Regional Aircraft Interiors Evaluation in a Real Time Ray-Traced Immersive Virtual Environment

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Abstract. This paper describes the Immersive VR Interiors Simulator developed by the VR Lab @ CIRA, the Italian Aerospace Research Centre, through which, leveraging the immersive approach and the first-person interaction, it was possible to carry out reachability, habitability and comfort tests of a new regional aircraft prototype.

More than one seats configuration was loaded in the app preparation phase in order to setup a switch logic among them. In the same way, by simply pressing the buttons on his/her handheld controller, users could change internal and external lights conditions.

The experimental activity was focused to the seating zone of the passengers' cabin. Overall cabin assessment, with the user standing in the cabin (including navigation, seat row ingress/egress and embarkment/disembarkment) and with the user in a seating position (PSU and try table reachability and usability tests) were carried out in order to improve and optimize the features of the aircraft interiors.

The protocol followed by CIRA for the human-in-the-loop subjective assessment of innovative design of regional aircraft interiors included two user questionnaires: the first one specific for the purposes of the core evaluation, the second one aiming at validating the user acceptance of VR, of the immersive approach, and of the specific VR application itself. In this paper, the results of a subjective test campaign made up of #24 testing subjects are presented.

Keywords: Subjective comfort assessment · Immersive VR · Unreal engine 4 · Aircraft interiors

1 Introduction

The immersive VR application described in this paper has been developed within the CASTLE project framework (CAbin Systems design Toward passenger welLbEing) [1] in order to carry out subjective tests of an innovative design concept for cabin interiors of a future regional aircraft. The workflow proposed consists of a user-centred evaluation process of design concepts to be performed when the interiors model is still at a digital design stage. In this way feedbacks on how comfortable the solutions have been perceived

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by sample passengers could be send to the designers at a very early stage of the project workflow and, over all, before to realize any physical mock-up of the aircraft [2].

In fact, even if the most relevant environment for such kind of comfort evaluation should be, of course, a physical mock-up of a real passenger cabin built up for the purpose, a virtual prototype can give designers a good feeling of future user acceptance before building up anything physical. Obviously as long as the virtual representation and the related experience are of a very good level of representativeness (the graphics representation has to be a credible virtual counterpart of the designed interiors in terms of 3D models and material rendering, and the sensory experience has not to be misleading for the testing people) [3].

User tests regarded various aspects of the comfort relevant to designers' interests: visual comfort (style, pleasantness), and ergonomic comfort (spaciousness, objects and command reachability and usability) [4].

2 The Immersive VR Application Used for Subjective Tests

The Virtual Interiors Immersive Simulator is based on the game engine software Unreal Engine 4 (UE4), developed by Epic Games [5], and allows to get a high-fidelity graphics experience achieved through the capabilities of setting all lighting parameters and materials characteristics.

The application employed CAD data supplied by the partners of CASTLE project. In particular, the models were sent to CIRA in STEP format for the 3D model part of the environment, while images were passed aside as material textures along with a comprehensive document describing the mapping of materials to interiors surfaces (Fig. 1).

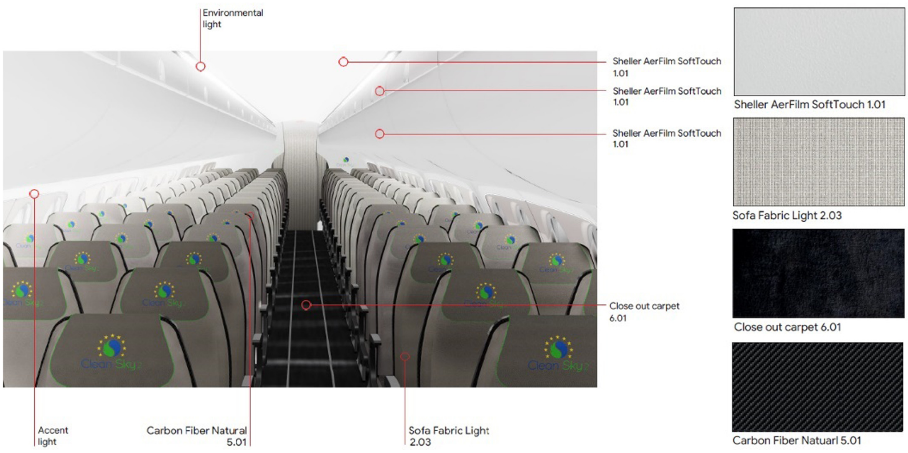


Fig. 1. Scheme definition of colours, materials and finishes for the VR model developed.

