Official URL :
https://doi.org/10.1109/VS-GAMES.2017.8055811

To cite this version:

Müller, Nicolas and Panzoli, David and Galaup, Michel and Lagarrigue, Pierre and Jessel, Jean-Pierre *Learning Mechanical Engineering in a Virtual Workshop: A Preliminary Study on Utilisability, Utility and Acceptability*. (2017) In: 9th International Conference on Games and Virtual Worlds for Serious Applications (VS-Games 2017), 6 September 2017 - 8 September 2017 (Athens, Greece).

Learning Mechanical Engineering in a Virtual Workshop

A preliminary study on utilisability, utility and acceptability

Nicolas Muller*, David Panzoli*, Michel Galaup†, Pierre Lagarrigue§, Jean-Pierre Jessel*
* IRIT UMR 5505 – University of Toulouse, INU Champollion, France
† EFTS – University of Toulouse II, INU Champollion, France
§ Institut Clement Ader EA 814, University of Toulouse, INU Champollion France
Contact: nicolas muller@irit.fr

***Abstract*— With the recent development of virtual reality (VR) technology, a variety of new tools can be imagined. This article presents a preliminary study on the use of VR for immersive learning games in the field of mechanical engineering. We present the design of such a game and the results of the experiments that followed the implementation of the game. This study was conducted with teachers and students from an undergraduate school of Mechanical Engineering and focuses on utility, usability and acceptability.**

Keywords—Immersive learning game; Virtual Reality; Human-Computer Interactions; User Experience; Mechanical Engineering.

I. INTRODUCTION

In the last few years, learning games have been popularized thanks to both their efficacy and their ability to engage the learner [1]. In particular 3D learning games have shown their proficiency in teaching professional skills [2].

Previous works on a mechanical engineering learning game [3] showed how they could be used to accelerate the learning process. Immersive learning games allows for a realistic representation of the work environment in which the learners can perform their professional activity. This unique characteristic can be coupled to the recent advances in the field of virtual reality (VR) to propose new learning experiences.

This paper focus on the design of an immersive learning game in VR for mechanical engineering and how it was received by teachers and students of this field.

The study uses the methodological framework described in [4] to analyse the design presented in this paper through three dimensions: usability, utility and acceptability [5].

II. PRESENTATION

Our aim is to design an immersive learning game that will facilitate and improve formations in mechanical engineering by giving access to machines that are expensive, removing the risks of working with those machines and allowing the students to make errors and experience scenarios that involve dysfunctions of the machines or even breaking costly devices. In this context we use VR to provide a realistic representation of the work environment and natural interactions with this environment.

The new generation of VR hardware coupled with their software integration in game engines reduces the complexity of the technical context and centers the focus on the design of the VR experience.

The interaction framework used in the experience we developed for this study is designed as a generic interaction framework for immersive learning games and focuses on natural interaction techniques that should facilitate knowledge transfer from the virtual world to the real world.

The experience is featured to provide learning by training [6] to teach the following machining skills:

- Turning using manually controlled lathe
- Setting up a CNC (Computer Numerical Control) lathe
- Machining using CNC lathe

Those machining skills are taught through two scenarios. In the first one, the goal is to realize two operations (facing and longitudinal turning) on a workpiece using a manually controlled lathe that is already set up. To perform those operations, it is necessary to be able to:

- Open/close the protecting cover
- Turn the machine on and off
- Use the hand wheels and read their graduated dials
- Put the working piece in the chuck
- Check the dimensions of the workpiece after turning

The second scenario is more complicated and involves setting up the tailstock center, palping the workpiece and starting the machining process on a CNC lathe. Those operations requires to:

- Open/close the door of the machine
- Move the tailstock
- Use the control panel of the machine

This research is supported by a local funding of the Region Midi-Pyrénées.

- Align the axis of the tailstock center with the one of the spindle using three adjustment screws
- Put the working piece in the chuck
- Choose the NC program and start the machining sequence
- Check the dimensions of the workpiece

Once deployed, all of these actions will be carried out by students that will be supervised by teachers, all of them with little to no experience in VR. This is an important point that will constraint design choices to make sure the proposed application is acceptable for novice users.

