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IMPACT OF MODEL FIDELITY IN FACTORY LAYOUT ASSESSMENT USING IMMERSIVE DISCRETE EVENT SIMULATION

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ABSTRACT

Discrete Event Simulation (DES) can help speed up the layout design process. It offers further benefits when combined with Virtual Reality (VR). The latest technology, Immersive Virtual Reality (IVR), immerses users in virtual prototypes of their manufacturing plants to-be, potentially helping decision-making. This work seeks to evaluate the impact of visual fidelity, which refers to the degree to which objects in VR conforms to the real world, using an IVR visualisation of the DES model of an actual shop floor. User studies are performed using scenarios populated with low- and high-fidelity models. Study participant carried out four tasks representative of layout decision-making. Limitations of existing IVR technology was found to cause motion sickness. The results indicate with the particular group of naïve modellers used that there is no significant difference in benefits between low and high fidelity, suggesting that low fidelity VR models may be more cost-effective for this group.

Keywords: Layout Design, Virtual Reality, Oculus Rift, Factory Layout, Virtual Environment, Discrete Event Simulation, Model Fidelity

1 INTRODUCTION

Shop floor layout design influences many aspects of productivity and costs. For instance, shop floor material handling tasks accounts for 15-50% of manufacturing costs and a good layout could drastically reduce that expenditure (Cullinane and Freeman 1985). An effective utilisation of available area could allow multiple tasks to be performed using the same equipment and labour force, further reducing costs. An optimised layout also helps to avoid bottlenecks that lead to the decrease of the work in progress and queuing time, thereby speeding up execution of orders (Fu and Kaku 1997). Furthermore, a well laid out facility contributes to effective health and safety implementation and control of operations.

Shop floor layout design can be optimised using Discrete Event Simulation (DES). DES works by modelling system state changes occurring at specific points in time, which are probabilistically determined by historical data. In DES, analysis of the past data is essential as well as the definition of the probability distribution that defines the activity duration. These activities are essential because DES entities are processed by passing through the activities and following defined rules, which can be easy or extremely complex (Brailsford and Hilton 2001). DES is suitable for comparing different layout scenarios of production lines or linear processes as it allows to easy visualization of computer animations, metrics and graphs (Sweetser 1999).

1.1 Discrete Event Simulation and Virtual Reality Visualisation

In the mid-1990s, DES implementations began to take advantage of 3D visualisation techniques. Its increasing popularity and its potential benefits compared to 2D are being recognised (Akpan and Brooks 2014; Akpan and Brooks 2012). Akpan and Brooks (2012) surveyed the opinions about benefits and drawbacks of 3D among the users of 3D and 2D simulation. Users reported that problem definition, model validation, scenario experimentation, error detection can all be improved by using 3D visualisation. Also 3D models are said to be easier to understand, more usable, and have higher credibility, hence the ability to demonstrate models to clients in 3D is highly valued. On the downside, users opined that 3D models are more difficult and take longer to build, require significantly more time and more expensive to produce than 2D.

Recently, due to the fast development of the technology and the new hardware available on the market, Immersive Virtual Reality (IVR) 3D visualisation has become more widespread. In order to test the feasibility of IVR, researchers have used both the Head-Mounted Display (HMD) and CAVE technologies interchangeably. IVR technology gives the user the psychophysical experience of being surrounded by a virtual environment (van Dam *et al.* 2000), providing new opportunities for visualising systems and their behaviours. There are other reasons why IVR can be better than standard 3D: IVR provides global context due to peripheral vision, it allows more natural exploration of the environment in which the user is immersed, provides more clues useful to investigate data quicker and reveal patterns in it. Also, in IVR, people replicate the same spatial errors as in the real world (e.g. the over- or under-estimation of height or width)(van Dam *et al.* 2000).

Apart from these generic benefits, IVR can offer specific advantages for DES especially in manufacturing. Korves and Loftus (2000) demonstrated the usefulness of IVR in layout planning by comparing it with non-immersive 3D visualisation. Their experiment was about assessing the position of objects (i.e. tables used for assembly and bolt-feeder), the position of parts and the material flow in a manufacturing workplace. They found the use of IVR and 3D for workplace appraisal do not show significant performance differences, but IVR was much better in the detection of flaws. A research on layout planning of a Manufacturing Cell (MC) shows that by using IVR the planner is able to quickly assess the layout and easily detect collisions between machines (Korves and Loftus 1999). Moreover, IVR can offer an immediate qualitative feedback if a new machine is to be setup in the factory or the consequences of the rearrangement of the pre-existing equipment (Smith and Heim 1999). A few of these benefits are summarised in Table 4.