The head-mounted display (HMD) for the immersive visualization maximizes the sense of "being at the center of the virtual scene" [6] for the user thanks to the coverage of its field of view by the graphic scene visualized. Thanks to its touch system able to return vibration feedback, very important for reachability analysis, the Oculus Rift headset, developed and manufactured by Oculus VR [7], a division of Facebook Inc., has been the Virtual Reality HMD used for the aircraft interiors' standing and sitting evaluation session of ergonomics.

The user assessment of comfort aspects of the passenger cabin of a regional aircraft requires the best lifelike rendering quality possible at immersive VR rates. Interactivity requirements include freely moving within the whole cabin environment, switching among different interiors configuration (seats materials, curtain and panels), interacting with objects and movable parts of furniture in the cabin interiors in order to perform tests wrt. his/her own body size [8–11].

The VR runtime application, even if conceived for real-time rendering for keeping up with interactive frame rates (target frame rate for the Oculus Rift is 90 Hz), offers to the users a quite good rendering quality with a high number of complex lights and expensive rendering effects (Fig. 2).

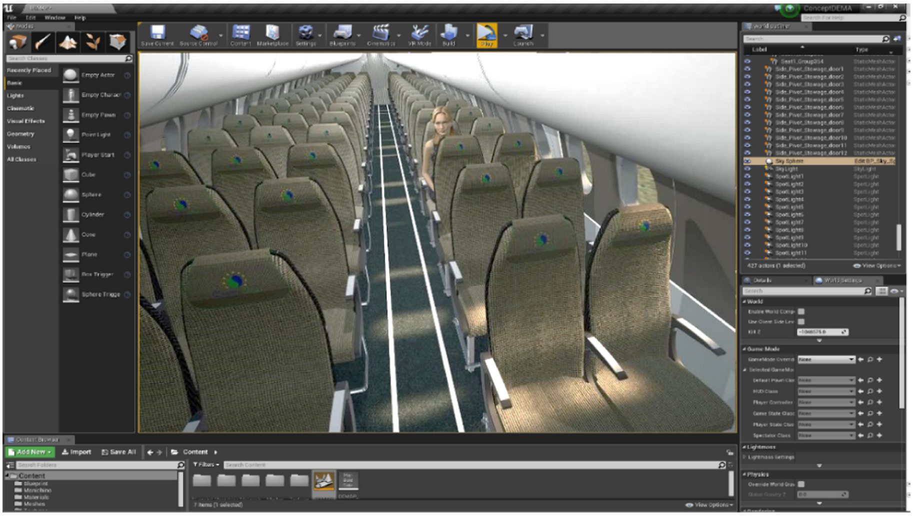


Fig. 2. The immersive VR application developed in Unreal Engine 4.26.

An avatar for male and female people, sized at start-up with the user in standing position, allows the users to see their own body into the virtual environment. The movement of the head, in terms of position and orientation (six degrees of freedom, 6-DoF) is connected to the virtual camera; the movement of the hands controls their virtual counterparts in the 3D scene. Furthermore, by only using head and hands HMD tracking data and the blending of predefined full body avatar animations, whole body movements are reproduced resembling user's actual ones.

Furthermore, an aircraft noise audio track was added into the virtual environment in order to increase the testers' sense of presence and the identification with the passenger role. A seats row, kindly provided by the seat designer and manufacturer partner in the project (Fig. 9), allows users to carry out the tasks in sitting position on a real aircraft seat corresponding to its virtual counterpart.

