# Evaluation of Virtual and Mixed Reality Technologies in Helicopter Simulation

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## ABSTRACT

Helicopters, because of their vertical take-off and landing capability, are an important vehicle for demanding missions such as search and rescue operations and transportation into confined areas. Therefore, training is essential to minimize the risk of helicopter missions due to human error. To date, more and more simulation is used for helicopter training where typically certified full-flight simulators are utilized. The use of simulation has several advantages. Challenging and risky tasks can be practiced in a safe environment. At the same time, the operational costs of a helicopter can be saved. Likewise, training scenarios can be simulated that cannot be trained in reality, such as a tail rotor failure. However, the use of simulation for training does not only have advantages. For example, simulation training can cause simulation sickness. Also, the lack of simulation fidelity can hinder transfer of training. With innovative technologies, there are new opportunities for helicopter simulation to increase the fidelity of the simulation. In this paper it is discussed to which extent Virtual Reality (VR), Mixed Reality (MR) and Augmented Reality (AR) technologies can be used as visual system in the helicopter simulation environment. The aim is to increase the immersion of the helicopter simulation and thus enhancing the learning effect and transfer of training. In a piloted study an AR (with see-through display), MR and VR (monitor-based display) setup is compared to conventional helicopter simulation at a research simulator.

## INTRODUCTION

Forecasts for the helicopter industry show that the demand for helicopter services such as Helicopter Emergency Medical Services (HEMS), surveillance, police, aerial work, agriculture and offshore operations are increasing (Ref. 1). At the same time, the industry is facing a shortage of helicopter pilots as experienced pilots retire, the industry is in competition with other professions due to a shortage of qualified professionals and the access to flight training facilities is limited. One way to improve the situation is to provide efficient and affordable flight training. In addition to regular helicopter flight training, simulators have been proven to be effective, safe and affordable for various aspects of pilot training (Ref. 2). The intention to use simulations for training is also part of the European Aviation Safety Agency (EASA) Rotorcraft Safety Roadmap (Ref. 1), which calls for the development of new types of training devices. The current requirements for helicopter training devices in Europe are summarized in the certification specification of Flight Simulation Training Devices (FSTD) (Ref. 3) by EASA. However, requirements are changing due to the growing technical possibilities and the increasing demands on pilots and the helicopter operations. In the meantime, two helicopter training devices (Robinson R22 Beta II as FNPT II and Airbus Helicopters H125 as FTD Level 3) with a Virtual Reality (VR) headset have been certified by EASA. The additional requirements for a VR technology-based helicopter cockpit are published in the FSTD Special Conditions for the use of Head Mounted Display (HMD) combined with a motion platform with reduced envelope (Ref. 4). Next to the regulations, research shows that VR and Mixed Reality (MR) technologies has the potential to increase training capability while decreasing costs.

According to Milgram et al. (Ref. 5), the Virtual Environment (VE) is defined as an environment in which a person is completely immersed in a synthetic world and it also can exceed the limits of physical reality. In contrast, the real world is limited by the laws of physics. Everything in between is defined as mixed reality, where the real and virtual worlds are blended together in various combinations. The next aspect to consider is not only the definition of reality, but also the underlying technology. A distinction is made between see-through displays and monitor-based displays. With see-through displays, often referred to as augmented displays or Augmented Reality (AR), the viewer can look through the display and see the real world with an overlay of virtual objects or sceneries. With this technology, awareness of the environment is very high because the viewer can perceive the real world directly. In monitor-based displays, both the virtual sceneries and the real world are shown in the display, with the real world being captured by a camera.

VR, MR and AR headsets are already in focus of different research fields like survival training, medicine, car but also airplane and helicopter simulations.

Studies have already investigated, whether VR headsets, in contrast to free-standing screens, make a difference in the perception of VR. In Ref. 6, the authors investigated the extent to

