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Immersive displays for building spatial knowledge in multi-UAV operations

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Abstract— **This paper presents an experiment to evaluate the effects of immersive displays in a multi-UAV context in which the operator may need to understand not only the 3D spatial relationships between the UAVs but also where the UAV is with respect to mountains or other obstacles. To this end, a 3D simulator was developed and displays were selected based on their Field-of-Regard (FoR). Participants supervised a multi-UAV operation and the acquired spatial knowledge was evaluated using a Situational Awareness Global Assessment Technique (SAGAT). Moreover, a NASA-TLX study was done to measure the workload of each display. Finally, results showed that a gradual increase of immersion improved the spatial understanding of the UAV operator.**

I. Introduction

Present UAVs are usually considered as safety-critical systems. Therefore, the presence of a human operator will continue for some time to be essential in task completion, particularly in complex situations, instances of UAV failures or automation bias [1].

One of the most important terms in aviation industry is Situation Awareness (SA). Expressions like *lack of SA* or *failure to maintain SA* refers to human machine malfunctions and are usually involved in many aircraft incidents ([2],[3]). A formal definition of SA was provided by Endsley [4]. She holds the view that SA could be broken down into three different levels (perception, comprehension and projection) and suggested that for building and maintain a high level of SA, these levels should be built upon each other.

Other part of current research is focused on single control of multiples UAVs ([5], [6]). This idea may well lead to an increased level of autonomy and concepts such as *man out-of-the-loop* or *trust in automation* has been identified as potential concerns. In a study of automation in UAVs [7], Billings pointed out that to command effectively, the operator had to be involved and informed. Furthermore, he suggested that the automated system had to be predictable.

Building and maintaining SA is a very complex issue because of the limitations of human cognitive resources. A decomposition of SA in multi-UAV environments was proposed by Drury [8]. According to his research, the understanding that the human operator has of the different UAVs is highly influenced by the spatial knowledge acquired during the mission. This knowledge is very dependent on how the operator interfaces with the system and how information is presented. In a study from [9], researchers from the University of Bologne incorporated Virtual Reality (VR) based immersion interfaces for a UAV operation, using a touch screen, 3D virtual displays and an audio feedback message generator.

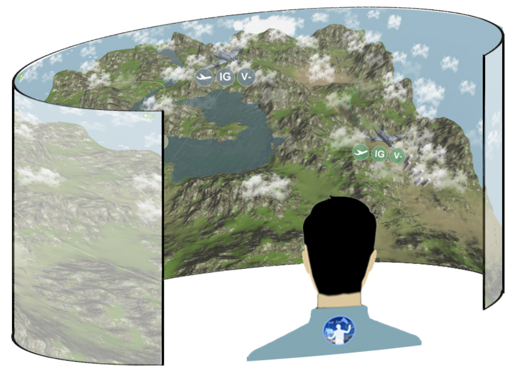

Fig. 1. Example of a human operator supervising a multi-UAV operation using an immersive display

Even though the interaction between the operator and the UAV has been widely addressed in recent years, most improvements have been achieved by using traditional 2D displays and basic interaction ([10], [11]). Nonetheless, it is possible to further improve the SA of the human operator by designing more natural interfaces and using VR technology. With this goal, the present work explores the development of VR environments in order to test the effectiveness of immersive displays for building spatial knowledge in a multi-UAV operation. A sketch of this concept is presented in figure 1.

The remainder of the paper is organized as follows. Section II describes spatial knowledge as an important part of operator's SA. A more in-deep description of the proposed framework is provided in Section III and IV. Section V outlines the experiment setup and the evaluation methodology. Section VI shows the experimental results. Finally, section VII summarizes the results of this work and draws conclusions.

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II. Spatial Knowledge in UAV operations

UAV operators are commonly experienced and skilled pilots who are moved from manned operations to supervision tasks. Since they are not physically located in the same frame of reference as the aircraft, decision making is supported by their cognitive model or SA level. This cognitive model (also called *the picture* in Air Traffic Control) rely on spatial knowledge, defined by [12] as the representation of the environment in memory.