The developed application allows the users to switch between two seat fabrics (in two different lining configuration), turn on/off the internal lights (and adapt the intensity), move across a day range the sun light, manually interact with the stowage bin, with the tray table and with the PSU (turning PSU light on/off) by means of the hand controllers, remove the front bulkhead curtain in order to access the service area, be teleported elsewhere in the cabin space.

Other commands are activated by an operator under tester request (all the user-activatable ones, teleport to specific zones, initial calibration of avatar mannequin size).

2.1 Global Illumination in Unreal

The application, thanks to Unreal Engine's dynamic lighting methods, offers a real-time Ray Traced Global Illumination (RTGI) solution to light the interiors scene with bounce lighting from dynamic light sources [12]. This solution enables the user to change lighting and automatically update to the objects within the scene, making it possible to simulate time of day transitions and turning on/off lights.

Through the Real-Time Ray Tracing (RTRT) it was possible to create an interactive experience with subtle lighting effects, more natural, producing soft shadowing for lights, accurate ambient occlusion (AO), interactive global illumination, reflections and more all happening in real-time [13, 14].

Ray Traced Shadows allowed to simulate soft area lighting effects for all the objects in the virtual cabin environment. This means that, based on the light's source size or source angle, an object's shadow has sharper shadows near the contact surface than farther away where it softens and widens (Fig. 3).

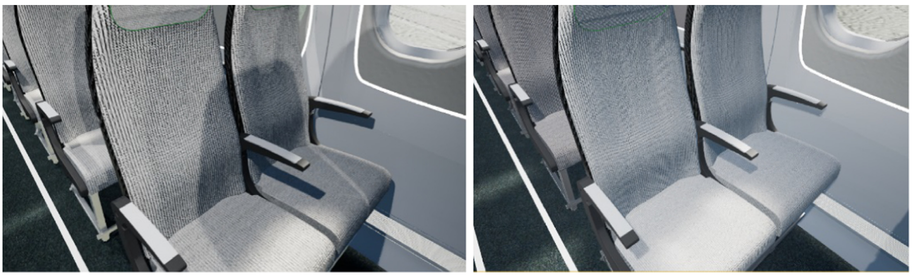


Fig. 3. Ray-traced shadows compared to (the less complex) non ray-traced ones.

Through the Ray Traced Reflections (RTR) it was possible to simulate accurate environment representation supporting multiple reflection bounces. Multiple bounces recreate real-time inter-reflection between reflective surfaces in the scene (Fig. 4).

Fig. 4. Ray-traced reflections on the back of the seats compared to non ray-traced ones.

Ray Traced Translucency (RTT) allowed to accurately represents glass materials with physically correct reflections, absorption, and refraction on transparent surfaces (Fig. 5).

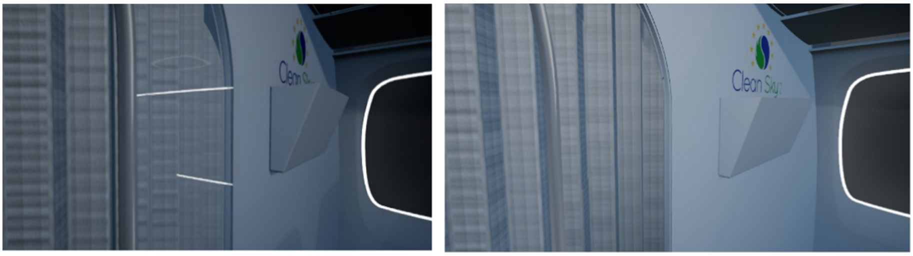


Fig. 5. Ray-traced glass translucency compared to non ray-traced one.

Due to the complexity of the scene, in order to give back some runtime performance, the ray tracing based global illumination method used was the final gather-based technique instead of the brute-force one that is more accurate but more expansive in terms of graphics performance. This technique introduces some limitations the main of which is that it's currently limited to a single bounce of indirect diffuse GI.

