Human-in-the-loop evaluation of an augmented reality based interface for the airport control tower



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**It is widely recognized that most industrial sectors will benefit from the use of augmented reality technologies in the near future. The aviation sector is one of the most promising fields for the implementation of augmented reality and synthetic vision based solutions, due to the operational challenges that it poses. In this context, an innovative airport control tower concept based on the use of modern augmented reality technologies has been developed and validated by means of human-in–the-loop experiments in a simulated environment. An optical-based Augmented Reality interface underpins the proposed concept that consists in providing Air Traffic Control Operators in the airport control tower with complete head-up information, as opposed to the current mix of information retrieval through both head-up real view and head-down interfaces. This paper describes the experimental set-up of the validation platform, the test execution and analyzes the obtained results, showing that the proposed application leads to improved human performance, safety and capacity. Specific measurement of the time spent by the operator working in either head-up or head-down position, show that the proposal has a clear effect in stimulating the Air Traffic Control Operator to work in a head-up position more than in a head-down position, with positive effects on his/her situational awareness and perceived workload, especially when dealing with low visibility conditions operational scenarios.**

## I. Introduction

Many of the advances in airport operational safety come in the form of visualization tools for tower controllers. A-SMGCS (Advanced Surface Movement Guidance Control Systems) based solutions, such as movement maps, conformance monitoring, and conflict detection are a few examples of these tools. But there is a paradox in developing these tools to increase tower controller's situational awareness. By creating additional computer displays that show the runway and taxiway layout, aircraft and mobile position, and detect actual and foreseen conflicts, the controller's vision is pulled away from the window view and the head-down time is increased [1]. New developments in the realm of Augmented Reality (AR) may be able to address this paradox.

The RETINA (Resilient Synthetic Vision for Advanced Control Tower Air Navigation Service Provision) project takes the idea of augmented vision and investigates its application to control towers through the use of synthetic vision

[2][3][4][5]. This concept has been implemented in aircrafts for many years through heads-up-displays [6] and has shown improvements in Situational Awareness (SA) that could be transferred to Air Traffic Control (ATC) with relatively low effort.

Previous studies into the use of AR in the control tower [7][8][9][10][11] used in-house developed prototypes to display the visualizations. Reisman et al. [7][8][9][11]developed a few user-centred design prototypes to test the soundness of Augmented Reality in Air Traffic Control Towers, leading to a positive evaluation of the over-all potential of AR technology to benefit control tower operations. The hardware used to build those prototypes is now outdated, contributing to the lack of confidence in the technology mainly due to the poor collimation performance. Further human factors research has demonstrated that direct head-up observation is of primary importance for Air Traffic Control Operators and that head-down time should be reduced in order to minimise the risk of not detecting unpredictable events [10] [12]. Those study were carried out to support the technology of remote and virtual control towers which are currently being developed, mainly to reduce the costs of real control towers at small secondary airports.

The RETINA proposal fills the gap of using current advances in AR to further investigate the application of an augmented reality tool in a real airport control tower environment. The state of the art was defined in terms of display technologies, data sources and standards. In addition, a task analysis of the control tower working environment, covering both standard and low visibility conditions was performed in order to identify the needs and constraints for the future synthetic vision and V/AR (Virtual/Augmented Reality) tools. For traffic information, well established ATM (Air Traffic Management) surveillance systems, e.g. Surface Movement Radar (SMR), and Airport Surveillance Radar (ASR) were addressed, along with recent technology developed for Remote Tower Operations (e.g. standard and infrared cameras). For weather-related information and digital NOTAM (NOtice To AirMen) the project looked at SWIM (System Wide Information Management). Technologies to sense the controllers' presence, position and line of sight within the working environment were also included.

A review of the current available means to provide augmented reality, either through display screens, head mounted displays, or handheld displays, was presented in order to select the most adequate means to validate the concept. A list of technologies was included addressing the benefits and drawbacks of each one as it applies to the RETINA concept. An analysis of the various technologies listed was performed to investigate the ergonomic viability and risks and benefits of each from a human factor perspective[14]. This review produced operational requirements for the synthetic vision systems to be included in the concept description.

## II. Impact of Augmented Reality on Air Traffic Control

Airport Control Service is provided by the Air Traffic Controllers (ATCO) in the Control Tower basically using sight, for this reason the control room in the Control tower is often called Visual Control Room. The Airport Control Service is the only air traffic service that is provided by human sight; the Approach Control Service and the Area


**Fig. 1 An operator wearing a head-mounted see through display in the control tower can see information superimposed to the real out of the tower view. In the example it is shown a label for taking off flight identification and status with alphanumeric dynamic text labels**

Control Service, i.e. the other Air Traffic Services, are provided only using surveillance (or as procedural service where the radar is not available but in any case without the use of direct sight on aircraft). The Air Traffic Controllers in a Control Tower are supported by several systems such as ground and air surveillance radars, flight data processing systems and meteo system. For each of these systems at least one screen or a Human Machine Interface (HMI) is available. This results in a continuous mix of head-down and head-up operations for the ATCO who is responsible for interpreting information from multiple screens and projecting the aircraft flight path in the near feature. For this purpose, the controller takes decisions, plans tasks and optimizes arrival and departure air traffic flow, also in contexts of time-pressure and high-workload. In low visibility conditions, when the out of view is limited by weather, the ATCO working method changes because of the limitation in the head-up operations. The operational concept investigated in this paper consists in providing the ATCO with operative information such as aircraft position, identification, aircraft state in the flight processing system (i.e. READY, ACTIVE, AIRBORNE, LANDED, TERMINATED, etc.), weather information, via an augmented reality interface (Fig. 1). The RETINA proposal consists in providing the ATCO with operative information in head-up view by means of an augmented reality interface.