1.2 Fidelity in Immersive VR

There has been many experimental investigations into the suitability of IVR for creating a sense of presence, dimension and distance perception, architecture evaluation, and training. The first experiments aimed to test the sense of presence in IVR as the one by Hendrix and Barfield (Hendrix and Barfield 1995): the experiment consisted of assessing the effects of auditory and visual display parameters on the level of presence through a subjective questionnaire. The hypothesis was that higher levels of parameters would have increased the sense of presence; it was found that only the visual display had an impact on presence (Hendrix and Barfield 1995).

A related experimentation in IVR has been on the perception of dimensions and the factors that can affect it. One of the first experiments dates back to 1997, when participants had to make judgments about object locations in a room based on observations in the real world, in VR, or in a picture. The results suggested that real world and VR not be significantly different, but in both cases people tend to focus their attention on objects themselves rather than on the location of objects (Arthur *et al.* 1997).

In a training experimentation with coal mine workers (Grabowski and Jankowski 2015) two different levels of fidelity were used, where fidelity refers to the quality of immersion. The high immersion fidelity IVR consisted of a HMD with 110 degrees field of vision (Oculus Rift DK1) along with head and hand tracking devices to aid navigation. In comparison, the moderate-fidelity IVR setup included a HMD with

45 degrees field of vision, a wired Razer Hydra controller and a joystick for navigation. The results show that the better immersion resulted in a more user friendly and effective training.

Table 4 *Qualitative comparison between 2D, 3D and IVR used in DES (After Akpan and Brooks, 2012; Korves and Loftus, 1999)*

FEATURES	2D DES	3D DES	IVR DES
Fast Problem Definition	-	+	+ +
Fast Model Validation	-	+	+
Easy Experimentation	-	+	+
Easy to build	+	-	- -
Low cost	+	-	- -
Error Detection	-	+	+ +
Easy Demonstration to client	- -	+	+
Workplace Appraisal	- -	+	+ +
Easy Material Flow Detection	-	+	+ +
Easy Collision Detection	- -	+	+ +

IVR offers the opportunity to recreate a virtual environment that approaches reality and this may be is useful for applications in layout design. There is a lack of investigation about the claimed advantages of an increase of fidelity for layout decisions in a manufacturing environment. This work aims to address this gap by experimentation centred on Oculus Rift DK2 technology.

2 MODEL DEVELOPMENT

As a prerequisite to experimentation, a shop floor model needs to be prepared in both high fidelity and low fidelity versions. Lanner's Witness version 14 was used as the main engine for reproducing an existing manufacturing shop floor and its VR capability was used to create the 3D model of the facility. The WITNESS option to stream the running simulation model to full immersive VR was chosen. This uses a dedicated VR software, Visionary Render from Virtalis, and this was used to add additional animations to the objects and to enable the IVR of the shop floor through an Oculus HMD. A 3D design software, Sketchup Pro 2015, was adopted to re-produce objects and equipment in the 3D environment.

Increase of fidelity refers not only to a better rendering of the quality of graphics and how close it is to reality (Figure 1), but it also concerns a higher degree of animations of objects and how they interact with users, in order to make IVR more similar to reality during experiments. For instance, a user employing top-down view cannot make out detailed movements on the shop floor, while a user walking around at head level will appreciate animations on tools and workpieces on the shop floor (Figure 2).

3 USER STUDY

A guiding research question for this work is: "Does a higher level of visual fidelity improves layout decision making?" In literature, investigation into the impact of IVR fidelity led to the discovery that higher fidelity of the environment helps to provide a more precise distance judgment (Phillips *et al.* 2009; Kunz *et al.* 2009). Consequently, this study starts with the belief that the results gathered from the high fidelity scenario would be better than the ones in low fidelity.

The design of the user studies was based on a previous research by Akpan and Brooks (2014) in which several experiments were carried out to compare 2D and 3D view in DES by using Witness. This framework tested two important task types in DES: observation of processes and completion of tasks. Along the way it also analysed the effect of fidelity between 2D and 3D.

