Virtual Reality platform to assess air traffic controllers' performance in Control Tower Operations

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Abstract — **The main aim of this paper is to demonstrate how virtual reality environment can be used to validate user requirements within a multimodal and immersive control tower operational environment, and to derive requirements for more immersive and multisensory operations in RTOs context. In order to achieve this objective, two macro-activities have been carried out, namely i) the development of the Virtual Reality (VR) set up for the measurement of situation awareness, workload and sense of presence in tower operations in a multisensory context ii) the definition of Tower Control scenarios to be reproduced in the Virtual Reality setting.**

The validation involved professional air traffic controllers who were required to perform different remote tower scenarios in the virtual experimental setting. The experimental setting consisted in a total of 8 runs per participant with two task difficulties (Easy x Hard) and 4 different sensory conditions: i) only visual, ii) visual and auditory iii) visual and vibrotactile, iv) visual, auditory and vibrotactile. The subjects' performance, workload level, sense of presence and immersion were measured using quantitative and qualitative measurements.

The results showed an increased performance when the Visual channel is enhanced by Audio or Haptic sensory modalities. On the contrary, when such two channels are provided at the same time, it seems to reduce performance, maybe because they become distracting for the subject. Regarding the sense of presence, Evidence collected in a preliminary phase of the study shows that the subjects' sense of presence and immersion changes according to the sensory feedback provided to them while performing an experimental task in a controlled environment.

***Keywords*—Air Traffic Control, Remote Tower Control, experimental exercises, human performance, user requirements.**

I. Introduction

THIS study has been performed in the framework of the European project MOTO funded by SESAR Joint Undertaking (SJU), the European public-private partnership which manages all research and development (R&D)activities in Europe, in the field of Air Traffic Management (ATM). The goal of the project is twofold: Firstly, to understand the role of multimodal perception in Tower Operations, in order to improve the controller performance; secondly to identify technical and operational requirements to allow a more immersive experience in the context of remote tower operations.

The concept of Remote Tower Operations (RTO) is based on the idea that the operator monitoring and controlling the traffic does not have to be located in the tower itself, but can operate from a distant site. The operator would control the airport by looking at screens where the situation is displayed in a similar way as what s/he could see "out of the window" in a tower on the airport.

The control procedures remain the same of the traditional ones, but are supported by a visualisation system placed in multiple locations of the remote airport, which use high resolution visual / infrared (IR) cameras and sensors to show a virtual picture of reality to the ATCO.

The Single European Sky ATM Research (SESAR) program has defined three different operational types of remote virtual tower:

- Single Remote Tower: One air traffic controller is responsible for operations at one airport at a time.
- Multiple Remote Tower: One air traffic controller is responsible for operations at more than one airport at the same time. This concept is completely new compared to current operations.
- Contingency Tower: A contingency facility to be used when an airport tower is unserviceable for a short period of time (e.g. fire, technical failure). Remote Tower operation will then assure at least a basic level of service.

The state of the art shows a relatively good convergence in the type of technologies being used to implement the remote tower concept. As video sensors, High Resolution cameras are used for daytime observation; Infrared (IR) cameras are used in low visibility conditions, and provide the typical weather without occlusion of the vision. PAN/TILT/ZOOM (PTZ) cameras are typically used to emulate the function of binoculars. The number of such cameras varies greatly depending on the actual airport setting, around an average of one up to two dozen cameras. Audio sensors are, in comparison, far less developed. The typical set-up is to capture and render ambient audio, possibly in a stereo setting. More complex audio set-ups, e.g. multichannel audio captured from more sources, are rarely used.

Finally, capturing and rendering vibrations is very rarely used. However, this option has a high potential of providing additional information to ATCOs during Remote Tower Operations.

In remote towers, video is typically rendered using an array of LCD screens or, alternatively, projectors aiming at a curved display. Panoramic angles range between 200 and 360 degrees. Audio is rendered using standard stereo technologies. Not sufficient details have been encountered concerning the rendering of vibrations in the RTOs, so this option appears to be rarely used (if at all). Interaction uses the typical devices present in a physical tower, with the salient presence of e-stripping as an innovative element.

A final interesting element is the relatively limited amount of innovative information visualization techniques being used to make operations in a remote tower setting more effective. In general, the interaction and data visualization devices present in the RTOs copy those being used in the actual physical tower, with small changes, e.g. to support switching contexts in the case of a multiple tower.

