (6-DoF), a large field of view (around 110 degrees) and a relatively low latency (around 20ms). Among the headsets we tested, HTC Vive, Oculus Rift and Oculus Quest all meet these requirements. In addition, a high speed and stable internet connection is preferable.
- **A feeling of presence in the virtual environment**: in this study we consider presence as a subjective feeling. Thus, we submitted a questionnaire to our users to assess the feeling of presence in our environment [20]. Their answers allowed us to conclude that all dimensions of the presence were felt in the environment, and that interactions with the environment increase the feeling of physical presence and presence of oneself. Interactions between learners (e.g. vocal communication) increase social presence and co-presence.
- **Configurable avatars**: an experiment carried out in our work has enabled us to observe that the avatar representation of users seem to have a significant impact on the sense of co-presence, engagement and motivation of learners to work together, with a preference for human avatars (see section VI). It is possible in our environment to use different avatars according to the activity, one of them being a reconstructed 3D model of the user.
- **A configurable environment**: another survey carried out as part of our work allowed us to observe that learners in a DL context have a preference for virtual environments that are similar to reality (e.g. a virtual classroom or museum). Our platform offers a default classroom with a virtual board on which the teacher can present his course. In addition, depending on the learning situation, the teacher can change the environment by choosing from a predefined set or by importing a 3D model.
- **An easy-to-use environment**: on the teacher side, all the preparation tasks to set up the environment are achieved via a simple web interface (see Figure 2). On the learner side, the use of the environment does not require any prior training and is accessible via a simple web browser if a full VR equipment is not available.
- **Compatibility with most headsets and computers**: the application supports the controllers of a majority of

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headsets (Oculus, HTC Vive, etc), or can be displayed on a computer screen and controlled with the mouse.

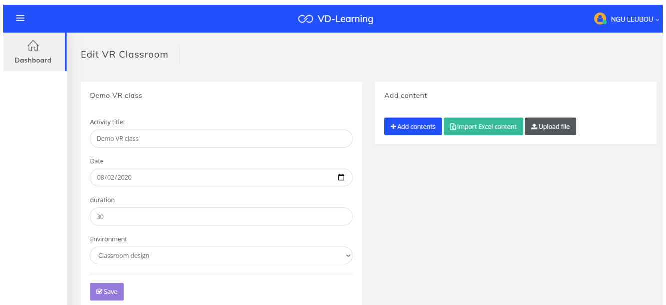

Fig. 2. Web interface for a VR classroom configuration

The features of our system presented below are grouped into two main categories: the features of the graphical user interface (GUI) and the features of the virtual environment, also called immersion and interaction (or I2) features. For the GUI the basic functionalities are accessible with a standard web browser and relate to actions carried out outside the virtual environment. I2 features are the activities that teachers and learners can perform in the virtual environment. These activities can be broken down into a few basic behaviors called “Virtual Behavioral Primitives" (VBP) [21].

A. GUI features

The GUI features include all actions performed outside of the virtual environment, performed directly from the computer and not from the headset. The functional and graphics rules applied for these features are the standard recommendations for GUI Design related to the ergonomics of web interfaces. These features include configuring users, preparing for a learning activity, and configuring the virtual environment. User configuration includes actions for creating a user account, managing profiles and roles, configuring the virtual representation of the user (avatar), modifying account information, connecting and disconnecting. The preparation of a learning situation is carried out by the teacher: creating a room, registering learners, creating a collaborative activity, adding resources to the activity (PDF slides or other documents, 3D objects, etc) and manage the access rights to allow learners to select and manipulate these resources. Figure 2 shows the use case for this activity. Finally, setting up the environment for a collaborative activity involves choosing a 3D environment or importing a new one. All actions are performed thanks to simple web forms as shown on Figure 2, which makes it very easy to use for teachers with no technical knowledge of programming or 3D. The aim is to reduce the "technological distance" that could appear because of to the complexity of virtual reality technology.

B. Virtual Behavioral Primitives

VBP are the set of basic actions that a user (learner or teacher) can perform in the virtual environment. In our case the goal is to identify VBP that contribute to the sense of co-presence and bring together learners who are geographically

Fig. 3. Use case for the preparation of a learning situation

separated, but also improve the user experience of learners. In other words, we seek to offer a technological solution to the problem of isolation linked to distance training and improve the commitment and motivation of learners to work together on a group activity. An experiment carried out in the environment in a distance learning situation enabled us to confirm the feeling of co-presence and closeness of learners, as well as the improvement of their user experience.

VBP can be classified into four categories [21]: (i) observe; (ii) move around; (iii) act on the virtual world; (iv) communicate with others or with the application. Our own VBP are listed below, and Figures 4 and 5 show different snapshots of our virtual environment.