(a) An actual testing rig *(b) High fidelity model* *(c) Low fidelity model*

Figure 1 *An actual testing rig and its 3D models*

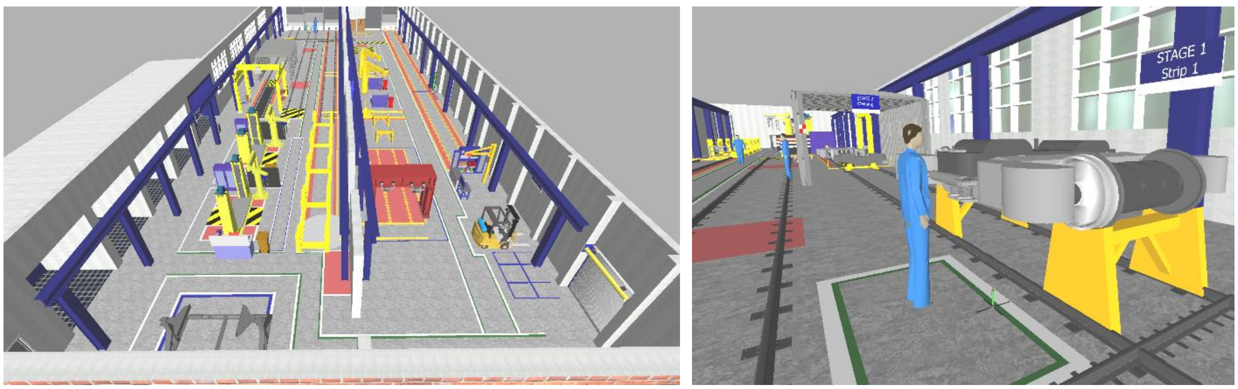

Figure 2 *Top down bird eye view (left) and a walking view (right) of the simulated facility*

Table 5 *Name, type, and time limits for each task of the user study*

Task	Name	Task Type	Time
1	Understand the system behaviour	Observation	10
2	Detection of material flow difficulties	Observation	5
3	Spot the error	Observation	10
4	Position a new equipment	Task completion	5

Despite the fact that the Akpan and Brooks's experiments provided a comprehensive spectrum of investigation in DES, they did not consider the IVR. This work adopts Akpan and Brooks framework and investigates the same task types. However, to accommodate IVR, the tasks themselves were adopted from the research by Korves and Loftus (1999), where they showed the advantages of IVR, as presented in Table 4. Four tasks were performed in strict sequence. The tasks, task types, and timings of the user study experiments is provided in Table 5.

Task 1 was aimed to test the two claimed advantages of IVR, which were (a) faster problem definition and (b) better workplace appraisal. In 10 minutes' immersion, test participants must comprehend the activities performed within the facility and identify important steps in the process. Task 1 is evaluated through eight questions: four questions on number of elements, in order to understand if a higher/lower degree of fidelity affected the participants' concentration; then four questions on process sequencing, to elicit participants' comprehension of the process.

Task 2 was aimed to test the claimed IVR ability to help users detect material flows faster, as cited in research by Korves and Loftus (1999). Participants observes the process for 5 minutes then try to identify potential locations of material handling trouble spot.

Task 3 was related to the stated IVR advantage of detecting errors. An error was introduced on purpose in the model and the participant was challenged to spot it as soon as possible.

Task 4 was about task completion. As this was the last task, it was assumed that the test participant should be quite familiar with the environment, having understood the process to a high degree. They are asked to find the best location to position a new equipment. This models a principal activity in layout decision-making, and is consistent with the advantage of using IVR for collision detection.

Fourteen participants attended the IVR DES user study session and were assigned the tasks above. They were divided into equal numbered sets for high fidelity and low fidelity scenario. It should be noted that the participants were not highly skilled in simulation modelling and also did not have any previous knowledge or experience of the facility under examination.

4 RESULTS

It was discovered that motion sickness caused by the Oculus was a key challenge, with 64% (9 participants) suffering from motion sickness after and during the user studies. Only 36% did not feel sick (Figure 3 left). More precisely, looking at the 9 participants, 67% (6 participants) performed the user study in high fidelity, whereas 33% (3 participants) in low fidelity. Due to the motion sickness, there is participant dropout after almost every task (Figure 3 right). This suggest that there is a need for a more detailed investigation of the causes of nausea in high fidelity. It should be noted that other non-immersive and immersive ways of viewing Witness simulation models in 3D do not cause this motion sickness.