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which training for earthquake behavior with a headset and a computer screen affected presence and immersion. Here it is shown that presence and immersion are significantly increased with a headset, it provides an all-around visual representation to the viewer, while the scenery on the screen is very limited. See-through and monitor-based headsets are also of interest in medicine, for example in catheter interventions, where the physician cannot see where to insert the catheter through the body without additional visualization. In Ref. 7, see-through and monitor-based displays for medical interventions are compared. In this paper it is stated that both systems have their advantages and it depends on the application which system is suitable. While the see-through display offers an unobstructed view of the real environment, the monitor-based headset has the ability to improve the synchronization of the real and virtual worlds in order to display both images simultaneously. In Ref. 8, the use of VR is investigated, for example to evaluate the interactions in a vehicle in a simulation instead of physically driving on the road which provides a safer test environment. VR is also used to make a proof of concept for new cockpit designs. For example it is used to evaluate virtual cockpits instruments for helicopter offshore operations in confined areas (Ref. 9). Three studies have been conducted to evaluate flight decks in early phase of the design process in Ref 10. Here, a focus is also put on the pilot's interaction within the cockpit. It is concluded that VR is a valuable addition, however, there are also some limitations like when using fully virtual buttons. It leads to slower movements of the pilot and a longer time to complete the tasks. Another study compared a VR and a physical flight simulator for cockpit familiarization (Ref. 11). It has been found that the participants were able to successfully complete the check procedures in both simulators. However, some reported symptoms of simulation sickness after being in the VR flight simulator. Also the usage of current VR/ MR headsets comes with a limitation of the field of view. In Ref. 12 the effects of field of view restrictions on the head movement of rotorcraft pilots are investigated. For this purpose, the pilots flew various maneuvers to determine the head movement with different fields of view. The results show that the pilot's head movement adapts as the field of view decreases. The pilot has to move his head to see visual cues that are not visible due to the limited field of view, whereas with a larger field of view the pilot could see the visual cues in his peripheral view. In addition, MR technology for helicopter training is also a focus in research. National Aeronautics and Space Administration (NASA) and Systems Technology, Inc. already have conducted a flight test with a MR headset to train an air-to-air refueling maneuver (Ref. 13). The pilot has flown a Learjet 3 wearing the MR headset. The tanker aircraft with the probe has been simulated and displayed in the headset of the pilot. The intent has been to mitigate the risk of loss of separation during the maneuver by replacing the tanker aircraft with a simulated aircraft. Based on these in-flight experiments additional flight test have been conducted in 2015 with a Fused Reality® Flight system (Ref. 14). After a familiarization time, the pilot task has been, for example, to perform a precision landing. It has been noted that cueing issues appeared due to the limited field of view.

This paper presents the results of the evaluation of AR (see-through display), MR and VR (monitor-based display) configurations as visual system for a helicopter simulator. At first the helicopter simulation environment is described. Subsequently, the paper outlines the simulation campaign conducted to evaluate the different configurations. Thereafter, the results are discussed and finally the findings, limitation and future work are presented.

## SYSTEM OVERVIEW

This section describes the helicopter facility, which is used for the simulation study. Subsequently, the experimental setup is presented in detail. It provides an overview of the different headset which are used and a detailed description of the MR, VR and AR configurations which are compared to each other.

### Simulation Facility

The piloted study has been conducted in the Dual Pilot Active Sidestick Demonstrator (2PASD) which is a fixed-based helicopter simulation environment operated by the German Aerospace Center (DLR) in Braunschweig (Ref. 15). The simulation features two pilot seats with coupled side sticks, five TV displays for the visual system and a nonlinear flight dynamics model of an EC135 helicopter (Ref. 16). The simulator provides a flight controller for stabilization of the aircraft. The following control response types were used: For pitch and roll axes, an attitude command attitude hold (ACAH) mode is enabled. In the yaw axis, rate damping is provided by a stability augmentations system (SAS), while collective inputs translate to rate of climb (RC) commands. The 2PASD with its conventional setup (Figure 1a) serves as the baseline for the study. For the MR configuration, a green box has been built around the cockpit to use chroma key (Figure 1b). In addition, tracking stations for the head tracking and light sources have been installed.

### Experimental Setup

Besides the five TV displays, the JVC HMD-VS1D and the Varjo-XR3 Focal Edition were used as the visual system. Table 1 gives an overview over the main technical specifications of the JVC (Ref. 17), Varjo (Ref. 18) and the TV displays.

**Table 1. Overview of Visual Systems.**

| Technical Specifications | JVC | Varjo XR-3 | TV Displays |
|---|---|---|---|
| Display System | see-through | monitor-based | screens |
| Field of View (h $\times$ v) | $120° \times 45°$ | $115° \times 90°$ | $148° \times 48°$ |
| Refresh Rate | 60 Hz/ 70 Hz | 90 Hz | - |
| Weight | 1320 g | 980 g | - |

(a) 2PASD with TV Displays.

(b) 2PASD with Greenbox.