Guglielmo Marconi International Airport in Bologna, Italy (LIPE) has been selected as operative scenario for the evaluation of this operative concept. This is a single runway airport with medium complexity layout and medium-light traffic: between 200 and 300 movements per day. It is equipped with Primary Surveillance RADAR and Secondary Surveillance RADAR (PSR/SSR), Surface Movement RADAR (SMR) and Instrumental Landing System (ILS) CAT

3B (i.e. landing operations cleared until 75m of RVR, Runway Visual Range, at touch down zone). Three operative positions are available in the Control Tower: Ground (GND), Coordinator (COO) and Tower (TWR). The GND also operates as Delivery and is responsible for providing air traffic services in the maneuvering area except the runway. The GND is also responsible for the ATC part of the Apron Management Service. The TWR is responsible for providing air traffic services on the runway and in the Aerodrome Traffic Zone, i.e. the airspace close to the airport (5NM radius centered on the airport and 2500ft max altitude).

Low Visibility Procedures (LVP), i.e. the procedures applied by the ATCO in case of fog or poor visibility, are available in Bologna Airport in accordance with three visibility conditions: visibility condition 1 (normal operations), visibility condition 2 (the maneuvering area is not completely visible by the Control Tower) and visibility condition 3 (Runway Visibility Range RVR less than 400 m). Currently passing from visibility condition 1 to visibility condition 3 the controller head-down and head-up operations change significantly. This results in a change of the working method depending on the visibility condition. Different conditions also imply different rules: for example, in case of low visibility the separation between aircrafts is increased due to the reduced taxi speed and due to the impossibility for the ATCO to reduce the separation by sight. Moreover, the number of flights managed per hour decreases with consequent increase in delays. In these situations, controller performance becomes both highly cognitive and problem solving inclined.

In order to evaluate the controller tasks and the possible impacts of the use of augmented reality based interface in the different operative scenarios defined by the visibility conditions, a specific S-R-K (Skill Rules and Knowledge) analysis has been performed [13]. The Skills, Rules, Knowledge (SRK) framework or SRK taxonomy defines three types of behaviour or psychological processes present in operator information processing. The SRK framework was developed by Rasmussen et al. to help designers combine information requirements for a system and aspects of human cognition. SRK framework is used in the Ecological Interface Design method is used to determine how information should be displayed to take advantage of human perception and psychomotor abilities. By supporting skill- and rule-based behaviours in familiar tasks, more cognitive resources may be devoted to knowledge-based behaviours, which are important for managing unanticipated events.

For each operative position in the Control Tower, the related tasks in the specific visibility conditions have been identified and analyzed, then the S-R-K taxonomy has been used to qualitatively assess the impact of the augmented reality on each controller task. The results obtained underline that all the information displayed via augmented reality potentially reduces the complexity of operations supporting important tasks, especially those that require conflict detection and resolution. The information displayed supports skill- and rule-based behavior in familiar tasks; in this way more cognitive resources may be dedicated to knowledge-based behavior, which is important for managing unanticipated events [2].

Validation exercises have been performed in a CAVE-like virtual environment [15] designed to recreate a sense of


**Fig. 2 The baseline equipment (left), the Spatial Display (SD) equipment (center), and the Head Mounted Display (HMD) equipment (right) share the replica of the out-of the-tower view and a head-down equipment. In addition to that, in the SD equipment (center) overlays are superimposed onto the out-of-the-tower view if the associated object falls within the spatial range of augmentation, i.e. 9 out of 32 tower windows. The HMD equipment (right) shows the same overlays as the SD for each item that falls into the HMD field of view. The HMD operator's personal view is shown at the bottom right corner**

immersion by means of three, rear-projected and flat screens. Experimental data has been collected, basically comparing two scenarios for each visibility condition: with and without augmented reality.

In the validation exercises, two technical solutions were evaluated against a baseline equipment (Fig. 2):

- See-Through Spatial Display (SD)
- See-Through Head Mounted Display (HMD)

Both solutions support the ATCO by providing information as overlapped onto the external view.

**Baseline**

The baseline solution consists in a replica of the out-of the-tower view along with a basic head-down interface comprising weather display, FDP(Flight Duty Period) display, ground and tower RADAR displays.