III. STATE OF THE ART

In this section we will dive into the design precepts of this immersive learning game. The main focus is on intuitiveness and ease of use. This was decided upon the assumption that the end-user, be it teacher or student, will very probably discover VR with this application.

With the huge investments in the field of VR, dedicated hardware and software have evolved quickly and are bound to continue doing so. While this offers new possibilities and facilitates content production, it also fastens the obsolescence of software solutions. To leverage that and offer compatibility with an array of hardware, our interaction framework i) is based on OpenVR [7] and ii) adds a compatibility layer allowing for the use of non-supported input devices. We chose to restrict to high-end VR devices that offer positional tracking of the user's point of view, positional tracking of at least one hand and the possibility of "clicking" for each tracked hand. At the moment our software is compatible with Oculus Rift's Touch controllers, HTC Vive controllers and Leap Motion. It also supports pointing devices such as a mouse (without VR display) or Daydream controller but this support is experimental and is not presented in this paper because viewpoint control solutions would have to be designed and implemented for those devices.

A. Games

One of our main sources of inspiration in the design of interactions for immersive learning games is VR games and particularly The Lab [8] (Fig. 1.) and Oculus First Contact [9] which are the two games that are "offered" with (respectively) the HTC Vive and the Oculus Touch. Those two games showcase the capabilities of VR and are meant to introduce the player to the use of the controllers. They have in common the extensive use of the virtual hand metaphor where the player can interact with the world using the controllers represented as tools (for The Lab) or as hands (for Oculus First Contact), placed in the virtual world with a 1-1 mapping to the real world. Other sources of inspirations are Fantastic Contraptions [10], The Gallery [11] and SoundStage [12].

In all those games most interactions use the virtual hand metaphor with direct mapping and usually one button to grab the object being touched or trigger the object in hand. In Fantastic Contraptions, Oculus First Contact and Soundstage the players can only move in the "tracked space" and no interaction allows them to reach out of this space. In The Lab and The Gallery, the user is also given the possibility to teleport with a button of the controller and the arrival point is chosen with a curved ray starting from the controller as shown in Fig. 1.

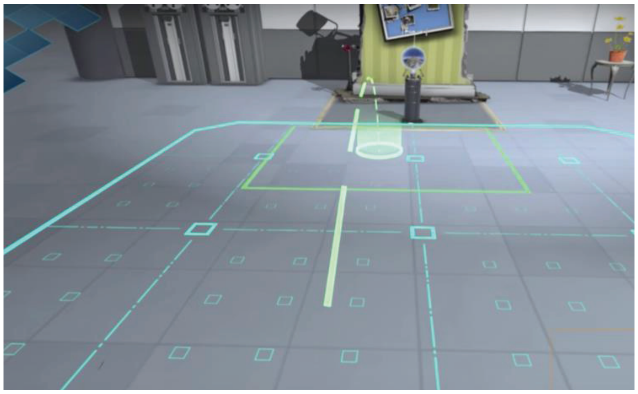


Fig. 1. The Lab travel metaphore [8]

All those experiences put together, one can play with a virtual robotic dog, repair a robot, protect a castle with a bow (The Lab); one can meet a robot and try a lot of different objects in Oculus First Contact; one can create fun contraptions in Fantastic Contraptions; one can explore a world and solve a mystery in The Gallery, and; one can build and use a modular synthesizer in Soundstage, all with very similar interaction techniques. Our interaction framework uses this virtual hand metaphor that allows flexibility in design and ease-of-use even for novice users.

B. Literature

Since its infancy in the 1990s VR for learning have seen a lot of interest from the scientific community. It has been used in the medical field to train surgeons or personnel at following procedures [13], in the bio-medical field to learn long procedures [14], in the military to train soldiers at firing in complex situations [15] and it has been used extensively for training in the aerospace field, from simulators to serious games to train personnel in an array of professions [16]. In the field of Mechanical Engineering, learning games have been used for several years and have shown great proficiency at optimizing training time and efficiency while being more enjoyable for the students than traditional games [3, 17].