In order to build spatial knowledge, the operator is continuously informed about both the position and attitude of the UAV. Extending this concept to a operation with N UAVs, the pose of each UAV can be defined as:

$$\begin{aligned} &P_1(x_1,y_1,z_1,\theta_1,\phi_1,t)\\ &P_2(x_2,y_2,z_2,\theta_2,\phi_2,t)\\ &P_3(x_3,y_3,z_3,\theta_3,\phi_3,t)\\ &\quad\vdots\\ &P_n(x_n,y_n,z_n,\theta_n,\phi_n,t) \end{aligned} \tag{1}$$

where (x_i,y_i,z_i) is the location of the UAV_i and (θ_i,ϕ_i) are the horizontal and vertical angles with $i\in[0,..,N]$. Current Ground Control Stations (GCS) provide this information to the operator using primary flight displays, geographical information systems or first person view cameras. Nonetheless, the transition from manned aircrafts to UAVs changed the way in which the operator obtained this information. In manned aviation, both visual and vestibular system are used to estimate distances and velocity. However, when supervising a UAV operation, the operator only interacts visually with different displays. Figure 2 illustrates the subsystems involved in this procedure.

According to Endsley's definition of SA [4], the pose of each UAV would correspond to the perception level (level 1). Level 2 SA requires integrating the perceptual information to understand how it will affect to the operation. Altitude deviations or covered distances are examples of level 2 SA related to spatial knowledge. Finally, the highest level (level 3) is the projection of future states of the system. In this level, previous experience and the operator's mental model are very important in order to estimate future events. For instance, predicting collision avoidance or future UAV poses would allow the operator to anticipate possible occurrences. Furthermore, this definition of SA involves a temporal component as shown in Equation 1. In relation to UAVs, spatial updating refers to the cognitive process that updates spatial relationships between the UAVs and the environment based on perceptual information. Giving support to spatial updating is a key factor in maintaining an overall SA level during all phases of the operation. According to a study by Cummings, operator's cognitive workload is most of the time very low (even producing boredom) during long-endurance missions [13]. This implies that, in a critical situation, the operator has to build or update his mental model and react accordingly in a short period of time.

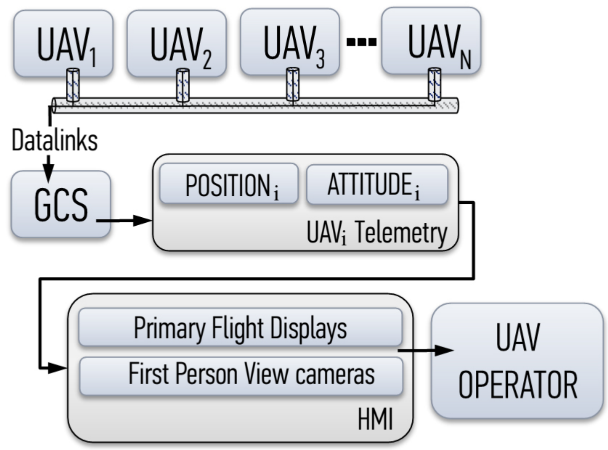

Fig. 2. Representation of information flow from UAVs to the operator related to spatial knowledge.

The purpose of this research is to study the effects of immersive interfaces for building spatial knowledge in a multi-UAV context. For this experiment, spatial knowledge has been identified as the awareness that the operator has of each UAV about:

Global UAV awareness: The operator has to know the location of each UAV in order to obtain a global context of the current situation.

Local UAV awareness: It refers to the understanding that the operator has of the UAV attitude. Horizontal and vertical angles indicates if the UAV is ascending, descending or describing a curved path.

Relational awareness: The operator needs to understand the 3D spatial relationships between the different UAVs, obstacles or targets.