**See-Through Spatial Display (SD)**

The see-through SD solution was implemented in a simulated environment since Augmented Reality technology for Spatial Display is not yet available and it is expected to be developed in the upcoming decades. The SD corresponds to 9 (on 32) tower windows overlapping most of the apron, taxiways, and runway of the airport. The augmented reality overlay is visible if the associated object falls within the spatial range of augmentation. Otherwise, no overlay is displayed. The most important information reported is meteo information, i.e. wind direction and speed, outside temperature and pressure, visibility, runway surface conditions, flight identification and status with alphanumeric dynamic labels (e.g. READY), alarm on NAVAIDS (NAVigation AIDS) and CTOT (calculated take off time). The head-up interface is supplemented by redundant head-down interface comprising weather display, FDP(Flight Duty Period) display, ground and tower RADAR displays, as in the baseline solution.

**See-Through Head Mounted Display (HMD)**

The HMD shows ad-hoc generated images based on the operative position, on the controller position in the visual control room, on gaze orientation, and visibility condition. In order to compare the two solutions, the HMD shows the same information as the SD, i.e . meteo information, flight identification and status , alarm on NAVAIDS (NAVigation AIDS) and CTOT (calculated take off time). For each aircraft/vehicle that falls into the HMD field of view an alphanumeric text label is displayed. It shows dynamic data in order to permit easy access to information not overloading the ATCO field of view. Also in this case, the head-up interface is supplemented by redundant head-down interface comprising weather display, FDP(Flight Duty Period) display, ground and tower RADAR displays, as in the baseline solution.

## III. Methods

### A. Apparatus Design

To evaluate the concept, a Real Time Human–in-the-Loop Simulation took place at the University of Bologna, involving three ATCOs and a pseudo-pilot manoeuvring all aircrafts and vehicles used in the simulation. The validation platform (Fig. 3) consists of a 4D model system exchanging data with the following four subsystems:

- Out of Tower View Generator (OOT): it provides the ATCO with a consistent and photorealistic view of the out of tower scene depicted onto CAVE-like virtual environment designed to recreate a sense of immersion by means of three, rear-projected and flat screens.The total projection area of the visualization system is 9m x 1.9m in a landscape orientation.
- Augmented Reality Overlay Application (AR App): it derives the relevant Augmented Reality Overlays and deploys them on the appropriate ATCO Head-Up Interface (being either Spatial Display or Head Mounted Display).
- Head-Down Equipment (HDE): it consists of a simplified interface that replicates the actual head-down equipment in the control tower. The interface is provided onto a 30" display placed onto a 75cm high table and put at a 20° angle to the table plane.
- Pseudo-pilot application (PP App): it allows the pseudo-pilot to monitor and update the state of the 4D model according to the commands provided by the ATCO by means of voice communication.

The platform can simulate any airport environment in different visibility conditions. As mentioned above, the

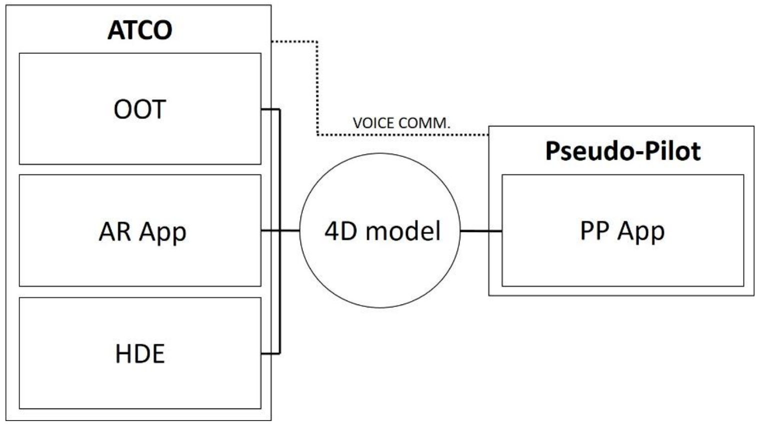


**Fig. 3 RETINA Validation Platform consists in an Air Traffic Controller post that communicates through voice to a pseudo-pilot post.The platform can simulate any airport environment in different visibility conditions by mmeans of a full 4D model system exchanging data with four subsystem: Out of Tower View Generator (OOT), Augmented Reality Overlay Application (AR App), Head-Down Equipment (HDE), Pseudo-pilot application (PP App).**

environment of Bologna airport was selected as reference scenario for the following reasons: i) simple layout with a single runway; ii) Bologna Airport is equipped with an A-SMGCS system providing aircraft with a radar view and identification for each aircraft and vehicle, and ILS CATIII for Low visibility procedures; iii) ATC Low Visibility Procedures are implemented and CAT II/III approach and LVTO (Low Visibility Take Off Operations) are available. Specific procedures for apron management are also available and implemented (often implicate ATCO head-down operations).

### B. Objectives and Metrics

The validation objective was to assess the impact of the introduction of the RETINA concept on the ATCO working methods considering three Key Performance Areas (KPAs), namely human performance, efficiency and safety.