Literature offers a taxonomy for interactions, splitting them in two categories: travel and selection-manipulation [18]. The locomotion technique in the mentioned games is teleportation with pointing and natural viewpoint control done through head-tracking. The reason is that most other techniques provoke different levels of visually induced motion sickness (VIMS) [19], although literature provides a solution to reduce this [20].

Traditionally selection-manipulation is separated in two families: virtual hand techniques and laser pointing techniques [21]. In games virtual hand techniques are preferred for interactions with objects in the virtual world and laser pointing is usually limited to application control in menus (except in the case of guns/bows that arguably use laser pointing techniques to allow interactions with unreachable objects).

Based on these observations, the framework presented in the next section offers virtual hand interaction techniques for objects in the virtual world whereas menus are controlled by laser pointing interaction techniques. No locomotion technique is integrated because, in the case of this immersive learning game, viewpoint control is only useful for going from a machine to another and it appeared that other techniques such as moving objects in the world instead of moving the player were easier to understand for novice users and avoided disorientation and motion sickness.

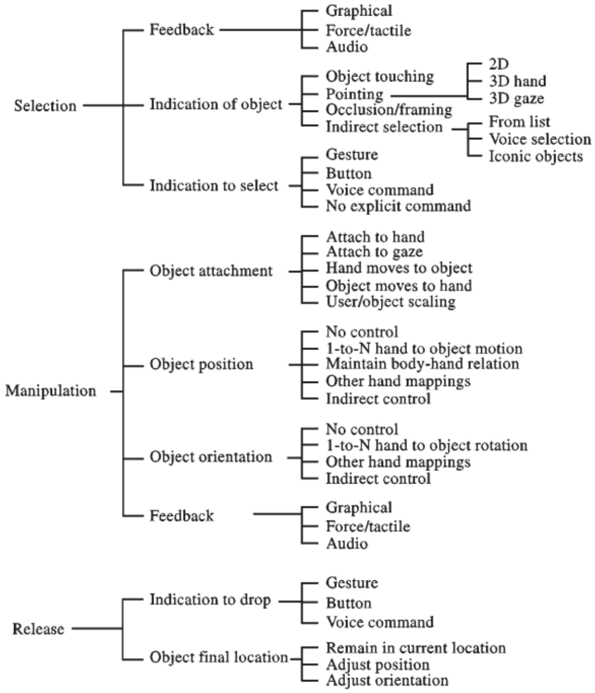


Fig. 2. Selection / Manipulation taxonomy [18]

IV. IMPLEMENTATION

In this section, we will describe the actual design choices and their implementation for this Mechanical Engineering learning game.

Our objective is to provide a virtual workshop in which students can learn to use machines through natural interactions that are close enough to reality to facilitate knowledge transposition in both directions: from past experience in the real workshop and to the future professional situations [22]. The transposition from reality to virtuality has been observed in informal experiments on The Lab's archery game where we noticed that users with previous experience in actual archery where better at the game than users who had never hold a bow. The transposition from the virtual world to the real world will have to be studied in our specific case but a recent study presents results in the case of learning long procedures in the bio-medical domain [14].

With this in mind, and following the precepts of the state of the art presented in the previous section, we decided to use the "simple" virtual hand metaphor.

In this specific scenario, travel had very little pedagogical value. The students and professionals that will play this game will either already be familiar with workshops or are being trained in one. Based on this assumption, we decided to offer the user the ability to choose the machine he wants to use in a menu instead of forcing him to travel from machine to machine, so as to minimise VIMS at the cost of losing the workshop layout.

Fig. 3. Opening the door of the CNC machine.

To help users get started with the application, reduce the cognitive load on novice users, facilitate interactions with the application, and facilitate multiplatform compatibility, we chose to use only one button for all interactions. When looking at the taxonomy Fig. 2, this choice means that indication to select is done by pressing the button and indication to drop is done by releasing this button. On physical controllers this button is the trigger whereas on leap motion it is emulated by closing the hand. When not interacting, the hand is represented by a virtual hand and pressing the trigger closes the hand (the hand closes linearly as the user presses the trigger and when pressed completely the hand is closed).