The previous definition of spatial knowledge would correspond to Endsley's level 1 SA. With this information, the operator would be able to build a mental model of the current situation. Nonetheless, derived knowledge such as the described trajectory, deviation from nominal values or future states of the system are also considered in this definition.

III. Immersive interfaces

Latest advances in Human-Machine Interaction (HMI) has been widely used in many telepresence systems ([14] and [15]). Particularly, immersive VR technology provide enhanced spatial cues in order to extract 3D information from the environment. In a experiment by [16], a comparison between head-tracking and joystick-controlled rotation was done. Results showed that physical rotations improved the ability of the user to maintain spatial orientation. Finally, an important feature of immersive displays is the sense of presence. This feature creates the illusion that the user is inside the VR system. However, this feeling depends on the characteristics and realism of the immersive system.

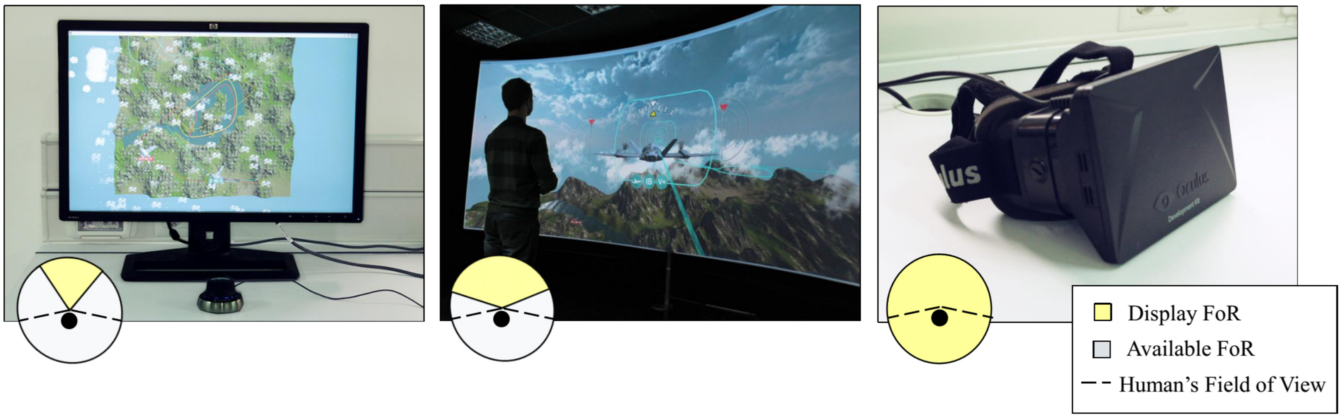

Fig. 3. (From left to right) Standard monitor solution in orthographic viewing mode (40° FoR at 1.5 metres), VR Screen from CATEC's facilities in egocentric viewing mode (100° FoR at 2 metres) and Oculus Rift (360° FoR)

Three different immersive displays were used in this paper. The selection of each interface was done according to their Field-of-Regard (FoR). This characteristic refers to the total amount of the physical space surrounding the user in which the 3D environment is projected. The selected interfaces are described below:

A. Monitor

Currently, this is the most adapted solution for the needs of a GCS. Standard monitors are used to show information from telemetry and payloads. They are portable and the cost is relatively low. On the other hand, monitors are not very immersive due to their reduced FoR, so the spatial perception is limited. In particular, a 24" monitor provided a 50° of horizontal FoR at 1.5 metres away from the display. Figure 3 (left) shows the selected monitor with a resolution of 1920x1080 pixels.