2.2 Physics-Based Manual Interaction

Physics simulations improves the immersion value of every virtual scene because it helps users believe that they are interacting with the simulation and that it is responding in a realistic way and thus empowers the virtual passenger to evaluate reachability and usability of the features of the virtual objects to be tested all around him/her [15, 16].

All the movable object in the application are subjected to physics and are joined to the scene with realistic hinge mechanisms. The stowage bin, the cup holder and the tray table to be tested all behave like their real counterparties. In particular, the stowage bin can be opened by a lock/unlock system connected to his handle (Fig. 6) as well as the tray table can be overturned by rotating the pawl locking (Fig. 7).

Furthermore, even if there isn't any haptic response when the objects subject to physics are touched, a first contact force feedback, provided by the hand controllers vibration, gives to the users the capability to understand when the collision between his/hers own hands and the virtual objects within the virtual world happen.

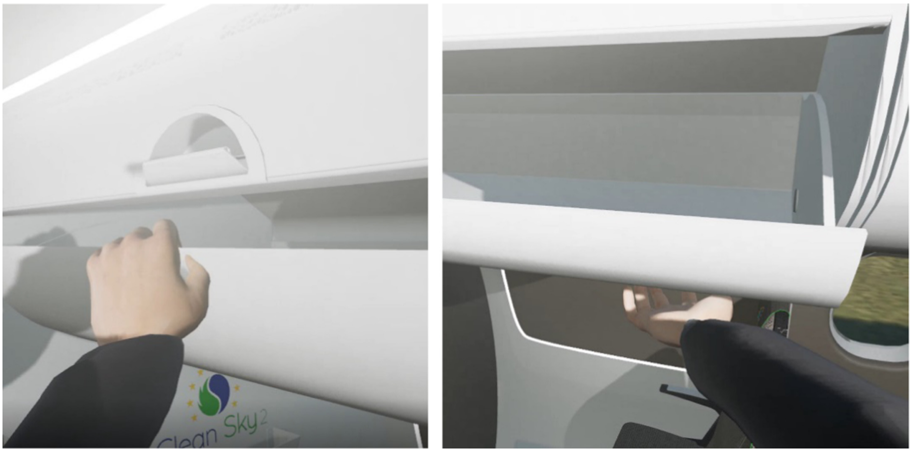


Fig. 6. Opening/closing the stowage bin.

Fig. 7. User opening the tray table.

3 The Concept Design Under Evaluation

The VR test campaign on the Regional Aircraft Interiors involved 24 people aged between 35 and 66 years with an average age of 49.7 years. The gender of participants was distributed between males and females with a significant prevalence of men (83.3% vs. 16.7%). Flight experience, measured in number of flights performed, was higher than 10 times for the 75% of the users. The heights were distributed from 160 cm to 195 cm with an average height of about 175 cm (Fig. 8).

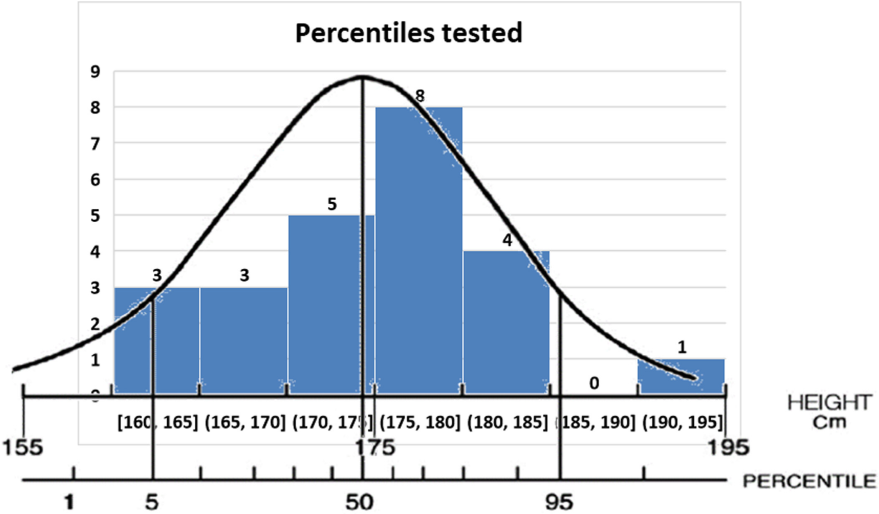


Fig. 8. Distribution of the height percentiles of the tested subjects.