**Figure 1. Different 2PASD Setups for the Piloted Campaign(© DLR).**

The Varjo is a monitor-based headset with a field of view of $115° \times 90°$ (horizontal $\times$ vertical). For the study, the Varjo XR-3 Focal Edition is used, where the focal distance is in between 30 cm to 80 cm. The Varjo also has also focus area within the rendered image in which the image is displayed in higher resolution. This is located in the lower center and has a field of view of $27° \times 27°$. This provides a much clearer image that makes it easier to read the cockpit instruments. The JVC headset, on the other hand, has a see-through display with a field of view of $120° \times 45°$, but with an open view of 72° vertically. Both headsets are connected to the computer used for rendering via a cable. For both headsets two VIVE Base Stations (Ref. 19) were used for head tracking. In the conventional setup (CON), the 2PASD features five TV displays each with 55 inch screen diagonal, which together provide a field of view of $148° \times 48°$. In the VR, AR and MR configurations, the visual environment is rendered with Unity. Since the 2PASD does not have a complete cockpit mock-up, parts of the cockpit have been displayed in the virtual world. For the different MR, VR and AR configurations, different mixtures of real and virtual worlds are required. For the VR and MR configuration the Varjo XR-3 has been used. In the VR configuration, the whole cockpit with its interior and the pilot as avatar have been visualized (Figure 2a). In this VR configuration, the movements of the control elements and, accordingly, the arm and leg movements were animated. However, no body or hand tracking has been included. The flight tasks of the study (see section Task Definition) requires no interaction with the cockpit, as the pilots must have both hands on the controls at all times during the maneuver. For the MR configuration, the virtual cockpit has been adapted by eliminating the cockpit displays and the controls. Instead of the virtual cockpit instruments, the 2PASD cockpit mock-up is used inclusive the controls and the displays for providing the Primary Flight Display (PFD) (see Figure 2b). For this blended reality chroma key is used. Everywhere around the pilot seats, the 2PASD displays for the cockpit instruments and the controls a green box has been installed. Wherever the color green was captured by the headset's cameras, the rendered image shows VR. Everywhere else, the image of the camera is shown. No masking has been used in this MR configuration. With masking, a defined area can be specified in which only the camera image is to be displayed in order to avoid chroma key artifacts. Another very important aspect of the MR configuration is the lighting setup. The MR configuration shows the best performance when the green box and the 2PASD mock-up are brightly illuminated. Nonetheless, shadows and reflections on the displays, for example, should be avoided. The headset from JVC has been used for the AR configuration. It is implemented in such a way that the virtual reality has been only displayed in the windows of the helicopter, everything else has been transparent. As a result, if the hands are within the defined window area, they are covered by the virtual images and are no longer visible to the pilot. The TV displays showed the same visual cues, only that it has been rendered with OpenGL. The five TV Display are arranged as follows: Two displays are arranged vertically on the left and right and the fifth display is arranged horizontally in the middle (Figure 1a).

## PILOTED SIMULATION CAMPAIGN

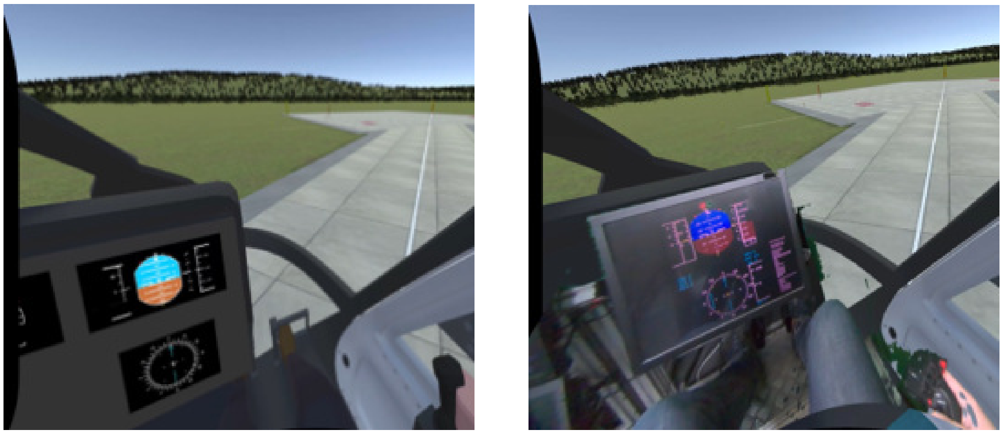
This section describes the setup of the simulation campaign, the task definition, the assessment methods employed and the experiences of the three pilots who have participated.

### Overview of tested configurations

Four different simulation setups were evaluated (see Table 2). In this study, the AR configuration represents the setup with see-through headset (JVC HMD-VS1D). The Varjo XR-3 has been used for the MR and VR configuration. The 2PASD with its conventional setup with the five TV displays is used as baseline for comparison.