- **Observation of the virtual environment**: our design choice focused primarily on visual observation and auditory observation. The users immersed in the virtual environment use their visual system to orient themselves, to search for someone or something, or to understand the environment. In addition, sound spatialization makes it possible to detect the origin of a sound, such as another user currently speaking or an interaction with the environment.
- **Movement in the virtual environment**: the human sensation of motion is given mainly by the visual and the vestibular systems. We can therefore easily give an impression of displacement by stimulating the sight, allowing users to change their virtual location without having to move their real body. Several types of movement can be considered in the virtual environment, including those that would be impossible to achieve in the real world such as teleportation or free flight movement. To choose the type of displacement, we created prototypes and submitted several options to end users. Their evaluations revealed that teleportation was less destabilizing than the other types, and that users quickly took perfect control of this type of travel.
- **Perform actions in the virtual world**: users can interact

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with virtual objects in various forms, such as selecting an object, translating and/or rotating an object (3-DoF), deforming an object, assembling several objects, or acting on the opacity or visibility. This multitude of actions allow teachers to script different learning situations according to the educational objectives, for example offering to manipulate real or representative objects such as a DNA sequence or a medical model in 3D as shown of Figure 5. The possibility of handling presentation documents in the virtual environment can help a teacher to deliver his lecture, or learners to present an oral defense in front of a jury.

- **Communication with others or with the application**: for now our application is limited to verbal communication between users, allowing interpersonal (between 2 learners), group (while carrying out a group activity) or mass communication (between the teacher and the class). We plan in the following versions to integrate non-verbal communications such as facial expression in avatars (see next section).

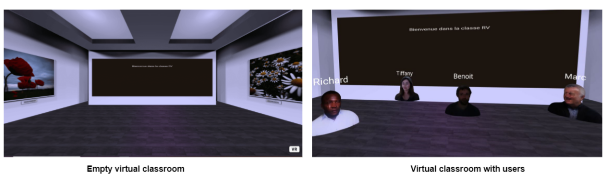

Fig. 4. Different views of our virtual classroom

Fig. 5. Collaborative manipulation of a 3D heart model

C. Future functionalities

Despite the functional richness of the current environment, we plan to add several new features in the future. We carried out a survey among current learners and teachers to help us identify several improvements for user experience and educational needs:

- **Expressive avatars**: according to Fabri and More [22], the introduction of emotional expressiveness can facilitate interpersonal communication in collaborative virtual environments. The avatar face, the primary device for interaction, should be able to display the six "universal" facial expressions of emotion: happiness, surprise, anger, fear, sadness and disgust [23]. The goal will be to verify the impact of this functionality on the user experience through four observables: (i) more involvement in a given task; (ii) more pleasure of the experience; (iii) a higher degree of presence; (iv) better performance in achieving the tasks.
- **Evaluation tools**: we wish to offer tools allowing teachers to evaluate the experience after the learning activity. This will involve collecting and analyzing data on the speaking time of each student, the duration of the connection, the time spent handling objects in the environment, the motion of users [24], etc.

V. Technical architecture of our collaborative VR environment

Existing works related to the creation of virtual environments allowed us to see that the first collaborative VR systems were based on a client-server architecture. The server ensured the connection between users and the synchronization of changes made in the environment for each user. One of the limits of this approach is the performance of the server, which must inform all clients after each change made in the environment (movement of a user, rotation of an object, etc). We preferred a solution based on a 3-tier architecture supporting WebRTC (Web Real-Time Communication); Figure 6 shows a simplified diagram of this technical architecture and details are discussed below.

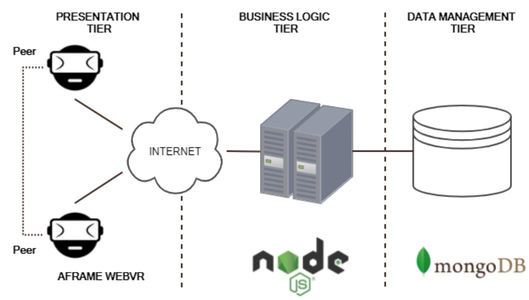

Fig. 6. Technical architecture of our application

A. 3-tier architecture description

The 3-tier architecture is a logical model which represents an application as a stack of three software layers or "tiers":

- **The user interface tier**: the first level corresponds the presentation layer, *i.e.* the visible and interactive part of the application for users. It provides a user-friendly input to communicate with the system using a web browser, and contains the HTML components necessary to collect and display information received from the business logic tier [25]. Communication with the web server is achieved via an HTTP protocol. Unlike standard web applications, the main constraint in our case is to allow users to be immersed in a virtual environment with the possibility of 3D interactions. We used the HTML5 language with the A-Frame JavaScript Framework allowing the creation of VR experiences [26].
- **Application logic tier**: the second level represents the processing layer and corresponds to the functional part of the application which implements the business logic

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and describes the operations on the data according to user requests, obtained from the previous layer. In our case all the user logic and role management, authentication, class management and activity management are implemented in this level. Our web server is implemented with Node.js in order to ensure good performances when processing large volumes of requests simultaneously.

- **The data tier**: finally the data layer corresponds to the database system, which must be able to send and store data manipulated in the application logic layer. Our application uses MongoDB for its simplicity, flexibility and scalability.