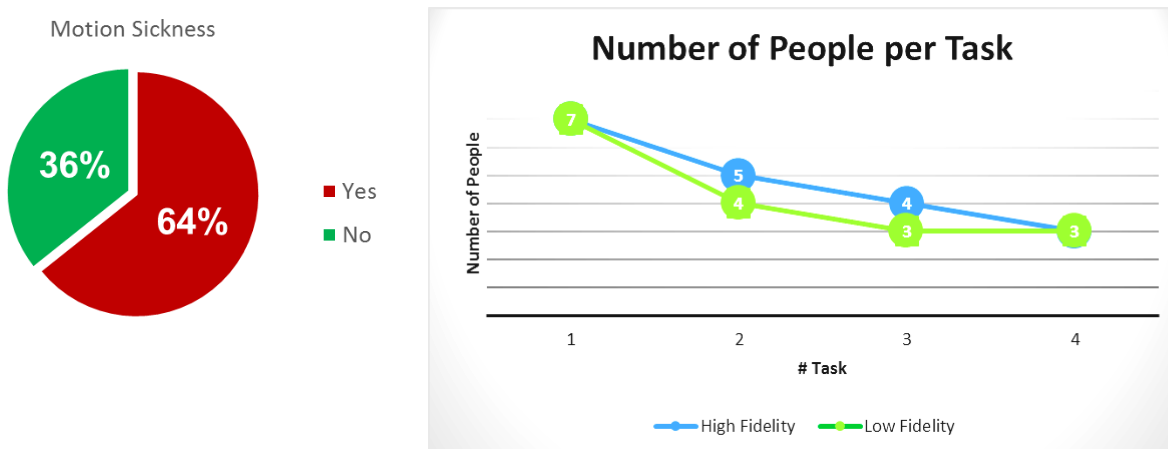

Figure 3 *Percentage of participants affected by motion sickness (left); number of participants per task (right) showing consistent dropout after each task due to motion sickness*

Performance data is collated and normalised based on the average score obtained in each task. Figure 4 shows the comparison between the normalised scores in high and low fidelity scenario. Figure 4 also depicts a trend for the scores obtained in low fidelity scenario to increase over time. Two different hypotheses allude to this: either participants became increasingly familiar with the immersive environment, impacting their performance; or the increase is because the reduction of participant numbers led to an increase in the average score. The latter hypothesis can be immediately discarded as the trend of high fidelity scores do not follow the same principle, even though the number of participants also decreased. From Figure 4, over the execution of the four tasks, there was a trend of improvement in low fidelity and an opposite trend in high fidelity.

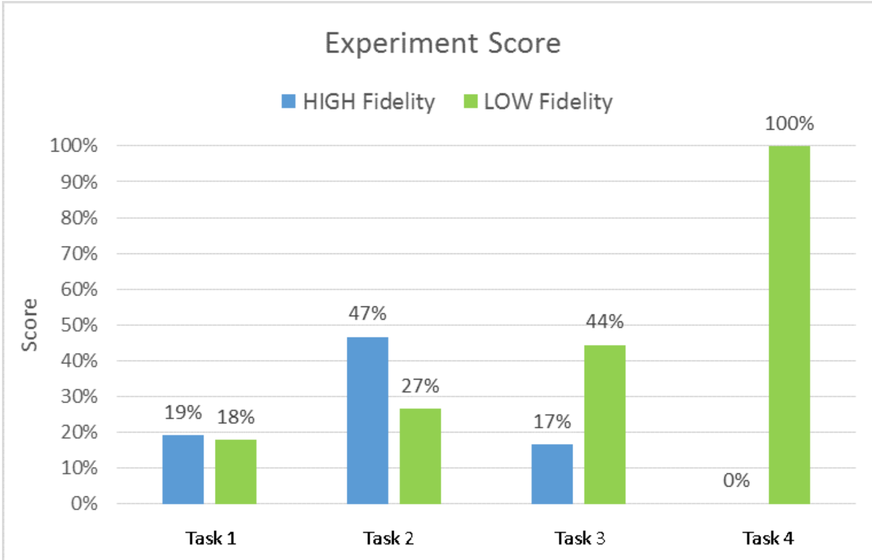

Figure 4 *Performance score for each task*

The six participants who successfully performed the entirety of the user study were split evenly between participants in low fidelity study and in high fidelity so their views can be directly compared from their answers to the evaluation questionnaire. This is reproduced in Appendix A of this paper. At the end of the user studies two out of three participants in high fidelity felt sick, while nobody in low fidelity reported any symptom of nausea. Analysing the comments of the "high fidelity participants", they indicated that they were distracted by the motion sickness, causing them to not pay enough attention to the task. In fact, more participants in the high fidelity scenario felt sick than low fidelity ones.