A. Virtual world interactions

Selection-manipulation in the virtual world is done with the "natural" virtual hand metaphor (Fig. 3.), if we look at the taxonomy in Fig. 2, it means that the user indicates the object to select by touching it and that the object is attached to the hand during manipulation. Selection feedback is done mostly through force feedback with controller vibration (on compatible devices). Pre-selection feedback is also provided graphically to the users with the goal of showing the affordance of the object they are about to use. This is done by changing the model of the virtual hand when they are touching a "Smart Object" (an object that can be interacted with). This visual cue is subtly showing that you can use the object by either changing the opacity of the hand (i.e. for handles Fig. 3) or changing the hand for a tool when required (i.e. for screws Fig. 4).

This was implemented using the Smart Object paradigm presented in [23]. Any object of the scene can be made interactable by making it a Smart Object. In our implementation, smart objects share all the aforementioned properties to which can be added "behaviours" that describe the behaviours of the object when interacting.

To achieve the range of interactions needed in our game, we used five behaviours:

- Constrained rotation: used for the protecting cover and the hand wheels. No control over the object's position, indirect control of the object's rotation (it follows the hand).
- Constrained translation: used for the CNC lathe's sliding door and for moving the tailstock. The object follows the hand in the allowed space and there is no rotation.
- Rotation using a tool: used for driving screws and for turning the rotating buttons of the CNC lathe. No control over position of the object, indirect control of rotation (same as constrained rotation). This behaviour overrides the object attachment and attaches the representation of the hand to the object to give the same "look and feel" than the constrained rotation behaviour.
- Button: used for the CNC lathe's interface, for choosing programs and to start and stop the manual lathe. No position nor rotation control, it is triggered by pressing the controller's button.
- Placement: used to put the workpiece in place. Position and rotation of the object are 1-to-1 to the hand and when released the position and rotation of the object are adjusted (repositioning either in the chuck or going back to the inventory).

For rotations, we chose indirect control because informal testing on few subjects showed that this control was both easier to understand and more precise. The exact implementation is not described in this paper.

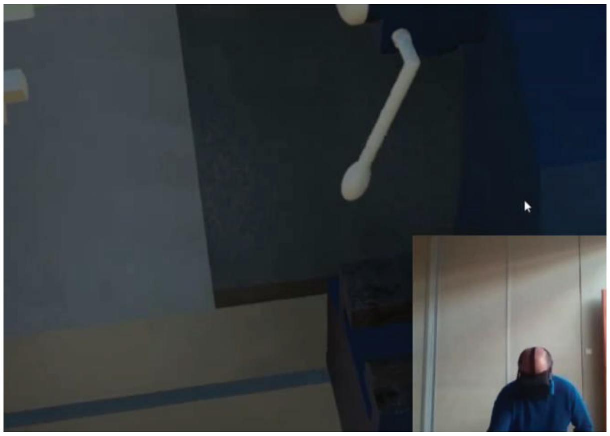


Fig. 4. Interacting with a screw – the vitual hand becomes a wrench that the user can rotate with appropriate hand gesture.

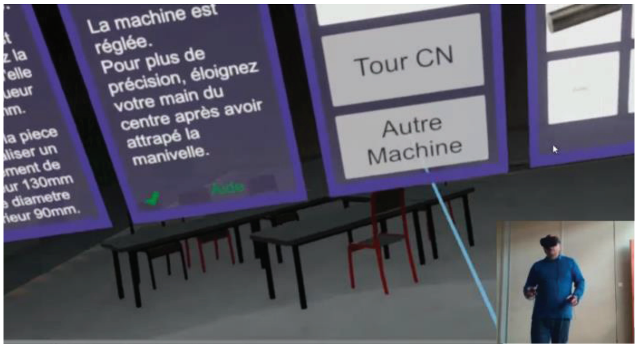
B. *Menus – VR Head-up display*

In this learning game, users are guided through a scenario that is displayed in a menu, that we called "VR Head-up display" (Fig. 5). This menu replaces traditional desktop menus and gives:

- The procedure to follow and the current position in this procedure
- Support on the current task
- An inventory separated in two parts : the available machines and the objects (currently the only object is the workpiece)

This menu slides down when looking up and slides back up when looking away. To signal its presence to the users, the game starts with the menu shown in front of the user with information on the first task.