In order to analyze RETINA concept KPAs, the following data were collected in the form of either objective quantitative measurement or subjective qualitative assessment:

- Head-Down Time
- Number of Switches Head-Down/Head-Up
- Throughput/Capacity
- Perceived Workload
- Information Accessibility

The quantitative metrics referred to the working position (Head-Down Time and number of switches) are collected by means of a camera embedded in a Microsoft Kinect sensor placed in front of the user at a sufficient distance to keep the user head in the sensor's field of view. The throughput is measured during the simulation as the number of aircraft

**Table 1 Sample of questionnaire used for the qualitative assessment. The first six questions address the perceived workload according to NASA TLX method whilst the last two questions concern information accessibility completeness and ease of access. The answer is provided as a score from 0 to 10 in a 21 points scale (half-scores admitted), were the scores 0, 5 and 10 correspond to the answers "very low", "fair" and "very high" respectively.**

| # | Area of Evaluation | Question |
|---|---|---|
| 1 | Human Performance | How mentally demanding was the exercise? |
| 2 | Human Performance | How physically demanding was the exercise? |
| 3 | Human Performance | How hurried or rush was the pace of the exercise? |
| 4 | Human Performance | How successful you were in accomplishing what you were asked to do? |
| 5 | Human Performance | How hard did you have to work to accomplish your level of performance? |
| 6 | Human Performance | How insecure, discouraged, irritated, stressed and annoyed were you? |
| 7 | Information accessibility | How well does the proposed interface provide all the information you would expect to have? |
| 8 | Information accessibility | How easy is the information displayed to find and intuitive? |

managed during the whole exercise and then it is normalized to the actual duration of the run in order to obtain the number of aircraft manged in the unit of time, expressed in movements per hour.

The qualitative metrics are obtained through offline questionnaires filled by subjects just after each run. The questionnaire consists in 8 questions and the answer is provided as a score from 0 to 10 in a 21 points scale (half-scores admitted), were the scores 0, 5 and 10 correspond to the answers "very low", "fair" and "very high" respectively. The first six questions address the perceived workload according to NASA TLX method [16] whilst the last two questions concern information accessibility completeness and ease of access (Table 1).

### C. Participants and Test Execution

The subjects who took part to the experiment are three Air Traffic Controllers, all operating at control towers at different airports. Their average experience in control tower operations is 12 years. The experimental plan consists in ten exercises, covering three visibility conditions, the technical solution to be compared (i.e. baseline, SD and HMD), and two levels of traffic density (Table 2). Each exercise is repeated three times, one for each air traffic controller taking part to the evaluation. Thus, on the whole, thirty exercises were run and the figures reported in the results section are obtained as average values on three subjects. Each exercise has an approximate duration of 30 minutes and they were randomly ordered within each visibility condition group. Each subject performed maximum three exercises per day with minimum intervals of 60 minutes between runs.

The number of subjects is limited in order to keep the validation to a reasonable duration. Moreover, the standard deviation of data collected on the three subjects is limited (Tables 3, 4, and 5). Thus the selected sample, although limited in size, can be considered as representative.

The exercises addressed three visibility conditions:

**Table 2 The experimental plan consists in ten exercises, covering three visibility conditions, the technical solution to be compared (i.e. baseline, SD and HMD), and two levels of traffic density.**

| Visibility Condition | Equipment | Traffic Density Restrictions | EXE-ID |
|---|---|---|---|
| CONDIVIS1 | Baseline | Medium | EXE-1 |
| | SD | Medium | EXE-3 |
| | HMD | Medium | EXE-2 |
| CONDIVIS2 | Baseline | Medium | EXE-4 |
| | SD | Medium | EXE-6 |
| | HMD | Medium | EXE-5 |
| | HMD (M/H) | Medium - High | EXE-7 |
| CONDIVIS3 | Baseline | Medium Traffic / Standard Restrictions | EXE-8 |
| | HMD STD | Medium Traffic / Standard Restrictions | EXE-9 |
| | HMD LIM | Medium Traffic / Limited Restrictions | EXE-10 |

- CONDI VIS 1 corresponds to visibility equal or greater than 5km and ceiling equal or greater than 1500ft. Specifically, it include the following scenarios.
  - VMC (Visual Meteorological Conditions) scenario: visibility equal or greater than 5km and ceiling equal or greater than 1500ft (Visual Flight Rules VFR available).
  - IMC (Instrument Meteorological Conditions) scenario: there are no conditions for the visual flights (only Special VFR).

  Visibility condition 1 (CONDI VIS 1) is considered where the visibility is sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance.
- CONDI VIS 2 corresponds to the IMC scenario in which visibility is sufficient for pilots to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic based on visual surveillance.
- CONDI VIS 3 corresponds to the IMC scenario in which visibility is sufficient for pilots to taxi but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference, and insufficient for personnel of control units to exercise control over all traffic based on visual surveillance. For taxiing, this is usually taken as visibility equivalent to an RVR of less than 400 m but more than 75 m.

On the whole, for each exercise performed on a RETINA solution, a similar exercise was conducted adopting the baseline equipment in order to compare data obtained vs success criteria and validation targets identified below.