**Table 2. Overview of Tested Configurations.**

| Configurations | JVC | Varjo XR-3 | TV Displays |
|---|---|---|---|
| Conventional | - | - | X |
| Virtual Reality | - | X | - |
| Mixed Reality | - | X | - |
| Augmented Reality | X | - | - |



(a) Virtual Reality Configuration. (b) Mixed Reality Configuration.

**Figure 2. Screenshots of the Piloted Campaign(© DLR).**

### Task Definition

For comparability, the pilots were asked to fly the hover and slalom maneuver based on the Mission-Task-Elements (MTE) of ADS-33 (Ref. 20). The hover maneuver should be initiated at a ground speed of 6 to 10 knots and with an altitude less than 20 ft. With the heading towards south, the pilot flies 45° relative to the heading of the helicopter to the hover point. As the pilot arrives at the hover point, they were asked to hold the hover position for 30 seconds. In Table 3 the performance parameters for the hover maneuver are shown.

**Table 3. MTE Hover Performance Parameters based on (Ref. 20).**

| Performance | Desired | Adequate |
|---|---|---|
| Attain a stabilized hover within X seconds of initiation of deceleration: | 3 sec | 8 sec |
| Maintain a stabilized hover for at least: | 30 sec | 30 sec |
| Maintain the longitudinal and lateral position within ±X ft of a point on the ground: | 3 ft | 6 ft |
| Maintain altitude within ±X ft: | 2 ft | 4 ft |
| Maintain heading within ±X deg: | 5 deg | 10 deg |

The slalom maneuver started directly with a stable flight with 60 knots. After the first gate the pilots starts to maneuver through the slalom course. Therefore, the pilots need to fly four smooth turns at 500 ft interval. The performance parameters of the slalom maneuver are in Table 4. To perform these maneuvers visual cues for each maneuver has been integrated in a MTE parkour for the scenario (Figure 3). The hover maneuver has been chosen to study, among other aspects, the effects of the visual systems on the pilot's peripheral vision. The

**Table 4. MTE Slalom Performance Parameters based on (Ref. 20).**

| Performance | Desired | Adequate |
|---|---|---|
| Maintain an airspeed of at least X knots throughout the course | 60 | 40 sec |
| Accomplish maneuver below reference altitude of X ft: | Lesser of twice rotor diameter or 100 ft | 100 ft |

slalom maneuver has been chosen because in this maneuver the helicopter moves rapidly and close to the ground, so many movements are displayed in the visual simulation that could lead, for example, to simulation sickness more quickly. Both, the hover maneuver and the slalom maneuver were flown three times in each configuration.

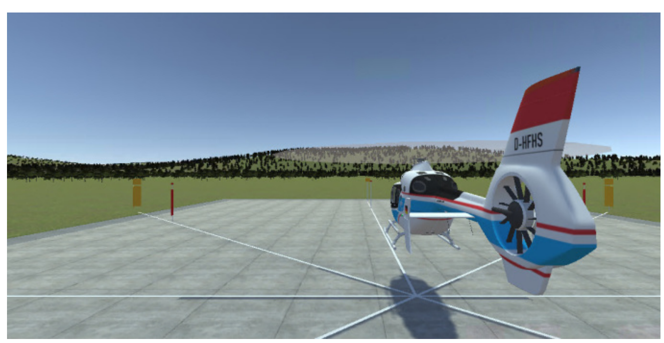


**Figure 3. Mission-Task-Elements Parcour - Visual Cues for Hover Maneuver (© DLR).**

### Assessment Methods

For the evaluation different assessment techniques have been applied. On the one side, standardized subjective assessment methods have been used: the Presence Questionnaire (PQ)

(Ref. 21) and the Simulation Sickness Questionnaire (SSQ) (Ref. 22). In addition, in the debriefing some ergonomic related questions have been asked. On the other side, for objective assessment flight data has been recorded to compare the flight performance of each pilot for the different configurations.

In the literature, the sense of presence appears to be the key factor for the evaluation of virtual environments (Ref. 23). However, there are different definitions on presence and also several questionnaires to evaluate it. The most common used questionnaire is the Presence Questionnaire (PQ) of Wittmer and Singer. They define presence as "the subjective experience of being in one place or environment, even when one is physically situated in another" (Ref. 21). The questionnaire consists of 32 questions and each question is assigned to at least one of the following factors, which have an influence on presence: Control Factors (CF), Sensory Factors (SF), Distraction Factors (DF) and Realism Factors (RF). The PQ uses a seven-point scale. Another commonly used questionaire is the questionnaire of Slater Usaoh and Steed (SUS) (Ref. 24). This questionnaire consists of six questions that aim to evaluate presence in relation to real experiences. As the PQ from Wittmer and Singer takes into account many aspects of the virtual and real environment with its extensive questions, it has been selected for the study and the SUS Questionnaire has been not used.