B. *WebRTC-based peer to peer communication*

WebRTC is a futuristic technology that offers real-time communication capabilities in audio, video and data transmission through web browsers using a JavaScript API [27]. It relies on a client-server architecture with the concept of peer-to-peer communication between browsers. One of the main advantages of using WebRTC is that it was proven to work efficiently in some existing web-based videoconferencing systems such as BigBlueButton [28].

In our case the use of webRTC allows to manage real-time connections in the VR environment, voice messages and synchronization for all users after a user moves or modifies the environment. To solve WebTRC issues typically experienced by users using a mobile device or connected through a firewall, we rely on a TURN server to handle the NAT perforation and establish the initial connection between users in a virtual room. Once the connection is established, no further action is required (see Figure 7).

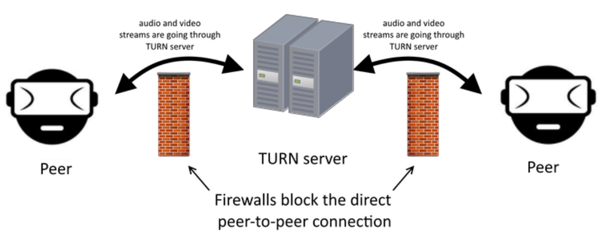

Fig. 7. Peer to peer communication with a TURN server

VI. First results

A first experiment with 22 learners was carried out in our collaborative VR environment, most of them having prior knowledge of such environments. The participants were divided into groups of 4 to 5 and were assigned a group learning activity. The experiment took place in three sequences of approximately 20 minutes each (a total of 1 hour for each group). During the first sequence, a teacher presented the activity to be carried out: imagine an innovative student startup project related to VR. In the second sequence, each group got to know each other inside the VR environment, discuss the activity, and prepare a Powerpoint presentation. Finally in the third sequence the group had to present its ideas to the teacher. Our experiment provided several observations thanks to a subjective questionnaire submitted to the participants. This part of our work is presented in another paper currenltly under review [20], and only the main results are given here. First, in the DL context the collaborative VR environment seems to contribute to the involvement of learners in the group activities realization. The level of involvement varies significantly depending on the representation of the avatars, with a higher level of involvement for human avatars representing the users (see Figure 4). We also observed that learners communicate warmly in the VR environment. Again, the degree of warmth felt in interpersonal communication seems to vary depending on the representation of the avatars, with warmer communications for human avatars.

On the other hand, learners do not very willingly share personal information in a VR environment, regardless of the avatar type. This result can be justified by the fact that our experiment lasted only 60 minutes in total. We believe that under these conditions the learners did not have time to feel comfortable and trust their peers, but this hypothesis deserves to be tested over a longer duration.

The learners who are physically far from each other in a DL context seek to recreate a feeling of proximity (*i.e.* to reduce the perceived distance between them). This feeling is perceived differently depending on the direction of the interpersonal relationships considered: oneself towards other learners, or the opposite direction. Perceptions of self-proximity to others seem to vary depending on the representation of avatars, with again a higher feeling of proximity for human avatars. On the other hand, the perception of the proximity of others to oneself does not seem to depend on the avatar. A logical explanation for this difference seems to be the fact that in the VR environment, learners do not see their own avatars but those of others. As the avatars used in our environment are not expressive enough, it also becomes more difficult to perceive the feelings of others.

Finally, in the virtual environment learners appreciate the voice chat with others regardless of the avatar. This interest could be justified by the difficulty of carrying out textual chat in the VR environment. And most importantly, the motivation of the learners for group activities is expressed by all participants, and once more this feeling of involvement increases with human avatars.

Our environment can be tested using the following link. It works with a standard web browser using the mouse and keyboard for navigation, or with Oculus or HTC headsets and motion controllers. The manipulation of 3D objects is not activated in this version, and all connected users will be assigned a default avatar. However it is possible to navigate around the classroom and communicate orally with the other users : https://vdlearning.fr/vrclassroom/5fad94fd0a9bf5fcfe0d8d34

VII. Conclusion

Our work aims at pointing out the essential functionalities for a web-based collaborative virtual environment in a distance learning context. We were able to identify features and virtual behavioral primitives to take into account in the creation of such environments, and we believe these results could be an important input for future designers.

This type of VR systems can be a part of the solution to the drop-out problems caused by learner isolation and observed in more traditional DL environments. VR definitely allows distance to gradually disappear by bringing learners "together", and improve the user experience. Although there is still little work in this specific area, we believe that our experiments show that researches in education science could benefit from this type of systems. We also demonstrate that recent technologies such as the A-Frame library or WebRTC offer great flexibility and ease in the development of web-based collaborative virtual environments, as well as efficient solutions to different technical issues. More and more projects arise that make use of similar technologies, e.g. https://hubs.mozilla.com/.

In the near future we intend to conduct more experiments and create more complex learning activities, and also focus in the future version on two major features based on user feedbacks as discussed in Section IV-C. The first is to improve the user experience of learners, especially the feeling of co-presence, by adding expressive avatars. We also wish to provide teachers with an analysis tool in order to assess the involvement of learners in an activity (speaking time, connection time, interaction with objects, etc). As a long-term goal we would also like to add more complex navigation and manipulation tools, possibly using hand representations.

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