This study was a step to the achievement of the first objective of the project: it aimed to define a set of tower operational scenarios, where the multimodal interaction can play a role during the controller's tasks. These scenarios have been used during the validation session in a virtual reality environment; here a group of professional ATCOs has been required to perform the selected scenarios in order to understand the impact of multimodal interaction on their performance.

II. Hypothesis and Research Questions

In everyday life we interact with the external world through our body and we are always aware that our own body belongs to us and that we are physically present in the world, even in situations where we may not be fully aware of the full spectrum of our perceptions. This basic assumption has been extensively investigated in psychology, philosophy, neuroscience, robotics and computer science in the theoretical framework of the Embodied cognition [1].

The concept of Embodiment Cognition appeals to the idea that cognition deeply depends on aspects of the agent's body, not only on the brain. In the Neuroscience domain it has been also described as the product of brain processes of i) multisensory integration of stimuli coming from the body and the external environment (i.e. visual, audio, tactile, vibration) and ii) their combination with motor actions elicited to interact with the world.

Recently, a growing number of scientific studies in the framework of the new Embodiment cognition approach highlighted the importance to investigate the consciousness to have a body, the way in which human beings interact with the environment through its action and the role played by our body in cognition, showing how the body characteristics affect cognitive activities. Indeed, embodied cognitive science aims to understand the full range of perceptual, cognitive, and motor capacities human beings possess as capacities that are dependent upon features of the physical body [2][3].

This may happen in different ways: firstly, body characteristics act as constraints for cognition's form and contents, because humans perceive the world, and act on it, via the body. Body characteristics regulate and pace the rhythm followed by cognition. Secondly, bodily states may affect thinking, as for instance when body postures have an influence on memories, or on the way a situation is assessed. Via the body, the external environment is able to affects task performance, decision making and natural activation of attentional system [4].

This scientific approach offers the advantage of investigating complex human behaviours during natural interactions in real-world environments, enriched simulations of the real world, thus resulting in a high level of ecological validity [5][6]. The more integrated the setting, the easier it is for humans to rely on "natural" mechanisms of dynamic attention switching and filtering. For instance, effects like the cocktail party [7] can only happen in a natural setting, e.g. for instance if the sound is spatialized. In the same manner, the unconscious monitoring of the environment via somatic pathways is very effective and efficient [8]. It does not require cognitive resources, but it effectively alerts the person when something unexpected happens. In an aviation study, Sklar and Sarter reported how haptic feedback would be the best way for pilots to monitor mode changes and intervene on unexpected ones [9].

The overall concept is that these opportunities could be used to convey information to controllers on out-of-sight traffic, airport areas, or even multiple airports.

The motivation for the study is that ATM Human Performance (HP) research has been traditionally focused on two senses: sight and hearing. Remote tower operations make no exception, with many efforts and resources focused on the acquisition of visual images, for instance by means of high-resolution cameras. State of the art video cameras located at various locations in the aerodrome vicinity are being used to project a real time image of the aerodrome and traffic situation onto the panoramic display, together with selectable options to choose the ambient noise of the aerodrome" [10][2]. Such a condition is far from a realistic multimodal experience, especially in a setting like a control tower where direct access to the real world via human senses may be crucial.

In control towers, controllers reported anecdotal evidence on how they rely on vibrations, sound distance and speed (of a thunderstorm for example), and in general on "sensations", to make their decisions. The MOTO project aims to advance the ATM knowledge on the real importance of these "sensations", showing how they may affect decision-making in non-obvious ways, starting from the following research hypotheses:

1. Are current Remote Tower technologies missing important elements, as far as reproducing realistic human perception is concerned?
2. What is the role of Embodied Cognition in human performance in control tower operations?

This study contributed to provide first evidence to answer the above questions. In particular, it aimed to explore the potentiality of virtual reality environment to reproduce an immersive and multimodal tower control environment, to assess user performance in that context, and to derive requirements for more immersive and multisensory operations in RTOs.

III. Virtual Reality Setting

In order to achieve the above-mentioned objective, two macro-activities have been carried on:

- Development of a Virtual Reality platform for Tower Control Operations;
- Definition of Tower Control scenarios to be reproduced in the VR.

The results gathered from the above-mentioned activities were the starting point for the preparation of the validation exercises.

A. Virtual Reality platform

The virtual reality platform was used to reproduce the control tower environment in order to understand how the different sensory modalities can impact Remote Tower Operations and how controllers use visual, auditory and vibrotactile information during their day-to-day operations.