Due to the COVID pandemic emergency, the subjective tests of the Regional Aircraft, held in the VR Lab @ CIRA, were conducted thanks to a sanitization device, the Cleanbox CX1 (see Fig. 9), which ensured to kill 99,8% of bacteria and viruses, including COVID-19, between one test and another.

Fig. 9. The immersive VR test setup @ CIRA VR Lab with the Cleanbox CX1 VR HMD sanitizing device and the physical seat row provided by the seat manufacturer partner in the project.

The questionnaire submitted after the test in immersive VR considers the ability to use arms and hands to do reachability tests, and to roughly measure spaciousness by relating to one-self avatar.

3.1 General Aesthetic: Design and Surface Properties

Testers were first asked about general design considerations on the proposed model (Fig. 10). All the people agreed that general style/aesthetic of the cabin was pleasant and at least 75% agreed that the cabin suggests a general feeling of well-being. As regards the style/aesthetics and the shape of the seat, between 80% and 90% of the users agreed that they were pleasant and comfortable. Of the two solutions proposed (see Table 1), two outs of three of the subjects tested preferred the first set of fabrics.

Almost 70% of participants at least agreed about the comfortable and pleasant appearance of the armrest shape but more than 33% of them remained undecided.

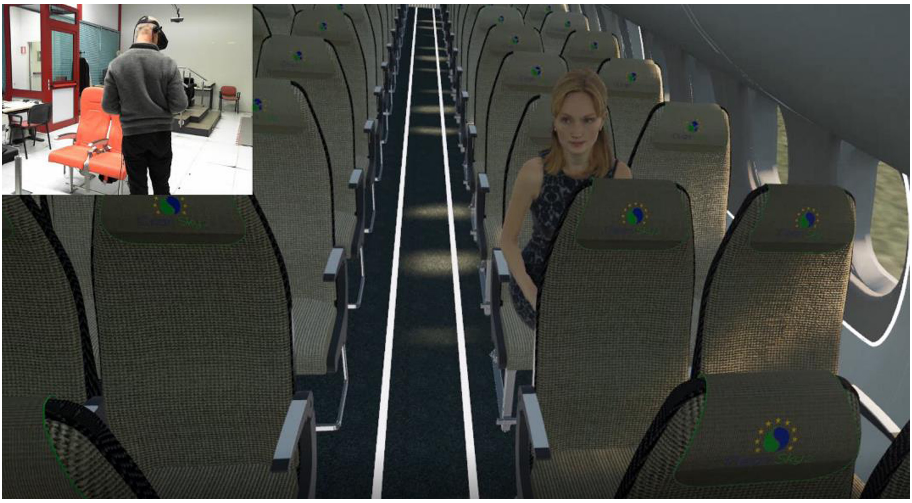


Fig. 10. General aesthetic of the cabin.

Table 1. The two sets of fabrics proposed for the cabin seats.

1	
2	

3.2 Tray Table

About the Tray Table (Fig. 11), more than 90% of the users agreed to consider it pleasant, easy to reach and to open/close. More than 75% at least agreed to consider the table adequate to eat/read/use the laptop even if more than 20% of them remained undecided.