The buttons can be interacted with from a distance. When pointing the menu a ray is shown. Indication on the object to select is done through pointing with the 3D hand, selection is validated with the trigger and there is no manipulation.



La machine est réglée. Pour plus de précision, éloignez votre main du centre après avoir attrapé la manivelle.

Fig. 5. VR Head-up display

This menu also allows for turning on and off a highlighting system that the smart objects that should be used to perform the current action.

V. STUDY DESIGN

The experiments were conducted with teachers and students of the IUT GMP de Toulouse (eq. to a two-year undergraduate school in Mechanical Engineering) with the objective of evaluating usability, acceptability and utility of the design described in the previous sections and get feedback from the teachers on how they could use this media and what would entice them to use it. Those feedbacks are key to the success of the learning game as teachers are decision-makers as to whether bring or not this new learning tool in the classrooms.

In this study, we investigate a range of indicators that allow us to put in perspective the different design choices we made and the scenario we implemented. The rest of the section will describe the methodology we followed, the protocol of the experiment and the scenario that was implemented.

A. Methodology

The evaluation of the user experience in the immersive learning environment has been conducted with the model proposed in [4]. This model offers a way to analyse the cognitive perception of the participants from their answers to a post-experiment survey. Sample questions to help evaluate presence, immersion, perceived usefulness, perceived ease of use, confirmation and intention to use the product are given in [4].

The dimension of presence (the feeling of being part of the virtual world), that has to be put in perspective with immersion (the feeling that the virtual world is real) was not evaluated in this study. Presence is achieved thanks to a dialogue between the virtual world and the user that enters it. In our case, as the prototype we describe is still in its infancy, this dialogue is restricted to written instructions given to the player that he can follow using objects of the environment. As presence is usually evaluated with questions revolving around human contact and sociability, we chose to put this metric aside for this first experiment.

The survey also included questions from the Revised Simulator Sickness Questionnaire (RSSQ) [24] to evaluate if participants were subject to cyber sickness after 30 minutes of using VR.

Finally, the game also collects traces of the user actions:

- Time spent on each step of the scenario
- Log of the interactions with smart objects
- Log of input devices (controllers and head)

The last log allows replaying in duplicate the experiment of a participant within the game engine for later analysis.

B. Sample demographics

This study was ran on 18 participants from an undergraduate school in Mechanical Engineering, 5 of them were students (28%) and 13 were teachers (72%). Most of them were male (89%). Fig. 6 shows the age distribution of the sample.

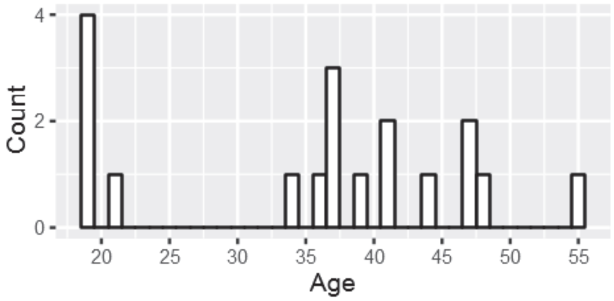


Fig. 6. Age distribution of the sample population (n=18)

None of them had tried “high-end” VR with positional tracking and controllers but few of them (22%) had already experienced some form of VR. They were mostly non-gamers with 50% not playing video games, 39% playing less than one hour a week and 11% playing between one and five hours a week.

C. Experimental protocol

The experiment consisted of four phases:

- Introduction to VR with Oculus First Contact (10 min.)
- Break: Briefing on the procedure they have to follow in the simulation (5min.)
- Testing the learning game (17min on average to complete the scenario)
- Debriefing and user survey

With most of the participants being novice in VR and particularly with the controllers, we chose to introduce them to the medium in a ludic way with Oculus First Contact. In this mini-game, you meet a robot that shows you an array of virtual devices you can interact with.