With the use of VR and MR headsets, simulation sickness may occur. Information from different sensory organs is used for the human sense of orientation. All sensory information are processed to determine the current position and movement in space. However, if the visual information creates a mismatch with the vestibular information, a sensory conflict occurs. If this conflict persists for some time, this can lead to simulation sickness. For the assessment of simulation sickness, also various types of questionnaires exists. The most widely used questionnaire is the SSQ (Refs. 25,26). The SSQ is a standard assessment method to quickly evaluate 16 physical symptoms which can occur during a simulation study. The participants may rate their symptoms with the different graduations none, light, moderate and severe. In addition to the subjective evaluation methods, the pilots' flight performance during the respective maneuvers is also evaluated. As the tasks for hovering and slalom flying are clearly defined, the flown maneuvers with different visual systems can be compared with each other.

### Pilot Experience

Overall, three helicopter pilots participated in the campaign (see Table 5). All were familiar with see-through and monitor-based headsets. Two of them were qualified as helicopter test pilots.

## RESULTS

In this section, the results of the piloted campaign are discussed. Firstly, the ratings of the PQ and the SSQ are presented of each pilot. Then the flight performance during hovering and slalom maneuvers achieved by pilot B with different configurations is analyzed. Due to the small number of participants in the simulation campaign and the associated low statistical significance of the results, no statistical analysis is carried out. The results represent initial findings and trend indicators.

**Table 5. Pilot Experience.**

| Pilot | Total Flight Hours | Test Pilot | HMD Experience |
|---|---|---|---|
| A | 6850 h | Yes | Yes |
| B | 850 h | No | Yes |
| C | 1500 h | Yes | Yes |

### Results of Questionnaires

In Figure 4 the Total Score (TS) of the PQ for the slalom task is shown for all pilots (Pilot A, B and C). The visualization of the PQ Score is adopted from Ref. 27, in which a grading scale is added to the PQ score in order to additionally evaluate the system in terms of usability. A grading score that is below 50 % of the PQ score is considered unacceptable, while in 10 % steps above 50 % upwards it is classified as unsatisfactory, marginal, satisfactory, very good and excellent. In this study the questions regarding audio were excluded as no audio has been used.

Pilot B and C rated the MR configuration both with a score of 5 out of 7 for the PQ Total Score (Figure 4). Both pilots commented that they preferred this configuration, since the immersion as well as the virtual world is best represented here. Also the VR configuration is rated 5 by Pilot B and 4.7 by Pilot C. Nonetheless, Pilot B stated that he prefers to see his real hands within the cockpit. The AR configuration has been rated less by Pilots B and C. All pilots stated that the small field of view of 45° horizontally of the see-through display is not sufficient to feel totally immersed. Pilot A compared it to the small windows of an airplane cockpit, while helicopter cockpits provide a wider field of view out the window. The ratings of Pilot B and C for the conventional simulation setup with the TV displays are 4.3 and 4.1, respectively. All pilots commented that the virtual world appears more three-dimensional within the headsets than on TV displays.
Pilot A also preferred the MR configuration. The feedback of Pilot A, however, is not reflected in the PQ Scores. Pilot A stated that not all of the questions in the questionnaire are particularly suitable for assessing the helicopter scenario.
The PQ is designed to measure presence in a virtual world. However, the questions are formulated in general terms. For an improved utilization of the PQ in the context of a helicopter simulation, some adjustments to the questions may be necessary. The other pilots' (Pilot B and C) PQ scores appear to be consistent with their comments.

To provide an overview, all PQ ratings are shown in a heat map (Figure 5), as no statistical analysis is possible due to the small number of pilots who have participated in the campaign. On the y-axis for all pilots all PQ Score are presented. It starts