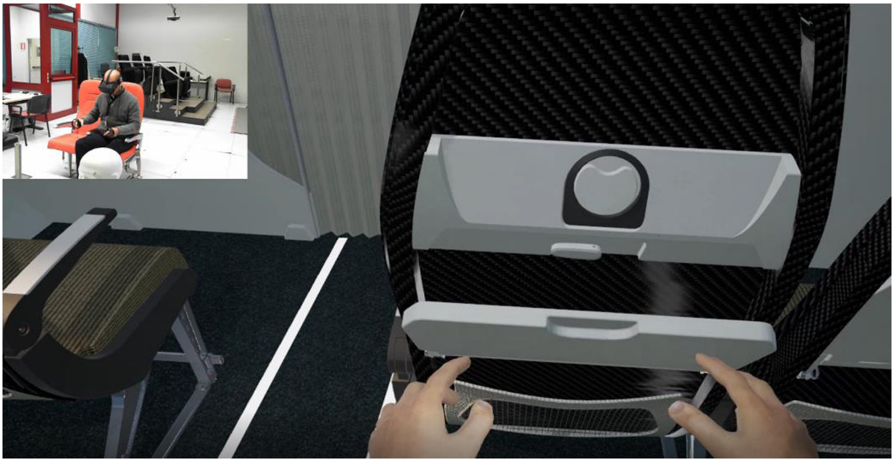


Fig. 11. Tray Table opening

3.3 General Posture, Accessibility and Living Space

The whole of the users agreed, strongly almost 40%, to be happy with the view from the seat and more than 80% had the feeling of being in a spacious environment. As concern the space around the seats, even if more than 80% agreed to consider sufficient the space for accessing the seat and the leg room, only 50% found the seat have enough space to stretch their own legs and almost 40% remained undecided on the availability of space (Fig. 12).

Fig. 12. Space for accessing the seats and the leg room

3.4 Cabin Lining

As concern the Cabin Lining, more than 95% of the participants agreed, strongly more than 40%, that the cabin ensures a good external view from the windows (Fig. 13).

Fig. 13. Evaluation of the view from the window

3.5 Stowage Bin and PSU

About the Stowage Bin, more than 90%of the users agreed to consider it easy to reach/use, almost 40% of them strongly and more than 95% of them agreed to consider the Stowage bin to be spacious enough for their luggage, almost 50% strongly. Concerning the PSU ease of use, almost 75% of them at least agreed but more than 20% disagreed. More than 85% at least agreed to consider the PSU easy to reach and less than 10% disagreed (Fig. 14).

Fig. 14. Stowage Bin and PSU accessibility tests.

4 Rationale of the Immersive VR-Based Subjective Evaluation Process

Subjective tests – i.e. tests done by humans by their senses as their own personal unchallengeable judgment, strongly depend on how each single tester actually perceive the submitted stimuli. In the case of comfort tests in an immersive virtual environment, test results are mostly dependent on how "good" is the virtual environment built to represent the design to give a rate. Stimuli are constituted by the 3D graphics rendered of the cabin environment to the HMD at interactive rate, by the interactions allowed to users within the cabin environment, and by the feedbacks the application has set up to alert the user [17].

By these considerations, a strong pre-condition for taking in the right consideration the results of a user's subjective test campaign is that the simulating virtual environment can be considered a valid synthetic representation of the proposed design from several point of views: the correspondence (adherence) to the designer's intentions (the VE well represents the designer's project), the way to leverage user senses to convey the project. Simply put, a very good design could be possibly judged negatively due to the poor way for the representing virtual environment to "present" it to human testers.

When building up a VE application, several source of errors could lead to a "bad" virtual representation, either of technical/technological nature (poor interface devices such as the HMD, its tracking capabilities, hand controllers, bad computer performances hitting the application frame rate and rising latency, low graphics rendering quality too far from reality, etc.), or dealing with a possible mis-correspondence of the 3D virtual model of the environment with the one the designer has modelled (3D shapes, materials, lights, external lighting conditions, etc.). The latter problem can arise when the design software and the one used for the VR are not the same or a data/format conversion has been needed for interfacing them, a/o when data passed from design to VR are possibly not complete or just "described" rather than hardcoded in data files. Other than doing the same work twice, this possibly leads to doing the same thing in different ways – e.g. a material could be characterized in different ways in two different software, not to mention that insufficient input could leave the VE implementer an "interpretation" freedom error prone [18].

Yet, while the data-related source of badness of a VR representation of a design can be worked around by a verification of the final VE by the designers, the application-related ones must be checked by submitting the VR application to a larger audience in order to be somehow "certified" by a sufficient number of judgments.