In the Virtual Reality environment, which was built with the Unity software, the visual and acoustic information recorded from the top of the Air Traffic Control Tower of the Italian airport of "Roma-Ciampino" have been reproduced. As this Italian airport does not have an insulated tower building, it was possible to record the environmental sound (e.g. aircraft's engine) and the vibrotactile information (e.g. wind speed) during a cycle of recording sessions that had the scope to gather the real airport auditory stimuli to be reproduced in the VR setting.

The end goal was to reproduce the actual perceptual space where air traffic controllers' work, in the VR environment. The virtual tower control environment was rendered using the head mounted HTC Vive display system. The setting was composed of the following equipment:

- VR ready desktop or laptop Pc with a graphic card GtX 970 or greater;
- HTC Vive with two controllers and a Vive lighthouse system;
- Headphones;
- A platform with embedded sensors which reproduced the vibrations recorder in the real tower to the subject chair;
- A monitor displaying what the user was experiencing inside the head mounted display;
- Keyboard and mouse used to manipulate the VR, as for example to start aircraft movements that the subject was expected to interact with.

The immersive environment reproduced the interior of a tower building and also the area including the runways and taxiways of the airport that the subject had to manage performing a set of tasks, as s/he was in a real control tower.

In the interior of the virtual tower, the Controller Working Position (CWP)[1] was recreated, including the virtual reproduction of the devices that the controllers use in everyday operations. The following devices have been developed:

- Display with information on the weather and on the runway in use;
- Tool with the NOTAM[2] information (e.g. restriction of traffic area during specific hours of the day);
- Electronic Paper Strips (EPS) where the information on the aircraft number, speed, route, destination and etc. are provided;
- Telephone and microphone to record message to be sent to the pilots;
- Air and ground radar.

The following image provides an idea of the VR setting.

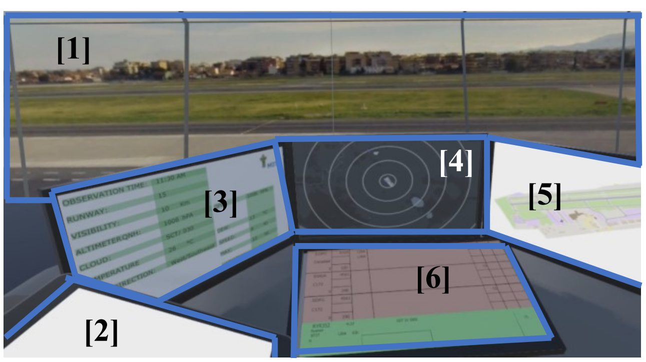

Fig. 1. Virtual Reality setting, [1] external view of the airport, [2] NOTAM tool, [3] Weather and runway information, [4] Air radar, [5] Ground radar, [Electronic Flight Strips.

Fig. 2. Validation exercise – On the left side the SME and the experimenter; on the right side the subject performing the scenarios

The subject was immersed in the VR setting through a head mounted display and she/he could interact with the virtual environment using two Vive controllers. This platform allows the user to perform ecological Air Traffic Controller's tasks as communicating with aircraft and ground vehicles, recording ATIS messages, and providing updated information on the weather conditions. While the user is performing the Air Traffic Control tasks, the experimenter manages the aircraft's movements in the VR environment. The simulation features customizable screens which reproduce tools used by the Air Traffic Controllers, as the information related to the departure and arrival of aircraft.

The subject could use the Vive controllers to communicate with the aircraft and other vehicles in the virtual environment. The communication has been simulated thanks to the involvement of the pseudo-pilot, who reproduced realistic oral exchanges with the ATCOs involved in the validation exercises. In the meanwhile, an experimenter prepared the equipment for the measurement of the brain activity and two experimenters provided the subjects with the questionnaires of Situation Awareness (SA), sense of presence and workload used to assess the subjects' performance. In particular, regarding the perceived workload, it has been used the NASA-TLX questionnaire [11], that is able to provide a weighted score of the subjective perceived workload, depending on 6 factors (i.e. Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, Frustration). With regard to the sense, a questionnaire of 3 items have been used and adapted from previous studies [12]; while for the assessment of the situation awareness an adapted version of the SASHA questionnaire have been applied [13].

The VR platform could also be implemented as training platform for Air Traffic Controllers who will have the responsibility to work in a remote tower control.