In particular, CONDIVIS 3 exercises are intended to compare HMD to baseline equipment in very bad weather conditions and they include a specific exercise in which the restrictions due to low-visibility procedures are removed. The two resulting scenarios are summarized below.

- Standard restrictions: the ATCO manages the traffic applying the current regulations LVP.
- Limited restrictions: LVP restrictions (ground-side) are removed.

Specifically, the "limited restrictions" scenario is the following:

- The use of Intermediate holding points is removed;
- The use of J exit taxiway is confirmed;
- The minimum spacing between aircraft on final is confirmed;
- The capacity constraints on the number of departures managed together (i.e. 2) is removed;
- The constraints on simultaneous pushback from contiguous blocks is removed.

## IV. Results

The following section describes the main results obtained through the validation of the RETINA proposal. At first, the results are reported in tables 3, 4, and 5 which show quantitative data obtained through objective measurements (table 3), and qualitative data obtained through subjective measurements (tables 4 and 5).

Then, for each visibility condition the most relevant results are analyzed through bar charts that help compare experimental figures.

**Table 3 Quantitative data collected during experiments are shown as average values along with standard deviations (in brackets). Each exercise was repeated by three different subjects. The first column reports the total time needed to carry out the exercise, the second and third columns report the share of time in head-up or head-down position respectively.The fourth column shows the number of switches, and the fifth column indicates the throughput of the exercise, i.e. the number of aircraft managed in the unit of time.**

| | | Total Time Mean (SD) [seconds] | Head-Up Time Mean (SD) [seconds] | Head-Down Time Mean (SD) [seconds] | N. of Switches Mean (SD) [-] | Throughput Mean (SD) [movements/hour] |
|---|---|---|---|---|---|---|
| CONDIVIS1 | Baseline | 1941 (136) | 1155 (144) | 786 (20) | 356 (40) | 17 (0.2) |
| | SD | 1933 (224) | 1658 (298) | 275 (105) | 213 (57) | 20 (2.5) |
| | HMD | 1628 (362) | 1491 (305) | 137 (75) | 82 (38) | 19 (0.7) |
| CONDIVIS2 | Baseline | 1935 (153) | 756 (128) | 1179 (148) | 279 (30) | 18 (1.6) |
| | SD | 1817 (22) | 1436 (144) | 382 (123) | 161 (34) | 21 (0.1) |
| | HMD | 1768 (171) | 1591 (169) | 177 (25) | 75 (4) | 19 (1.2) |
| | HMD (M/H) | 1383 (83) | 1162 (150) | 221 (80) | 67 (15) | 25 (0.1) |
| CONDIVIS3 | Baseline | 1709 (149) | 454 (167) | 1256 (33) | 193 (47) | 17 (1.5) |
| | HMD STD | 1903 (146) | 1696 (171) | 207 (44) | 55 (7) | 14 (0.7) |
| | HMD LIM | 1832 (22) | 1665 (61) | 167 (48) | 78 (13) | 21 (0.2) |

**Table 4 The table refers to the six dimensions of operator's load according to NASA TLX method. Qualitative data collected during experiments are shown as average values along with standard deviations (in brackets). Each exercise was repeated by three different subjects filling questionnaires just after each exercise run.**

| | | Mental Demand | Physical Demand | Temporal Demand | Performance | Effort | Frustration |
|---|---|---|---|---|---|---|---|
| CONDIVIS1 | Baseline | 5.3 (0.47) | 4.2 (0.85) | 4.5 (1.87) | 7.2 (0.24) | 5.0 (1.41) | 4.3 (2.05) |
| | SD | 4.5 (1.08) | 3.8 (1.43) | 4.3 (1.70) | 7.2 (0.24) | 4.7 (1.93) | 2.5 (1.08) |
| | HMD | 4.5 (1.22) | 4.5 (1.78) | 4.5 (1.87) | 7.7 (0.24) | 3.8 (1.31) | 2.8 (1.03) |
| CONDIVIS2 | Baseline | 5.2 (2.25) | 4.5 (1.87) | 4.7 (2.05) | 7.0 (0.00) | 5.3 (2.39) | 3.2 (1.89) |
| | SD | 3.5 (1.47) | 3.3 (1.43) | 3.8 (1.31) | 7.7 0.24) | 4.0 (0.41) | 4.3 (1.89) |
| | HMD | 4.3 (1.31) | 5.5 (0.00) | 4.3 (0.47) | 7.0 (0.00) | 4.5 (0.41) | 3.0 (0.82) |
| | HMD (M/H) | 4.5 (1.87) | 5.3 (0.24) | 4.5 (0.41) | 7.2 (0.62) | 4.2 (0.85) | 3.3 (0.62) |
| CONDIVIS3 | Baseline | 5.8 (1.43) | 4.3 (1.89) | 5.7 (0.94) | 7.0 (0.00) | 5.3 (0.85) | 3.2 (0.85) |
| | HMD STD | 5.7 (0.24) | 5.5 (0.71) | 5.2 (0.94) | 7.3 (0.47) | 4.8 (0.62) | 3.5 (0.82) |
| | HMD LIM | 4.7 (0.85) | 5.0 (1.08) | 4.5 (1.47) | 7.8 (0.85) | 3.7 (0.62) | 2.8 (0.62) |