Then, before starting the experiment in the workshop, we showed them the machining procedure they would have to follow in the game. All information given in the procedure were also displayed in the VR head-up display all along the experiment so that users could be aware at any time of what action was expected from them in the scenario. This way, we made sure the potential wanderings and hesitations could be attributed to the interaction system without ambiguity.

Table I shows the steps the participants had to follow in the game. Each step had to be completed before continuing the experiment to ensure that all smart objects are used during the course of the game.

VI. RESULTS

In this section we will present and discuss the results of the experiments. We will start with the results of the user experience survey, followed with an interpretation of the traces acquired during the experiment and finish with the results of the cyber sickness questionnaire.

TABLE I. STEPS

ID	Action
0	Select the manual lathe
1	Perform a facing operation
2	Perform a turning operation
3	Select the CNC lathe
4	Open the door
5	Move the tailstock
6	Use the top screw
7	Use the left-bottom screw
8	Use the right-bottom screw
9	Finish adjusting the tailstock centre

ID	Action
10	Select the touch probe
11	Use the command panel to probe the top of the workpiece
12	Probe the front of the workpiece
13	Select the machining tool
14	Close the door
15	Bring the tailstock centre out
16	Launch the machining program

Fig. 7. List of actions in the learning game.

Before filling the survey all participants were told to refer solely to the immersive learning game they tested when answering the questions and not to take into account the introductory part of the experiment.

A. User experience

The questions of this part of the survey are all rated on a 7-grade Likert scale with 1 meaning they disagree with the assertion presented and 7 that they fully agree with it.

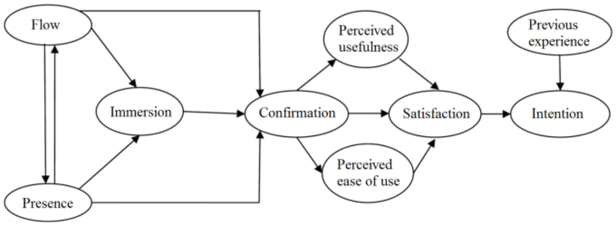


Fig. 8. User experience model [4]. Arrows show relations between the variables (i.e.: presence have an impact on immersion)

Fig. 8. shows the model presented in [4] and the relation between the indicators that we evaluated. Fig. 9. presents the result of the user experience survey that was filled by the participants after the experiment.

Those results are the compilation of the answers given by the participants and gives six metrics:

- Confirmation (of the participant's expectations)
- Perceived ease of use
- Immersion (did the participant lose track of time / of where he was)
- Intention to use
- Satisfaction
- Perceived usefulness

Those measures show that the design that was experimented was perceived by the users as useful –average rating of usefulness is 5.7/7 – and easy to use –rating of ease-of-use is 5.46/7. We can also deduce from the measure of "intention to use" (average rating is 5.8/7) that they found it was acceptable. Those three indicators (utility, usability and acceptability) have been proposed in [5] as the main factors of success for a learning game.

Those results have to be mitigated by the influence of confirmation on the indicators we chose to observe. Confirmation is the degree to which the application answered the expectations of the participant and impacts directly perceived usefulness and ease-of-use and indirectly intention to use the application (as illustrated by the arrows from the "confirmation" node to the "perceived usefulness" and "perceived ease of use" nodes in Fig. 8). With the participants being novices to VR, their expectations were low thus creating a bias in their perception of utility and usability through the "wow" effect. This would have to be mitigated in future studies to evaluate how experienced user would receive this immersive learning game.