B. VR Screen

The second interface under test was a surround-screen display. This kind of screen typically has a higher FoR in comparison with monitors. Nonetheless, it is not a portable system due to the screen size and its cost is greater than other solutions. The selected display is located in the Virtual Reality room at CATEC's facilities and provide an horizontal FoR of 100° at 2 metres away the screen with a resolution of 2460x1050 (figure 3, center)

C. Oculus Rift

Finally, the last interface is a Head-Mounted Display. This visual display integrates electronics and optical components in order to track the head movement. Images are directly projected in a fixed screen in front of the user's eye. Regarding FoR, this system provide a 360° vision thanks to the head-tracking system. However, simulator sickness is a very common issue and the use of this system is usually restricted in time. For this experiment, an Oculus Rift DK1 was used with a resolution of 800x600 pixels each eye (figure 3, right).

IV. Multi-UAV simulator

The aim of this study is to evaluate how immersive displays could improve the spatial knowledge of a UAV operator. For this purpose, a multi-UAV simulator was built using VR technology. Virtual worlds are commonly used during UAV operations to maintain the operator's SA about the location of the UAV and its payload. Furthermore, the generation of Digital Elevation Models (DEMs) from UAV imagery increased accuracy in the last decade [17], allowing the 3D reconstruction of the real world.

For this research, a synthetic terrain was built using the graphic engine Unity 3D to represent a virtual environment. In this 3D environment, it is possible to integrate information from weather conditions, vegetation or buildings in order to provide a high sense of presence to the operator. The terrain simulates a mountain landscape with a lake and it has two UAV airports. The implementation of the UAVs was done using a multi-agent approach based on Finite-States Machines (FSMs). The behaviour of the UAVs is the following: each UAV takes-off from one airport and follows a 3D waypoint-based path. When the UAV reaches the target area, it stays in a special path for a random time with the aim of simulating a particular UAV action. Finally, the UAV returns to home-base using a return to home path. This definition for a single UAV operation is extended to a multi-UAV case in which N UAVs can be defined.

The development of the multi-UAV simulator was specially designed to test different immersive interfaces. In order to build spatial knowledge, two frames of reference were proposed: orthographic and egocentric. The first viewing mode could be considered an orthographic map that provides global information about all the UAVs at the same time, as shown in figure 4. The latter refers to a modified egocentric frame of reference, simulating a 3D primary flight display (figure 4, down).

Depending on the selected view, different information is displayed. In egocentric view, a radar system give information about other UAVs. There are N-1 indicators located

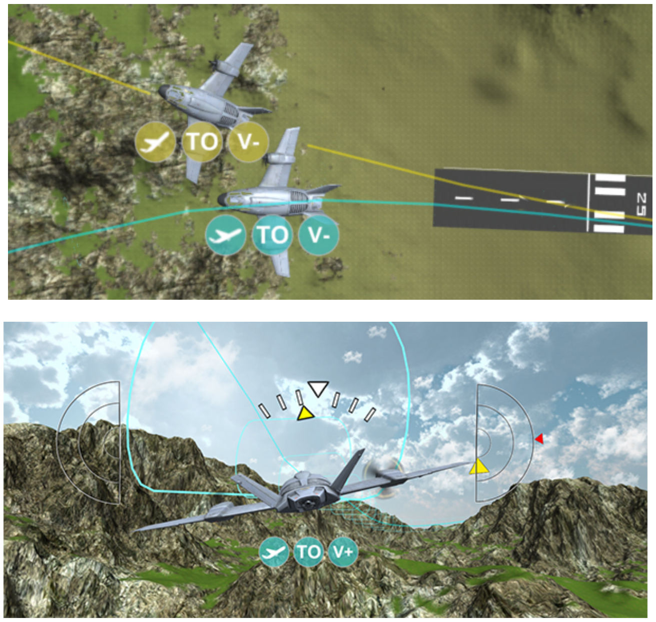

Fig. 4. (From up to down) Orthographic viewing mode. Egocentric viewing mode

in three levels depending on the distance between the UAV and the target. The position in the radar is calculated by the horizontal angle. Furthermore, a roll indicator and a 3D path tunnel are also displayed. Finally, both in orthographic and egocentric view, circular widgets were designed to inform about elevation, mission progress and acceleration as seen in Figure 4.