**Table 5 The table refers to information accessibility subjective assessment, with specific reference to completeness (first column) and ease of access (second column).Qualitative data collected during experiments are shown as average values along with standard deviations (in brackets). Each exercise was repeated by three different subjects filling questionnaires just after each exercise run.**

| | | Information Completeness | Information Ease of Access |
|---|---|---|---|
| CONDIVIS1 | Baseline | 7.2 (0.62) | 7.2 (0.85) |
| | SD | 7.8 (0.62) | 8.2 (1.03) |
| | HMD | 8.2 (0.47) | 8.2 (1.18) |
| CONDIVIS2 | Baseline | 6.0 (0.82) | 6.3 (0.47) |
| | SD | 7.5 (0.41) | 7.7 (0.62) |
| | HMD | 6.8 (1.31) | 7.3 (1.18) |
| | HMD (M/H) | 6.7 (1.03) | 7.2 (1.31) |
| CONDIVIS3 | Baseline | 6.2 (0.85) | 6.7 (0.47) |
| | HMD STD | 7.5 (1.08) | 7.7 (0.94) |
| | HMD LIM | 8.3 (0.61) | 8.0 (0.82) |

### A. Head-Up/Head-Down Time

The following charts compare the percentages of Head-Down/Head-up Time for the proposed solutions against baseline solution in three different visibility conditions.