Thus, side by side the comfort test of the new-generation interiors proposed for the business jet a subjective test of the immersive VR application itself must be done with the idea that it constitutes the transfer medium of the design to be evaluated to the testers, and that a bad VE application ends up to invalidate results of the subjective tests regarding the design.

The protocol followed by CIRA for the subjective testing of the Regional aircraft included two user questionnaires, based on Likert five-points scales [19]. The first one specific for the purposes of the core evaluation i.e. the comfort aspects, a second one aiming at validating the user acceptance of VR, of the immersive approach, and of the VR application just experience.

5 Results of the Subjective Tests Regarding the Immersive VR Approach and the VR Application

The whole of the users enjoyed the VR Experience. As anticipated, the same #24 people, that tested the design against aesthetics and accessibility aspects, were asked to evaluate the application used for the VR experience, and, in general, the immersive VR approach for the purposes of the tasks requested. In the following a synthesis of the user considerations and related rates.

The Virtual Reality experience has been fascinating (charming), fine, good, and nice for all the participants, warm, active, predictable and funny for a large part of the audience, and almost not frightening or sad at all for all the users.

Almost 90% of the testers was able to control events. The environment responded to the actions nearly 95% of the testers have undertaken. Experiences done in the virtual environment have seemed quite conforming with those of the real world at least partly to whole of the users and enough to almost 90% of them.

About 90% of the users felt at least quite able to explore and actively inspect the environment with sight, as well as they felt the feeling of moving within the virtual environment very convincing, partially about 10% of them. More than 85% of them was very or quite able to carefully examine the objects in the virtual environment.

Three out of four testers adapted to the virtual environment experience at least quickly. 75% of the testers felt almost enough competent in moving and interacting with the virtual environment at the end of the experience and the percentage rises to over 95% if we consider also people who felt mediumly competent.

The quality of the head-mounted display interfered or distracted little three out of four testers during the performance of the assigned tasks or the activities required. Almost the whole of the users answered that the quality of the graphics rendering affected positively the execution of the assigned tasks or the required activities. On the other and, the interface devices (HMD, the connecting cable, hand controllers) have interfered little or very little with the execution of the assigned tasks or the required activities for 70% of the testers but much or very much for more than 10% of them.

The small tracked area limited, in more of 50% of the cases little or not at all and in the other cases partially or much, the performance of the required activities.

Three out of four testers have been able to concentrate much on the tasks assigned or on the tasks required rather than on the mechanisms used to perform these tasks or activities.

The users rated the Virtual Reality experience as a whole positive or very positive. Their performance in the Virtual Reality environment was satisfactory for more than 95% of the participants.

Among the sensory aspects of Virtual Reality that could be improved, most rated were:

- the perception of oneself;
- the perception of touching objects;
- sound/noise as manipulation feedback;
- the congruence between the movement of objects and the sound associated with it.

Practical aspects of Virtual Reality tested that could be most improved by the testers'opinion:

- the HMD comfort;
- the hand controller comfort;
- the tracked area;
- the area where the VR experience has been held.

Most of them could actually reproduce in real the operations performed in Virtual Reality.

Almost all of the testers could explore the environment by moving with their head, while a total of almost 80% could actually explore the environment by moving with their whole body. The large majority of them felt comfortable in the virtual environment.

During the Virtual Reality experience, as well as at the end of the Virtual Reality experience they felt:

- very little disoriented;
- little or normally emotioned;
- little or very little troubled;
- very little indifferent;
- much or normally happy;
- very little embarrassed;
- normally or much satisfied;
- little or very little frustrated;
- very little or normally relieved;
- very little disappointed.

During and at the end of the Virtual Reality experience, they have experienced very little of all these sensations: nausea, disgust, stress, dizziness, tension, anxiety, boredom (being annoyed), while at the end they zeroed almost all these negative sensations.

As to users' opinion, performance that can be obtained in Virtual Reality mostly depends on the functionality of a Virtual Reality application and on technological capabilities of Virtual Reality rather on individual skills or person's mood.