The novelty introduced by the VR setting in this project was related to the possibility of reproducing a control tower environment in order to investigate the ATCO's performance within different sensory modalities. The workload, situation awareness and sense of presence have been measured using a

[1] The operator's work station including necessary systems for the provision of the Air Traffic Service.

[2] Unclassified advisories that contain information on the availability of the airport and of the airspace to be communicated to pilots, to alert them of potential hazards.

combination of subjective measurements (questionnaires and debriefings).

IV. Scenario Definition

The aim of this activity was to identify and select scenarios of current tower operations where multisensory perception plays a role. Several steps have been carried out to identify the most suitable scenarios to be reproduced in the VR setting. The iterative process took into considerations both the feedbacks coming from Air Traffic Controllers and the technical constraints of the VR environment.

The following activities have been performed for the development of the final version of the scenarios:

- Gap analysis and desk research of existing scenarios of Remote Tower Operations;
- Interviews and workshops with ATCOs;

An initial set of four scenarios have been created and, then, they have been discussed with experts of Air traffic Control during the workshops. The final group of scenarios have been later tested in the VR setting and adapted to the technical needs.

1) Desk research

During the desk research, a particular attention was given to the templates and formats used and to those scenarios that could have been relevant for the embodiment concept.

The following list of documents and projects has been reviewed for the above-mentioned objective:

- SESAR JU, D35 OSED for Remote Provision of ATS to Aerodromes, 2015;
- SESAR JU, LSD.02.04- Remote Tower Demonstration Plan Second Review, 2016;
- RACOON project:
  - LSD.02.03-RACOON-Demonstration Plan, 2016;
  - LSD.02.03 D03 RACOON Demonstration Report, 2016.
- SESAR JU, DEL-06.09.03-D15-HF HP Assessment Report for Single Remote TWR, 2013;
- FÜRSTENAU, Norbert (ed.). *Virtual and Remote Control Tower: Research, Design, Development and Validation*. Springer, 2016.

2) Interviews

The interview was structured in a brief introduction on the study to give the participants an overview of the objectives, then seven questions on the following topics have been done:,

- Interviewee's experience with Remote Tower Control;
- Differences and similarities between current tower and RTO operations;
- Multimodal interaction (involving sight, hearing, tactile perception, etc.) between ATCO and working environment during current control operations;
- Information received by and provided to ATCOs during the (multimodal) interaction;
- Phases of flight impacted by the multimodal interaction.

The interview was submitted by two human factors experts to three Italian Air Traffic Controllers (ATCOs):

- 1 ATCO from Milan airport "Milano-Malpensa";
- 1 ATCO from Bologna airport "Guglielmo Marconi";
- 1 ATCO from Venice airport "Marco-Polo di Tessera".

The interviews had duration of around an hour. A report has been produced at the end of the three interview sessions and the results are described in the following sections.

From the desk research and the analysis of the interviews results, a specific template has been created with the aim to present and describe the scenarios in an easy to understand way, during the workshops organized to discuss and consolidate the scenarios with experts of Air Traffic Control.

The scenarios were based on relevant Tower Operations where ATCOs are expected to maintain a good Situational Awareness (SA) and an acceptable level of workload.

The situations described in the scenarios have been chosen based on the input from the interviewed ATCOs and have been considered relevant for the multimodal interaction, as for example, in regard to the scenario of "Heavy fog", a lack of visual stimuli could be balanced by other sensory perceptions (as the auditory ones), able to send supporting information to the ATCO for the completion of his/her tasks. The "Runway Inspection" has been selected because in the interviews it was identified as a situation that can have a negative impact on the situation awareness and, thus, the exploration of the integration of multimodal stimuli could help the ATCOs to be more aware of the context, maintaining acceptable level of the performance.

In addition, the scenarios describe both nominal and non-nominal situations, in different meteorological conditions and considering multiple phases of flight, in order to have also a range of representative descriptions of the tasks the ATCOs could have to deal with in remote tower operations.

3) Workshops

The preliminary scenarios described above have been assessed during two workshops with professional ATCOs.

The workshop ATCOs feedback addressed typical control tower events (take off, landing taxing, push back) where the multimodal integration is expected to play a role.