In the simulator, there are N+1 cameras (1 orthographic and N egocentric) depending on the number of UAVs. User interaction was defined to change the viewpoint and the selected camera. The default view mode is orthographic and the operator is able to switch to an egocentric view by pressing down an special button associated to a particular UAV. When the button is released, the system switches back to orthographic view. The UAV operator can also rotate the viewpoint of the camera by using a 3 Degrees-Of-Freedom (DoF) mouse. This feature is more useful in egocentric view, because the operator can obtain information from the UAV vicinity. In addition, in the Oculus Rift case, the 3-DoF mouse was replaced by the head-tracking system, enabling a more natural interaction.

V. Experiment Setup

Participants in this study were required to use the proposed simulator in order to maintain their SA about the location of each UAV in mission. However, in a real context, the overall operator's workload would increase due to commanding or payload monitoring tasks. For this reason, three UAVs were selected to represent a realistic multi-UAV scenario. Each participant supervised three UAV operations using different immersive displays (monitor, VR screen and Oculus Rift). The order of both the operations and the interfaces were randomly assigned to participants with the purpose of not introducing any bias. Eight individual subjects were recruited as volunteers from CATEC. Half of this group had previous experience piloting UAVs, meanwhile the other half did not. The experiment were divided in three sessions, each one with the same scheduling:

- Mission briefing.
- Specific interface training.
- Mission execution.
- In-mission questionnaire.
- Workload questionnaire.
- Talking debriefing.

First of all, mission planning and the scenario was presented to the operator in a short briefing. Then, an specific interface training was required for the operator to get used to the user interaction. Finally, the operator had to fill a written questionnaire to measure his spatial knowledge and workload.

		Questions
SAGAT	Lvl 3 SA	What is the future location of UAV_i?
		What is the next change of attitude of UAV_i?
	Lvl 2 SA	What has been the path followed by UAV_i?
		What was the last change of attitude of UAV_i?
	Lvl 1 SA	What is the current location of UAV_i?
		What is the current attitude of UAV_i?
	Relational	Where is UAV_i with regard to UAV_j?
		Where is UAV_i with regard to home base?
NASA-TLX		MENTAL DEMAND Low High PHYSICAL DEMAND Low High

TABLE I

EXAMPLES OF QUESTIONS USED IN THIS EXPERIMENT

Evaluation methodology was based on two different approaches: SAGAT [18] and NASA-TLX [19]. Using the SAGAT, the simulation was frozen at a random point during the operation. The operator was then required to answer a written questionnaire in order to compare his mental model with reality. Questions were selected according to the previous definition of spatial knowledge. Each questionnaire had ten questions regarding the current pose of the UAVs (level 1 SA), the past state or comprehension (level 2 SA), the estimated future location (level 3 SA) and the 3D spatial relationships between UAVs or obstacles (relational SA). A small database of forty questions was made so the questionnaire was randomly selected in each trial. On the other hand, NASA Task Load Index (NASA-TLX) is a multi-dimensional scale designed to estimate the operator's workload while performing a task. It consists of six subscales that represent the subjective workload experienced by the operator. These scales involves mental, physical and temporal demand, effort, frustration and performance. Table I shows a subset of the questions used in this experiment.