About 90% of the interviewed think it is possible to make a visual quality assessment in Virtual Reality and that it is possible to carry out an assessment of the reachability of commands and accessibility of objects.

Thus, by concluding, the comprehensive additional questionnaire has pointed out that both immersive VR and the specific VR application have largely passed the acceptability threshold to be considered reliable for the task of the subjective tests proposed.

6 Concluding Remarks

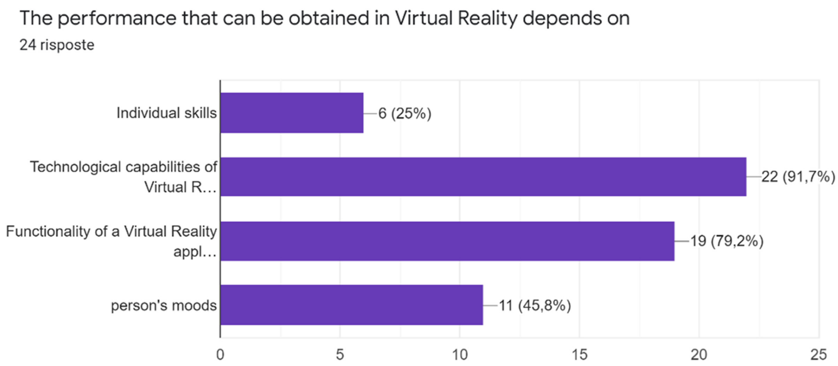
For what concerns the visual comfort, the test campaign showed that most of the users found the proposed configurations pleasant and comfortable.

The interactions with the objects during the execution of the assigned tasks were considered adequately good. Notwithstanding the lack of a haptic feedback, the tray table, the PSU and the seats allowed the users to interact with them, for the proposed tests, in a sufficiently natural way.

The evaluations made by the analyzed group of users regarding living space comfort were quite satisfactory. Only the space for stretching legs was judged insufficient or difficult to assess especially by taller people.

User answers collected for the second questionnaire have, in turn, validated in a very positive way the VR application used, and the immersive VR approach for subjective comfort tests. This gives more confidence in the results of the subjective tests of the design concept that was under primary assessment.

Definitely, the interviewed think it is possible to make a visual quality assessment in Virtual Reality and that it is possible to carry out an assessment of the reachability of commands and accessibility of objects.



7 Conclusions and Future Works

For our VR research lab the presented application has been the first opportunity to test the use of ray tracing in a pre-production industrial application leveraging the newest NVIDIA GeForce GTX 3090 graphics card. The support of hardware-accelerated ray tracing in Unreal 4.26 has been implemented timely and quite in continuity with the rendering parameters ruling the non-GI rendering infrastructure, thus being able to enable ray traced scene rendering by few switches and parameters adjusting in the IDE. By not pushing output quality uselessly too far, graphics performances – our main concern – was never an issue, and the GPU performance graph shows there's still a margin for further rendering quality improvement.

We look forward to evolve future projects of this kind to a multisensory VE, in which the testing passenger feels more and more immersed in a lifelike cabin environment. Additional sensory feedback to feed a user in order to contribute to identify oneself with the impersonating role may include temperature, humidity, and air flows, airline brand smells, more audio feedbacks for whatever happened in the cabin, tactile and grasping force feedback for ergonomics evaluations, rumble feedbacks to key parts of the user body bumping to environment (e.g. knees bumping into the front seat when seated and getting up), and populating the cabin with realistically moving autonomous virtual passengers.

Finally, whilst subjective, confronting their own sensations with the one of others in a collaborative virtual environment, thus actually helping each other in forming one's own opinion may surely improve the robustness of the process quality of the assessments, aside from definitely making the joint testing experience fun.

The feedback obtained from the virtual simulation analysis of comfort will be verified and eventually validated through physic tests in the cabin full scale demonstrator as part of the activities of Leonardo - Aircraft Division for REG-IADP WP 3.2.

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