Once concluded the introduction and the overview of the project, the preliminary scenarios (reported in the previous section) were presented to the participants. In both the workshops, the discussion was focused on the role of the embodiment and of the multisensory interaction during the operations described in the scenarios, with references to ATCOs personal experience of the control tower environment. The participants were also asked to provide further examples of multimodal stimuli that may impact on the tower operations, in addition to those presented by the HF group.

The most relevant information provided by the participants was related to the auditory channel and to the characteristics of the tower building.

In regard to the auditory channel, the perception of sound and vibration were reported by the ATCOs as crucial indications for the understanding and the awareness of the environment occurrences during day-to-day operations.

In fact, low visibility conditions can have an impact on the ATCO's perception of multimodal stimuli, in particular of the auditory ones. To this end, a specific example was made by one of the participant, who reported a non-nominal situation with low visibility condition, due to heavy fog, and during which the radar was switched off owing to a malfunctioning.

In that situation, the controller relied on the successful landing of an aircraft declaring fuel emergency, through the perception of the aircraft engine reverse sound, as no visual information was available.

In that case the sound of the engine gave the ATCO the confirmation of the aircraft landing.

Other comments were made for thunderstorms when, according to the controllers, sound conveys useful pieces of information. The direction of the rain and its sound could help to understand the situation and improve the situation awareness of the controllers, and in this regard it was argued that in RTOs, in case of different weather conditions between the airport where the control is performing the control tasks and the remote airport, the ATCO needs to do a mental operation to put her/himself in the same situation as if s/he was controlling locally.

ATCOs report also that in case of use of engine reverse during the deceleration run, this typical sound could also help to estimate the (future) position of the aircraft.

For example, in case of a tight sequencing, it could be useful to know how the aircraft on the runway is acting and the reverse sound may give indication of an higher rate of deceleration (then the aircraft may be faster in vacating the runway (RWY). This may support the ATCOs working methods to better optimize the arrival sequencing. Moreover, it was argued that the auditory stimuli can complete the visual information, as for example in case of an engine failure or when multiple vehicles are controlled, as in the case of controlling Instrument Flight Rules (IFR)[3] and Visual Flight Rules (VFR)[4] flights at the same time.

According to the participants, when the controller perceives the sound, s/he has already made the decisions. The sensory information is more a confirmation that comes when the controller has already started the task. Despite that, it was also highlighted that with low traffic conditions the sound stimulus can be useful to attract the attention of the controller.

With regard to the auditory perceptions, the wind direction is considered very relevant information during the landing phase. Beside the data reported by the anemometer the ATCOs use also some points of reference to understand the wind direction. The points of reference depend on the kind of airport; they can be different from one airport to another. For example, in Fiumicino the controllers look at the position of the oil tankers next to the airport, while in Venice ATCOs use the wind sock. In Remote Tower Operations the possibility to visualise these points of reference could be useful to the ATCO in order to have a feedback on wind direction, integrated with the auditory information, according to the controller's experience in an insulated tower building or not.

Participants reported that this kind of auditory stimulus could be a good support in a small airport to be controlled from a remote tower, as it can give additional information on changes in the environment.

V. EXPERIMENTAL EXERCISE

Following the workshops, the preliminary scenarios have been modified and then re-assessed in a second workshop with ATCOs, in order to adapt them to the technical constraints of the Virtual Setting in which they have been reproduced for the simulation sessions.

Taking into consideration the feedback provided by the ATCOs, the following final set of scenarios have been implemented in the Virtual Reality facility:

- SCN 1. ATIS information scenario (v.Easy | v.Hard);
- SCN 2. VFR position (v.Easy | v.Hard);
- SCN 3. NOTAM search (v.Easy | v.Hard);
- SCN 4. VFR Circuit Maneuvers (v.Easy | v.Hard).

In order to measure the level of ATCOs performance, the four scenarios had all an easy and hard version, where the characteristics of the traffic were modulated, adding more aircraft movements in the hard conditions. In addition, each version was also performed with different sensory conditions, with the aim to assess if the integration of multiple stimuli could have an impact on the subjects' execution of the tasks.

[3] Rules and regulations to be applied when flying using outside visual reference is not safe.

[4] Rules and regulations that gover flight operations when the general good weather conditions and visibility allow the pilots to see where he/she is going.

Below a summary of the scenarios implemented in the Virtual Reality setting:

- 4 Easy vs 4 Complex Scenarios;
- 5-6 minutes Tower Scenarios;
- Sensory modalities conditions (Visual (V); Visual and Auditory (VA); Visual-Auditory and Vibrotactile (VAV); Visual and Vibrotactile (VV).