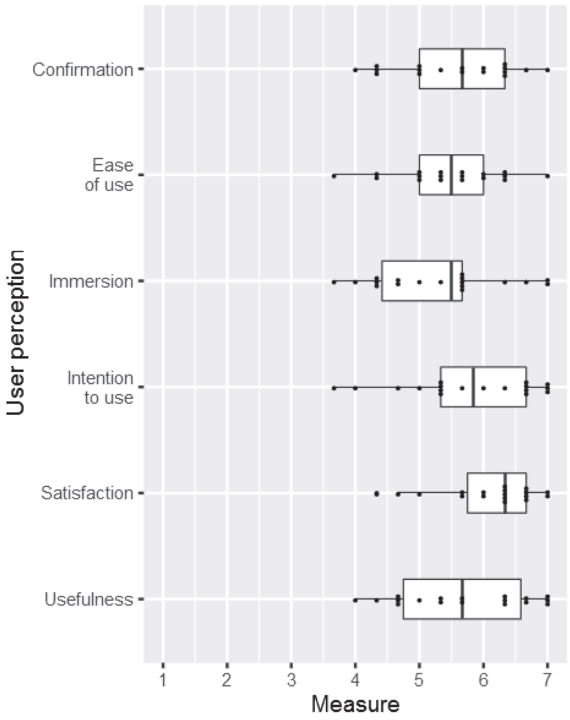


Fig. 9. Results of the user experience survey (n=18); measures are the mean value of the degree to which participants agreed with assertions presented to them. They rated those assertions on 7-grade Likert scale (1: completely disagrees, 7: completely agrees). Three asertions were presented for each indicator.

B. Traces

In this subsection we will focus on information we extracted from the traces logged during the experiment. We will focus on two indicators: the repartition of time spent while in the simulation and the time spent for each step of the scenario by the participants. Those indicators give cues on the actual usability of the prototype.

Unfortunately, due to technical difficulties (laptop overheating), some of the data were unusable resulting in a smaller sample size for this section (8 teachers, 4 students).

Fig. 10 shows the repartition of time spent in the game. The users spent 41% of the time interacting, 22% of the time looking at the menu where the instructions were given and 38% observing.

It is interesting to note that a significant amount of time was spent observing. Some of this is due to animations but most of this time was spent either thinking or observing the environment.

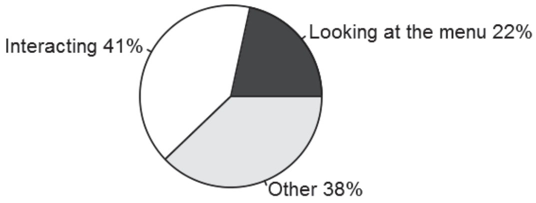


Fig. 10. Repartition of time spent on the game. (n=12)

Another point to note is that participants spent 22% of their time looking at the head-up display, and some of them raised observations regarding the ergonomics of this menu that forces to look up for a long time (3.5 minutes on average). While none had problems using it and the possibilities it offered were useful, in hindsight we wonder if instructions could not be displayed somewhere else in the scene to avoid forcing the menu for too long. This kind of menu could be used instead for application control such as restarting the game, changing scene, or any other action that is not recurrent but has to be accessible at any point.

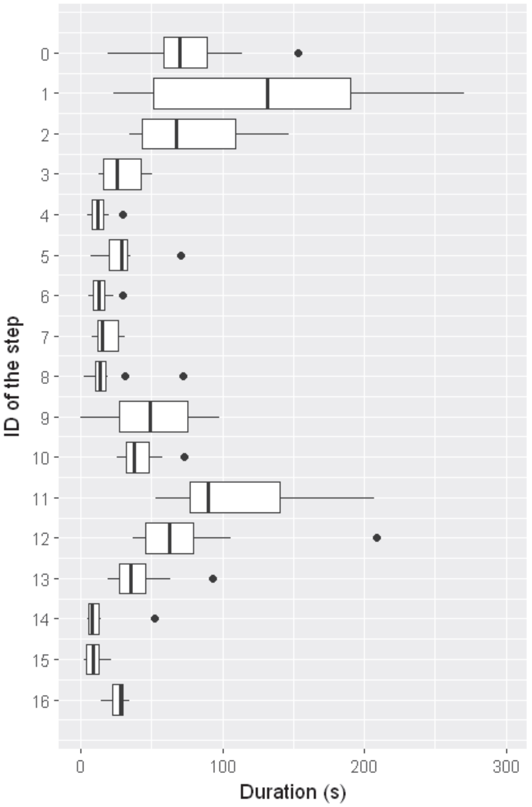


Fig. 11. Repartition of time spent by participants on each step of the scenario. (n=12)