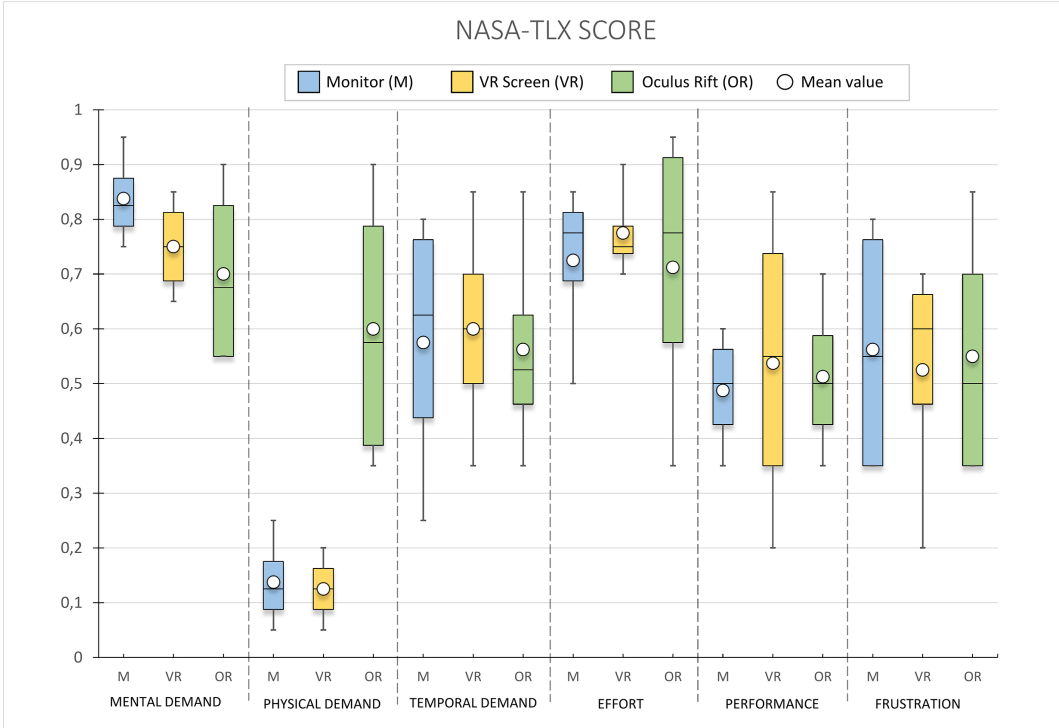

Fig. 5. Results from NASA-TLX evaluation for the three tested displays.

VI. Results

Eight participants performed three experiments using different immersive displays. These displays were evaluated using two metrics: NASA-TLX and SAGAT. In order to define a final score, both SAGAT and NASA-TLX were used. An ideal solution would maximize the SAGAT score (related to the acquired spatial knowledge) and minimize the mean workload (NASA-TLX).

Figure 5 illustrates the results from the NASA-TLX for the three proposed displays. Since the data met the assumptions of analysis of variance, different ANOVA tests were performed for statistical analysis (with $\alpha = 0.05$). First, a gradual decrease in the mental demand mean value could be observed. Nonetheless, one-way ANOVA test showed that there were no statistically differences between groups, $F_{MD}(2,21) = 1.22, (p = 0.33)$. The Oculus Rift had the worst mean score in physical demand in comparison with other solutions. In this case, there was a statistically significant difference between interfaces as determined by the one-way ANOVA test, $F_{PD}(2,21) = 10.57, (p = 0.004)$. The other parameters present similar statistical distributions $(p_{TD}, p_{EF}, p_{PE}, p_{FR} > 0.05)$.

In total, every participant answered three questionnaires with ten questions about the UAVs in mission. Using this methodology, spatial knowledge was translated to a SAGAT score. Results from the experiments are shown in figure 6. From this figure, it can be seen that immersive displays improved the acquired spatial knowledge. Particularly, the most immersive solutions (VR and Oculus Rift) increased the mean score in comparison with the monitor. A final ANOVA test confirmed this statistical variability, $F_{SAGAT}(2,21) = 5.49, (p = 0.02)$.