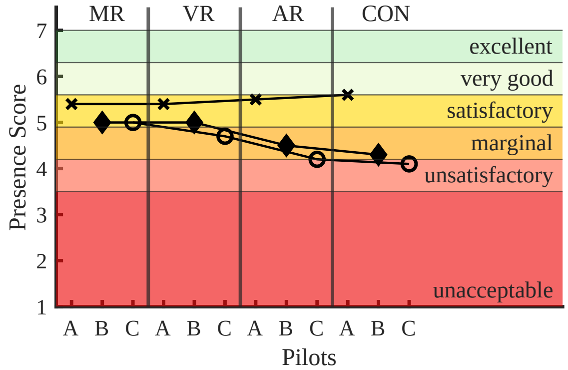



**Figure 4. PQ Total Score for all Pilots.**

with the TS of the PQ, then the Score of the CF, the SF, the DF and the RF for each pilot are shown. On the x-axis the maneuver with the corresponding configurations are listed. The color legend is equivalent to the color coding of Figure 4.
For pilot B and C, a trend can be seen in the graph that both preferred the configurations with the Varjo headset (MR and VR configuration). This can be seen as the color turns from green/light orange to dark orange/red from left to the right in diagram. The evaluation of the Realism Factor of Pilot B (RF of MR 5.4, VR 5.6, AR 4.6 and CON 4.2 ) and C (RF of MR 4.8, VR 4.2, AR 4.0 and CON 3.6) supports their statements that they felt much more part of the VE with the MR and VR configuration. Pilot B said that the immersion is higher with the Varjo headset (MR and VR configuration), because with the JVC headset (AR configuration) you also perceive more of the real world in places that should actually be overlaid by the virtual world. Although the instruments were easy to read with the see-through display, the pilot mentioned that the main task in these maneuvers is related to visual cues in the external view/virtual world and thus looking out the windows is most important. Pilot C stated that although the JVC headset has a larger field of view horizontally, it is perceived smaller compared to the Varjo headset. Also that the peripheral view is missing with the JVC headset. Also Pilot A stated that the field of view of the JVC headset is not suitable for the flight task. The PQ Score of all pilots for the MR and VR configuration are rated according the grading as satisfactory, which indicates that there is further potential for optimization. The PQ Score represents the statements of Pilot B and C quite well. Nevertheless, there is a mismatch with the feedback statements of Pilot A, which is due to the fact that the pilot found the questionnaire challenging to fill out in respect to the helicopter simulation environment. Lastly, all pilots stated that they preferred the MR setup with the Varjo the most.

The results of the SSQ have been calculated based on the formula in (Ref. 22) and are shown in Appendix A. This results for the hover maneuver of Pilot C with the MR configuration to a total score of 11 out of 236 score points (Table 6). The two other pilots A and B rated all configurations without symptoms.
Pilot C rated slight discomfort and slight dizziness (open eyes) during the hover maneuver for the MR configuration only.

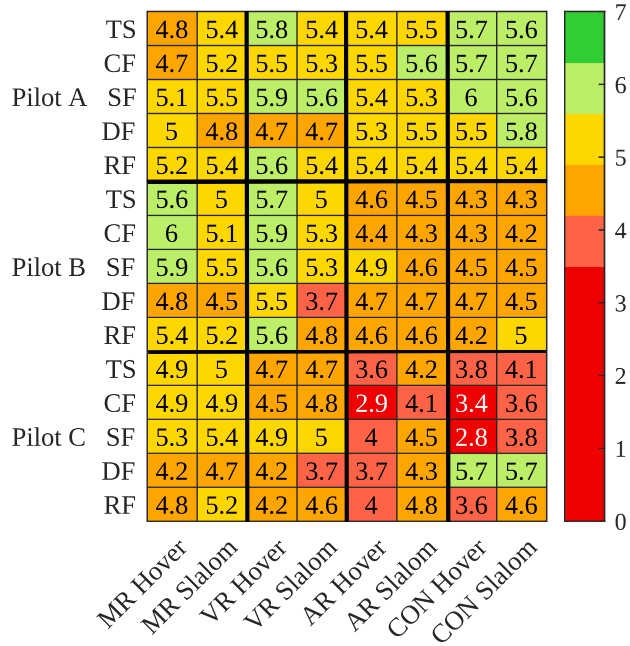



**Figure 5. Heatmap of PQ Total Score, Score of Control Factors (CF), Sensory Factors (SF), Distraction Factor (DF) and Realism Factor (RF).**

The symptoms occurred only for a short time as pilot C decelerated from the low speed flight to the hover point. Due to rapid maneuvering in the transition to hover phase, the helicopter made a roll movement which lead to fast moving images of the surroundings which were displayed in the headset. This supports the guideline of (Ref. 28) where it is stated that for VR developing it should be considered to "avoid sharp and/or unexpected camera rotations" to reduce the symptoms. Therefore, the rating is not necessarily only related to the MR configuration. These symptoms may have occurred in the other configurations if the maneuver had been performed in the same way.
All in all, within this study only within the MR configuration slightly symptoms appeared with Pilot C by performing a more dynamic maneuver, whereas the two other pilots A and B did not experience any symptoms.