When looking at Fig. 11 some sequences stand out with high variance on time spent by the participants. Step 0 is not significant because it also includes the time the participant took to fit the headset and make sure everything was correct. The others are steps 1, 2, 9, 11 and 12. They correspond to activities that are more complex. Step 1 and 2 are machining the workpiece with a manual lathe and require skills. Step 9 consists of using three screws to finish setting up the tailstock center. This task requires precision and a good understanding of the interaction between the screws and the axis of the tailstock center. Similarly in steps 11 and 12, the user has to approach the workpiece with a touch probe using the command panel while taking care of not breaking the probe. Step 13 is not complex but the variance between participants is due to the fact that some participants took the time to disengage the probe before selecting the machining tool.

C. Cyber sickness

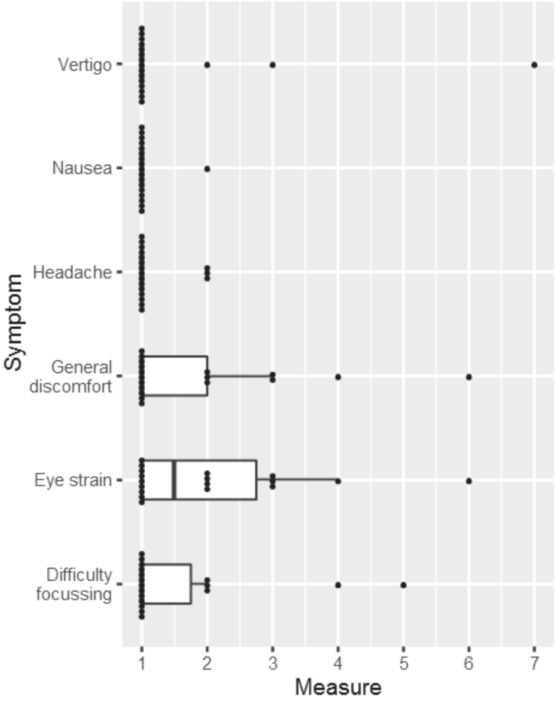


Fig. 12. Repartition of the evaluation of symptoms felt by participants after the experiment (n=18). The participants had to fill a 7-grade Likert scale (1 means that they did no feel the symptom).

When working with VR, cyber sickness is a really important factor to take into account, particularly for an immersive learning game that will be used by students for training. Upon completion of the session, a shortened version of the RSSQ [24] was handed to the participants. The results, summarised on Fig. 12, show that most of the participants experienced little to no simulation sickness, with the most uncomfortable symptoms not being felt with the exception of one participant that felt vertigo during the experiment and stopped without finishing. In the open question on simulator sickness he wrote that he felt "disconnected with the environment" and he reported that he had trouble keeping his sense of balance with the headset on. The only other comment in the open question is that “the image was blurred because the headset was moving”.

Those results are encouraging but a more elaborate study would have to be ran with a longer immersion time and more participants to allow for more accuracy. Yet, it seems that the design we chose with no travel mechanics is provoking little simulator sickness and that the residual inconveniences may not be avoidable with this technology.

VII. CONCLUSION

In this paper we have presented a preliminary study on the use of consumer-grade VR devices for immersive learning in the field of Mechanical Engineering. We described the design of an immersive learning game in VR and a method to evaluate the user experience.

The analysis presented in this paper explores three dimensions: usability, utility and acceptability. The results of this first exploratory experiment demonstrated high interest from the teachers and the students and are encouraging for the future.

Discussions with the teachers allowed us to understand how they wish to explore and use a virtual workshop and gave guidelines for developing a VR training world in the mechanical engineering field. Those discussions gave us material for future development and directions we can explore to facilitate their work and improve the training in Mechanical Engineering. Future studies will have to be ran with more participants in different stages of their training and explore the pedagogical value of immersive learning games in this field.

ACKNOWLEDGMENT

We would like to thank the teachers from the IUT GMP for their welcome and their participation in the experiment, Cyrielle Guimbal for modeling the environment, Elian Cocchi for his work as an intern on the development of the game and Catherine Lelardeux head of the Mecagenius® project without whom this work would not have been possible.

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