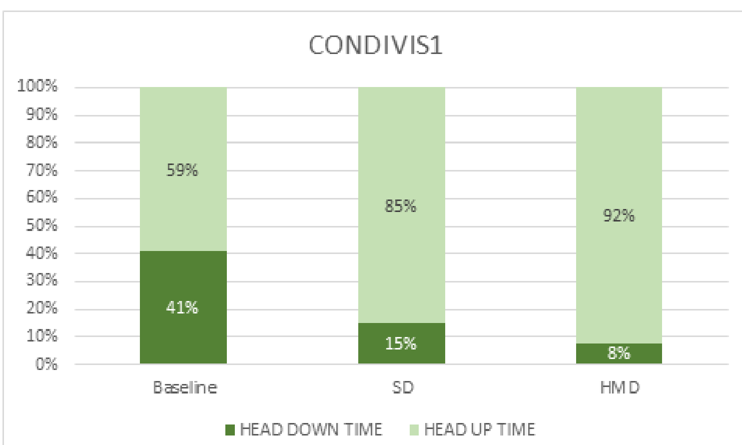


**Fig. 4 Share of time spent Head-Down/Head-Up by the user in CONDIVIS1 exercises. Average values on three subjects.**

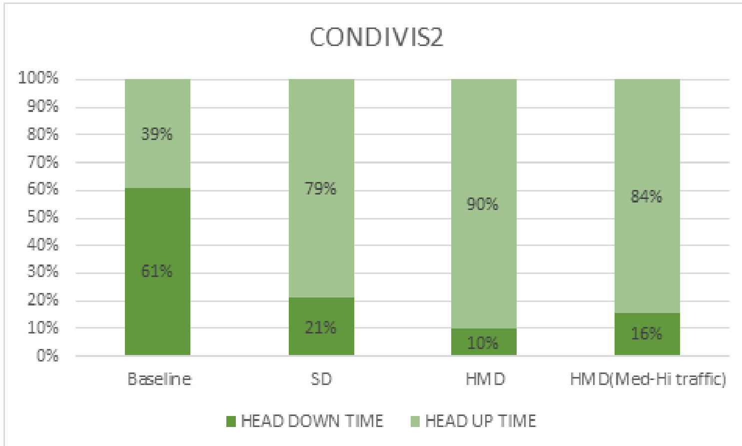


**Fig. 5 Share of time spent Head-Down/Head-Up by the user in CONDI VIS2 exercises. Average values on three subjects.**

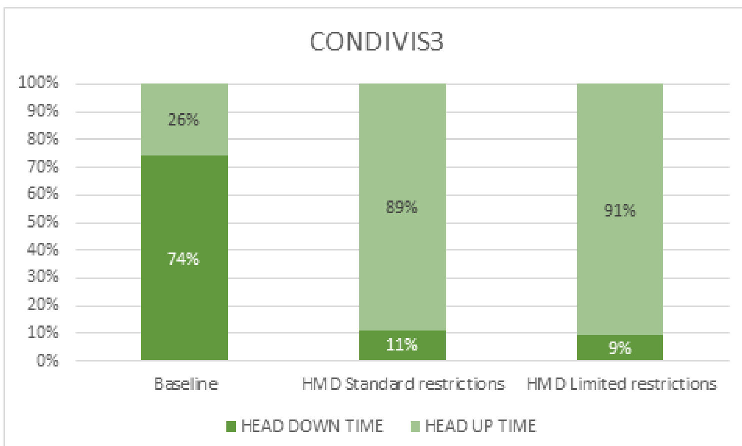


**Fig. 6 Share of time spent Head-Down/Head-Up by the user in CONDIVIS3 exercises. Average values on three subjects.**

Figure 4 displays Head-Down Time vs Head-Up Time in CONDIVIS1 for Baseline, Spatial Display, Head Mounted Display Equipment. Figure 5 displays Head-Down Time vs Head-Up Time in CONDIVIS2 for Baseline, Spatial Display, Head Mounted Display Equipment in two different traffic scenarios (medium and medium-high traffic levels). Figure 6 displays Head-Down Time vs Head-Up Time in CONDIVIS3 in both Standard and Limited restriction scenarios compared to the Baseline.

### B. Perceived workload

The following charts compare the perceived workload, assessed by means of NASA TLX questionnaires [16], for the proposed solutions against baseline solution in three different visibility conditions.

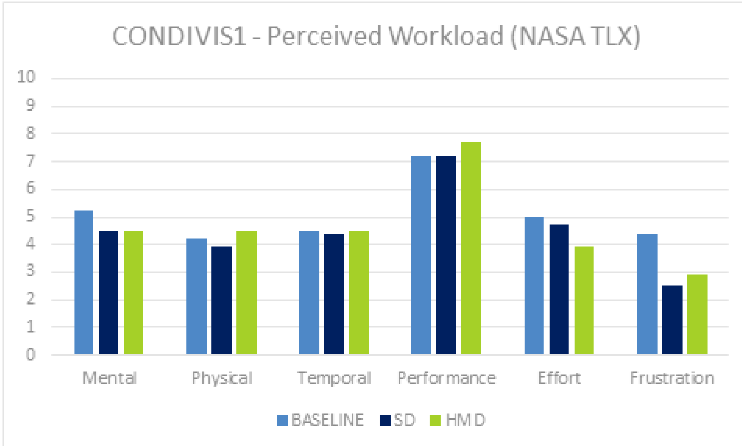


**Fig. 7 Perceived workload in CONDIVIS1 was measured using NASA TLX questionnaires with the following equipment: baseline (light blue), Spatial Display (blue), Head Mounted Display (green). Average values on three subjects.**

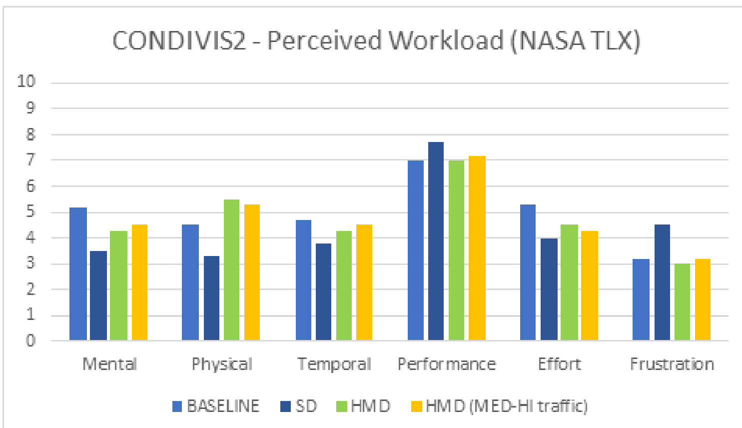


**Fig. 8 Perceived workload in CONDIVIS2 was measured using NASA TLX questionnaires with the following equipment: baseline (light blue), Spatial Display (blue), Head Mounted Display (green). The fourth bar of each set represents an increased traffic scenario with HMD equipment (orange). Average values on three subjects.**

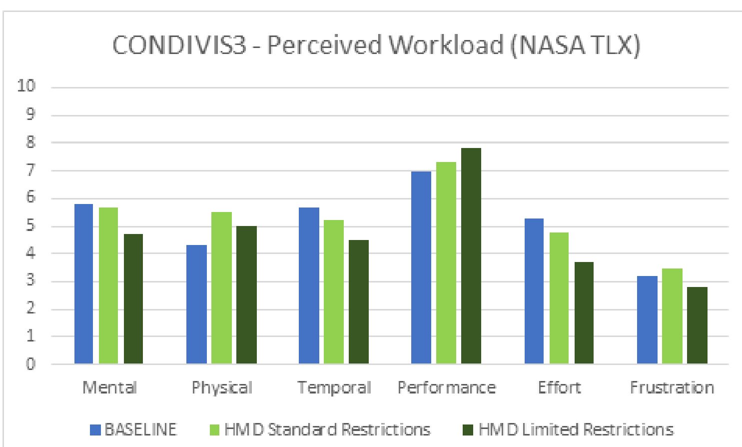


**Fig. 9 Perceived workload in CONDIVIS3 was measured using NASA TLX questionnaires with the following equipment: baseline (light blue), Head Mounted Display with standard restrictions (green), Head Mounted Display with Limited Restrictions (dark green). Average values on three subjects.**

Figure 7 displays the results of perceived workload assessment in CONDIVIS1 for Baseline, Spatial Display, Head Mounted Display Equipment. Figure 8 displays the results of perceived workload assessment in CONDIVIS2 for the Baseline, RETINA Spatial Display, and RETINA Head Mounted Display Equipment in two different traffic scenarios (medium and medium-high traffic levels). Figure 9 displays the results perceived workload assessment in CONDIVIS3 in both Standard and Limited restriction scenarios compared to the Baseline.