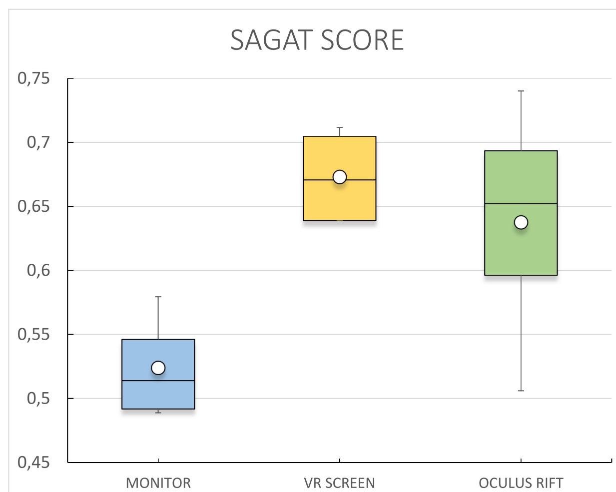

Fig. 6. SAGAT score representing the spatial knowledge acquired by the UAV operator. The y-axis was properly scaled for visualization purposes.

Finally, figure 7 illustrates both metrics together. In relation to the workload, a raw NASA-TLX (RTLX) measurement was calculated [19]. In the case of the SAGAT score, the mean value was selected. As mentioned earlier, a final comparison was done according to the previous values. The monitor display had the lowest SAGAT/NASA-RTLX ratio. A similar value was obtained in the case of the Oculus Rift. Lastly, the highest ratio was registered by the VR screen.

VII. Conclusions

The main purpose of the research presented in this paper has been to draw attention to the integration of immersive displays in UAV operations. Particularly, spatial knowledge was defined as an important part of the operator's SA. The main aspect of this study lies in both the consideration of a multi-UAV environment and the selected evaluation methodology. This evaluation was based on two different approaches: NASA-TLX and SAGAT.

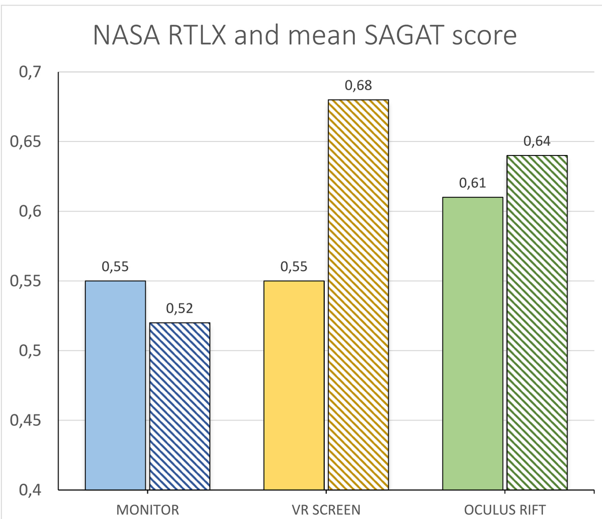

Fig. 7. Representation of raw NASA-TLX (solid fill) and SAGAT (dashed fill) score for each proposed display. The y-axis in figure was properly scaled for visualization purposes.

From the research that has been carried out, it is possible to conclude that spatial knowledge could be improved increasing the immersion level of the UAV operator. The VR display and the Oculus Rift obtained better results than the monitor solution. Nonetheless, total immersion technology presents drawbacks that could increase the overall operator's workload. An interesting point during experiments was the association between spatial knowledge and human memory. In the training session, participants spent much time during the evaluation remembering where the UAVs were located. A piece of paper with a simplified map was provided in order to solve this issue. In relation to subject selection, there was no particular difference between subjects with or without prior experience in piloting UAVs. The only difference was that pilots and GCS operators required less training than the others.

Finally, more research into immersive displays is still necessary before obtaining a definitive answer on how this technology could support a multi-UAV operation. In addition, this research could be complemented with physiological methods to validate the obtained results.

References

[1] F. Jentsch and M. Barnes. *Human-Robot Interactions in Future Military Operations*. Human Factors in Defence. Ashgate Publishing, Limited, 2012.