**Table 6. Simulation Sickness Questionnaire Total Score of the Hover (H) and Slalom (S) Maneuver.**

| Config. | Pilot A | | Pilot B | | Pilot C | |
|---|---|---|---|---|---|---|
| | H | S | H | S | H | S |
| CON | 0 | 0 | 0 | 0 | 0 | 0 |
| VR | 0 | 0 | 0 | 0 | 0 | 0 |
| MR | 0 | 0 | 0 | 0 | 11 | 0 |
| AR | 0 | 0 | 0 | 0 | 0 | 0 |

### Results of Flight Performance

As the flight performance of all pilots show comparable results, the flight performances of Pilot B are shown as an example. Figure 6 shows the best flight performance according to the MTE performance parameters (see section Task Definition) of the hover maneuver, selected from three runs, for each configuration MR, VR, AR and CON of Pilot B. If the data is within the green area of the diagram, the pilot performend within the desired limits. The yellow area marks the adequate limits. In the two upper plots, the x- and y - position over time is visualized. Pilot B managed to stay within the desired parameters for the MR, VR and AR configuration. With the CON configuration, the performance is within the adequate limits. Pilot B has been also able to maintain the height with all configurations within the desired limits. Nonetheless, the heading varied within the adequate limits. Considering all performances of all pilots regarding the heading of the hover maneuver, the pilots were mostly challenged to maintain the heading with the CON configuration. In almost every configuration, the pilots stated that they are missing the peripheral vision within the hover maneuver. Pilot C compared the reduced field of view with his experience when wear night vision goggles. Due to the limited view, more head movements were necessary to see the visual cues. Within the MR, VR and AR configuration, additionally, the pilots experienced that with the movement of the head the image blurred briefly.

In Figure 7 the performance of Pilot B during the slalom maneuver is shown. The upper diagram shows the path (x- and y - coordinate) of the helicopter through the slalom. At the beginning, the tracks for each configuration are very similar. In the third turn, the tracks start to diverge. The reason for this could be that from the second turn on, it has been more challenging for the pilot to keep the ground speed and altitude, which can be seen in the middle graph showing ground speed and the bottom graph showing radar altitude. Pilot B has difficulties maintaining the height after the first turn with the conventional simulator setup with the TV displays. All in all, there are no significant differences in the flight performance of all pilots between the configurations, except that it is noticeable that all pilots with the conventional setup of the 2PASD had difficulties flying through the last gate. All pilots missed the last gate, sometimes very close (see Figure 7). In the other configurations, they managed to fly through the last gate much more frequently. Pilot B stated that the limited view of the TV displays proved orientation difficult. In addition, Pilot B mentioned that on the image on the TV displays appeared 2-dimensional which makes it more difficult to estimate height and velocity of the helicopter. Also Pilot C claimed that the all-round vision has been better with the MR, VR and AR configurations. Furthermore, Pilot A explained that also the TV frame obscuring parts of the view.

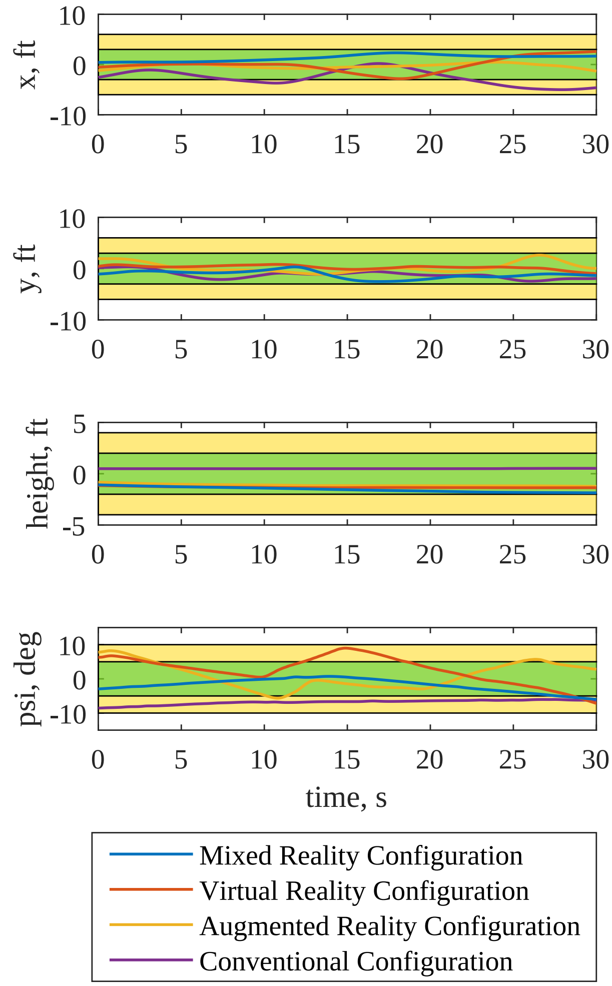



**Figure 6. Pilot B Hover Performance.**

## FURTHER FINDINGS, LIMITATIONS AND FUTURE WORK

In this section general findings are presented. It is followed by detailed description of the findings and limitations of each configuration (MR, VR and AR). In addition, possible optimization are proposed.