## V. Discussion and Conclusions

The analysis of results shows that the introduction of the RETINA proposal has an overall positive effect in target key performance areas (Human Performance and Efficiency).

Firstly, both RETINA solutions provide a substantial reduction of Head-Down Time compared to the baseline equipment (Table 3). The reduction effect is remarkable when adopting the HMD solution whereas with this solution the time the user spends head-down drops to 8% of the Total Duration of the Exercise (Baseline 41% - Spatial Display 15%) in CONDIVIS1 (Fig.4). Then, head-down time plummets to 10% of the Total Duration of the Exercise (Baseline 61% - Spatial Display 21%) in medium traffic conditions in CONDIVIS2 (Fig.5), culminating in a dramatic reduction of Head-Down Time vs Head-Up Time in both Standard (11%) and Limited restriction (9%) scenarios compared to the Baseline (74%) in CONDIVIS3 (Fig.6).

Looking at the number of switches between head-down and head-up working positions, it is worth noticing that both RETINA solutions provide a substantial reduction of number of switches compared to the baseline equipment (Table 3). The reduction effect is remarkable when adopting the HMD solution whereas with this solution the number of switches between Head-Down and Head-Up positions drops to 82 (Baseline 356 - Spatial Display 213) in CONDIVIS1, and to to 75 (Baseline 279 - Spatial Display 161) in medium traffic conditions in CONDIVIS2. Also, in CONDIVIS3 the number of switches in both Standard (55) and Limited restriction (78) scenarios is much lower compared to the Baseline (193).

As far as capacity is concerned, both RETINA solutions provide an increase in the number of aircraft safely managed by the operator in the unit of time compared to the baseline equipment in both CONDIVIS1 and CONDIVIS2, as shown in Table 3. Looking at CONDIVIS3 results, it is interesting to notice that, when restrictions apply, the throughput in CONDIVIS3 with HMD solution is reduced compared to the baseline whilst, as expected, the introduction of RETINA HMD solution makes it possible to test the removal of some restrictions. Thus, the results confirm that HMD solution is effective in achieving higher traffic volumes.

Qualitative subjective data show interesting figures about the workload perceived by the subjects when adopting the RETINA proposal compared to the baseline equipment (Table 4). Specifically, in both CONDIVIS1 and CONDIVIS2 scenarios, it is possible to observe that the perceived workload is slightly reduced with either Spatial Display or Head Mounted Display equipment with respect to the baseline equipment (Figg. 7 and 8). In CONDIVIS3, despite a slight increase in physical effort required by the use of a wearable device, the perceived workload is generally reduced with

Head Mounted Display equipment with respect to the baseline equipment (Fig.9).

The information accessibility is marginally improved by the introduction of RETINA proposal in CONDIVIS1 and CONDIVIS2 whilst, in CONDIVIS3, the HMD solution provides good improvements to information accessibility in terms of both completeness and ease of access of the information. The effect is more evident when low visibility restrictions are relaxed (Table 5).

From an operational perspective, the added value of using the RETINA proposal in comparison with current tower operations is supported by the following remarks:

- the RETINA proposal has a clear effect in stimulating the ATCO to work in a head-up position more than in a head-down position.
- The ATCO is provided with a unique conformal representation of all the needed information that is currently provided by means of several visual inputs.
- When low visibility conditions apply, the use of RETINA tools provides the ATCO with a head-up conformal view of all needed information, leading to the reduction of current restrictions due to LVP, with consequent increased throughput.
- The proposed solutions provide quantified benefits in terms of perceived mental workload, temporal workload, performance, effort, frustration, information accessibility, and head-down time.
- The operational benefits provided by the two conceptual solutions explored, namely HMD and SD, are comparable.
- RETINA tools proved to preserve safety. Moreover, they lead to safety improvement as they enhance situational awareness.

As far as technical issues are concerned, the work performed proved the following achievements:

- Compatibility of the technology used with the current data provision format;
- Capability of tracking the user position;
- Capability of providing the user with a conformal head-up view of synthetic information overlapped to the out of tower view.

As far as the SD solution is concerned, it is worth remembering that the Augmented Reality technology for this solution is not yet available, thus this solution achieves Technology Readiness Level TRL2. On the other hand, since the HMD Augmented Reality technology is more mature, its application does achieve Technology Readiness Level TRL3. However, since this technology is not mature enough for full deployment in a safety critical environment, further research is required to demonstrate it in a real environment.

On the whole, the impact of the use of the AR HMD equipment on the ATCO working method was globally considered as positive. A more extensive usability experimental campaign is needed to assess user acceptance.

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