[2] Kevin W. Williams and Williams Kw. A summary of unmanned aircraft accident/incident data: Human factors implications. *U.S. Department of Transportation, Federal Aviation Administration, Civil Aerospace Medical Institute, Oklahoma City*, 4, 2004.

[3] M.M. Nasir and Qin Shi-Yin. Notice of violation of ieee publication principles investigation of human factors in uav accidents based on analysis of statistical data. In *Instrumentation, Measurement, Computer, Communication and Control, 2011 First International Conference on*, pages 1011–1015, Oct 2011.

[4] M.R. Endsley. *Designing for Situation Awareness: An Approach to User-Centered Design, Second Edition*. Designing for Situation Awareness: An Approach to User-centered Design. Taylor & Francis, 2011.

[5] M.L. Cummings, J.P. How, A. Whitten, and O. Toupet. The impact of human-automation collaboration in decentralized multiple unmanned vehicle control. *Proceedings of the IEEE*, 100(3):660–671, March 2012.

[6] J.Y.C. Chen, M.J. Barnes, and M. Harper-Sciarini. Supervisory control of multiple robots: Human-performance issues and user-interface design. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 41(4):435–454, July 2011.

[7] C.E. Billings. *Aviation automation: the search for a human-centered approach*. Human factors in transportation. Lawrence Erlbaum Associates Publishers, 1996.

[8] Jill L. Drury, Laurel Riek, and Nathan Rackliffe. A decomposition of UAV-related situation awareness. *Proceeding of the 1st ACM SIGCHI/SIGART conference on Human-robot interaction - HRI '06*, page 88, 2006.

[9] Francesca De Crescenzio, Giovanni Miranda, Franco Persiani, and Tiziano Bombardi. A first implementation of an advanced 3d interface to control and supervise uav (uninhabited aerial vehicles) missions. *Presence: Teleoper. Virtual Environ.*, 18(3):171–184, June 2009.

[10] M.L. Cummings and P.J. Mitchell. Managing Multiple UAVs Through a Timeline Display. *Infotech@Aerospace*, pages 1–13, September 2005.

[11] Christian Fuchs, S Ferreira, J Sousa, and G Gonçalves. Adaptive consoles for supervisory control of multiple unmanned aerial vehicles. *Human-Computer Interaction. ...*, pages 678–687, 2013.

[12] R.G. Golledge. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. Johns Hopkins University Press, 1999.

[13] Mary L. Cummings, C. Mastracchio, Kristopher M. Thornburg, and A. Mkrtchyan. Boredom and distraction in multiple unmanned vehicle supervisory control. *Interacting with Computers*, 25(1):34–47, 2013.

[14] Sunao Hashimoto, Akihiko Ishida, Masahiko Inami, and Takeo Igarashi. Touchme: An augmented reality based remote robot manipulation. In *The 21st International Conference on Artificial Reality and Telexistence, Proceedings of ICAT2011*, 2011.

[15] Stefanie Zollmann, Christof Hoppe, Tobias Langlotz, and Gerhard Reitmayr. Flyar: Augmented reality supported micro aerial vehicle navigation. *Visualization and Computer Graphics, IEEE Transactions on*, 20(4):560–568, 2014.

[16] Sarah S. Chance, Florence Gaunet, Andrew C. Beall, and Jack M. Loomis. Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence: Teleoper. Virtual Environ.*, 7(2):168–178, April 1998.

[17] J.J. Ruiz, L. Diaz-Mas, F. Perez, and A. Viguria. Evaluating the Accuracy of DEM Generation Algorithms from UAV Imagery. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, (2):333–337, August 2013.

[18] Mica R Endsley. Direct measurement of situation awareness: Validity and use of sagat. *Situation awareness analysis and measurement*, 10, 2000.

[19] Sandra G. Hart. Nasa-Task Load Index (Nasa-TLX); 20 Years Later. In *Human Factors and Ergonomics Society Annual Meeting*, volume 50, 2006.