It is also interesting to note and compare the total time spent in IVR between the two groups. Altogether, the high fidelity participants spent 242 minutes in immersive environment, while low fidelity participants spent only 197 minutes.

5 DISCUSSION

The result of the experiments do not support the hypothesis that a higher degree of visual fidelity would aid layout decision making. In fact higher visual fidelity seems to correlate with lower performance. Participants in low fidelity scenario obtained higher scores (+37% on average) than the opposite group. Thus, the additional efforts and time to develop the high fidelity scenario, five times more than low fidelity does not appear to be cost effective. Nevertheless, the lower performance of high-fidelity IVR seem to be due to motion sickness, which is most likely due to the shortcomings of the test equipment rather than the inherent characteristics of high fidelity immersive environments.

Additionally, it was found that the text labels attached to low fidelity parts may have influenced the outcome of the user studies since it is easier to understand which part is which by reading a label rather than looking at details. This labelling was unavoidable due to the lack of other distinguishing marks at low fidelity. This effect is more evident analysing the results of task 3, where participants had to spot one error, done on purpose, in the model. The error consisted in the substitution of the wheels with the bolster in one assembly step of the process; participants in low fidelity both answered faster and achieved a higher score than in high fidelity. This is supported by participant comments, where low fidelity IVR users confirmed that task 3 was easy to carry out because the labels helped them.

Motion sickness greatly affected participants performance and the experimental results, particularly in the high fidelity scenario. Generally, in high fidelity six over seven participants (86%) felt sick. This merits further analysis. The only participant who did not suffer nausea is a heavy videogame user and has had more than 5 years' experience in simulation, suggesting that experience may help in combating motion sickness. However, contradicting this, another heavy videogame user participating in high fidelity scenario did suffer motion sickness. After further investigation, it was found that the first participant used a fast mode, while the second opted for a slower setting. The contradictory finding may have been caused by different selection of the simulation rate of movement.

Regarding the increased period of immersion for high-fidelity scenario participants, a possible explanation could be that in high fidelity scenario participants were distracted by the amount of environment details, e.g. losing time to look at the accuracy of the machineries or parts. This increases the likelihood of motion sickness and consequent reduction of performance (Figure 5).

To fully understand the root causes of the motion sickness a detailed analysis of the participants' comments after the user study is necessary. They reported display problems during the user studies: a continuous flashing along the most complex shapes, some object edges were jagged and a level of jerky object motion. The most likely reason for this is hardware and software limitations. Despite the workstation-class graphic cards used (NVIDIA Quadro K5000M), the load from the high-fidelity scenario caused some motion freezing and consequent choppy movements of objects. The Oculus screen display was not sufficiently detailed causing the aliasing or staircase effect (jagged effect). It is reasonable to attribute this effect to Oculus Rift because the aliasing was not evident on the computer screen at all. On the other hand, after studying various videos of the Oculus Rift on internet and having tried the demo provided with the device, the staircase effect was not evident. Therefore this problem may be possible to overcome with different Oculus drivers and settings.

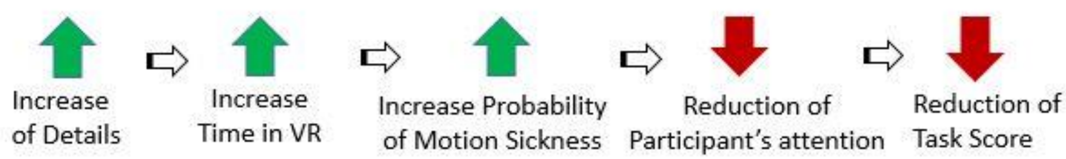

Figure 5 *Sequence of events that leads to low scores in the user studies*

Finally, the strategy adopted to carry out the tasks is another important factor influencing motion sickness. Two different strategies were observed: walking around in the facility ('walking strategy'), adopting a stationary position above the facility looking at the process from the top down ('bird eye strategy'). In one instance, a participant decided to walk around in the first task, stopping one time, while in the second task adopted chose the Bird Eye strategy and finally for the third task reverting to walk again. After the third task, the participant was overcome by motion sickness. Maybe due to BE strategy in the second task he was able to keep doing the user study, as he did not move too much. Looking at his profile, he never played videogames and performed the user study in high fidelity scenario, so the probability of motion sickness was very high.

It was found that participants who adopted the bird eye strategy and minimised their movement in immersive environment did not feel sick. However, all participants who fully adopted the bird eye strategy belong to the low fidelity user study group. It is thus impossible to make any conclusion about which are more likely to reduce motion sickness: the movement-minimising strategy or the low fidelity environment itself.