The experimental exercise consisted in a small-scale human-in-the-loop simulation with a total of 7 professional air traffic controllers, who had to perform Tower Control tasks during the scenarios reproduced in the Virtual Reality (VR) setting. The objective of the validation was to investigate whether the degree to which ATCOs feel to be physically present (sense of presence) and immersed (immersion) into virtual reality influences his performance in Tower Operations.

The experimental setting consisted in a total of eight runs per participant with two task difficulties (easy, hard) and four different sensory conditions: i) only visual; ii) visual and auditory; iii) visual and haptic; and iv) visual, auditory and haptic. The eight runs represented scenarios of Tower Operations, during which it was asked to the controllers to perform one or more monitoring and/or controlling tasks, as if he/she was acting in real tower control situations.

The experimental protocol that has been followed is provided in the table below.

TABLE I
EXPERIMENTAL PROTOCOL

VALIDATION EXERCISE STEP	**ACTIVITIES**
INTRODUCTION	• Welcome and Introduction • Questions and Answers • ATCO to complete consent Form (2) and Biographical questionnaire • Setting up the participant
FAMILIARIZATION	ATCO training with VR environment and controls
BASELINE	Baseline SCN
MOTO EXPERIMENTAL SCENARIO	8 scenarios
SENSE OF PRESENCE BASELINE	Final VR environment

VI. RESULTS

The first results coming from the subjective questionnaire analysis and SMEs reports have been reported in the following. The analysis of neurophysiological data is currently being performed.

In particular, repeated measures ANOVA (CI=0.95) have been performed on conditions (i.e. V, VA, VAV, VV) and difficulty levels (i.e. Easy, Hard). Results highlights that the subjects perceived as more difficult the Hard related scenarios with respect to the Easy ones ($p<0.05$), confirming that scenarios have been well designed in terms of difficulty. In addition, analysis on “Perceived performance index”, achieved by the NASA-TLX questionnaire, highlight that the performance of ATCOs could be enhanced by integrating the Visual channel with just one more sensory modality (i.e. Audio or Vibrotactile). On the contrary, by mixing and providing ATCOs with both Audio and Vibrotactile stimuli at the same time, it seems to induce a degradation of performance, maybe due to distracting stimuli contribution that is higher than their informative contents, as the figure above shows.

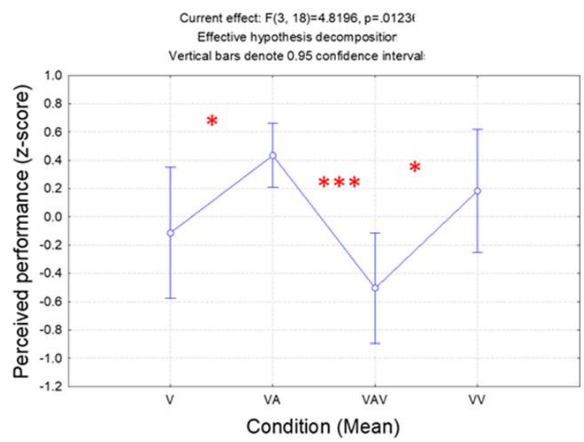

Fig. 3. The vertical bars, corrected by using z-score normalization, showed perceived performance across the different sensory modalities conditions.

Evidence collected in a preliminary phase of the study shows that the subjects’ sense of presence and immersion changes according to task the sensory feedback provided to them while performing an experimental task in a controlled environment. While the combination of visual and haptic sensorial input did not seem to significantly improve subjects’ sense of presence a statistical difference was found between V and the VA conditions. In other words, the sense of presence and immersion was improved in the multisensory experimental conditions when compared with the visual condition.

VII. CONCLUSIONS

This study demonstrated that the use of the Virtual Reality setting can be a valid method to measure situation awareness, perceived mental workload and sense of presence in tower control operations. It can be also adapted for different studies that aim to assess the human performance in complex-safety systems and for scenarios otherwise difficult to access in real context.

In order to reproduce an acceptable level of realism it is fundamental to analyse the main operational characteristics of the environment. The analysis should bring out the main aspects to be implemented in VR through iterative process involving actual operational experts. In this regard, the contribution of the ATM experts for the definition of the final set of validation scenarios contributed decisively to the increase of the level of ATM task realism and coherency for the subject involved in the simulation exercises.

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