6 CONCLUSION

The continuous changing of the market and the increase of variability of customer demand is pushing future factories to be more flexible. Among the many analytical tools available, Discrete Event Simulation (DES) and Immersive Virtual Reality (IVR) are among the most innovative and promising.

This research has presented the study of the impact of visual fidelity, which refers to the degree to which objects' aspect in VR conforms to the objects' aspect in the real world, on layout decision-making. Two scenarios with different fidelity (high and low) of a real facility have been developed and two Witness models have been created using the shop floor data gathered. Fourteen respondents have attended the user study, where both the scenarios and the simulation model have been used.

It was found that there is a decreasing trend of participants' performance throughout the user study, particularly in high fidelity due to the increase of nausea symptoms. This include users dropping out even only after performing one task due to motion sickness.

The results of the user studies show that there is not a significant difference between high and low fidelity results and, considering the time and the efforts made to create the high fidelity scenario, low fidelity results to be a more cost-effective solution.

Additional findings indicate that the adopted IVR system caused motion sickness in the majority of the participants. Fidelity is also found to be not the only important concept in layout-decision making. For example, the visualisation of the simulation time, which in this example was not displayed in IVR, has an impact on layout decisions as it helps, and maybe speeds, the understanding of the process and the events.

Therefore, these two findings can be used as a base for future researches in IVR. Firstly, one work should investigate if the suspected causes of motion sickness are correct and if a further investment in a more recent and powerful hardware can lead to different conclusions about fidelity. In the case in which the high fidelity helped to achieve better scores, a new research should investigate the extent to which the details have to be represented, that is the right trade-off between efforts and degree of visual fidelity.

Secondly, there is a need to statistically validate the conclusions of the project thesis and a future research can be focused on this. The sample size used (14 participants) cannot be used to give statistically significant results but it contributes to the growing body of data on the use of VR in manufacturing.

Finally, future investigation may need to ensure that participants do not try to adopt strategies which renders them immobile ('bird eye strategy'). It is suggested to avoid that behaviour for two reasons: it skewed the results and it is not in keeping with the idea of IVR, because it essentially employed the IVR to provide a glorified 2D plan view.

It should be noted that there are many other aspects of this work that can also lead to further study:

- Model fidelity is a continuous scale and the terms used in this paper of "high" and "low" are relative. There are also many different standards of high fidelity view in Virtual Reality and this study has only used one example. View complexity and fidelity are not the same thing and complexity can radically affect 3D performance. There is much more to learn about the appropriateness of different types of views for this type of model.
- The types of participant in a study may affect results. Users of a model may typically be more familiar with a facility than was the case here. This domain knowledge may affect greatly the interaction and understanding of the model.
- Although this study concentrated on IVR views with Oculus there are many other ways for immersive VR to be viewed, for example on large wall displays with 3D glasses. The results for model fidelity may be different in this type of environment and for individual or multiple concurrent use.

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A APPENDIX: SELECTED PARTICIPANTS' COMMENTS

- I felt dizzy. The 3D space mouse is ok but the Oculus is very tiring. I saw blur and flashing when I moved. It was not easy to understand the process because I did not see the operations.
- I have the feeling of nausea. I felt distressed. The Oculus is heavy for my nose. After a while, I think the animation affected my sensation.
- I am feeling good. I would like to see the parts from one stage to the other, otherwise it is difficult to understand the right process. I did not like the fact that the computer was freezing.
- I lost time to ensure not to be sick, so I could accomplish the task.
- I could not see all facility because the setting was too slow but it was necessary otherwise I would feel sick.
- I am feeling less good than before. I could not see far from me because of the lens of the Oculus. I would like to be faster but I couldn't because when I did I felt not so good.
- I feel good. The equipment is fine and user friendly. The label on the parts helped me during the experiment, very easy.
- I am a little dizzy. The Oculus was slow and I cannot move my head because it gave me instability.. The animations were too blocky and finishing the task was too difficult.
- I am not good. The mouse is ok, but the resolution of the Oculus was too low may it influenced my feeling. I spent more time not to be sick than memorise and finish the task.
- I am good. The interaction between mouse and Oculus needs improvements: it is unnatural to move the head without moving in the same direction. All stations looks the same, I wanted more details.
- I am ok. At the start was a little difficult and noisy, then I familiarised and everything was perfect.

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