### General Findings

After evaluating the MR and AR configuration, the pilots were asked to read an eye chart on a letter size paper with numbers in font sizes of 10 pt to 100 pt. All pilots were able to read all lines with both headsets with the paper in their hands. They were also shown an International Civil Aviation Organization (ICAO) map on a display mounted to the left in front of the pilot. As the pilots were not able to bring the display close to them, they had to lean forward or read the display from a distance (about 75 cm). The pilot described that it has been difficult with the Varjo to read, for example, the radio frequency of an airport because the image has been slightly blurred. Another pilot said that blue signs on the ICAO map were difficult to read. Other information has been partly illegible. With the

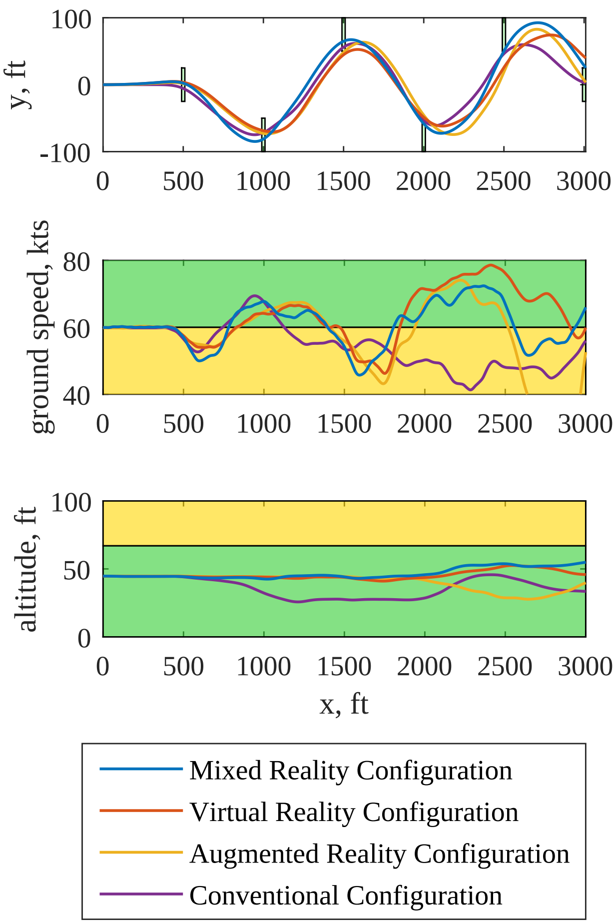



**Figure 7. Pilot B Slalom Performance.**

JVC headset in contrast, the ICAO map has been more legible. The pilots gave the feedback that the PFD has been best readable with the VR configuration. In the debriefing, all pilots have been asked if they noticed any discomfort with the headsets, especially if they experienced any discomfort due to physical symptoms like headache, pain or tension of the neck. No physical symptoms were reported. The pilots stated that the headset is similar in weight to the helmet they wear during the flight. It might would have a greater impact if the duration of the maneuver has been longer. The pilots only wore the headset for about 15 to 20 minutes before they were allowed to take off their headsets to complete the questionnaires.

**Findings of Mixed Reality Configuration**

In addition to the helicopter mock-up, the MR configuration required an MR headset, a green box, head tracking and light sources to provide an immersive experience. In the study, some image artifacts occurred due to the chroma key. There were also some reflections on the PFD due to the additional light sources. The pilots also stated that the image became somewhat blurred during rapid head movements. Another important aspect is the performance of the head tracking and the computer used for rendering. Both need to perform well to insure an image in the headset without noticeable latency. The MR configuration could be optimized by masking the cockpit area to avoid artifacts. The next step would be to investigate the interaction in a fully equipped cockpit. For helicopter flight training, it is important that the pilots can operate the systems within the cockpit. From changing the radio frequency to carrying out an emergency procedure, cockpit interaction is necessary to use the helicopter simulator for training. Furthermore, testing the headset with a motion platform could contribute to an enhanced immersive experience. All pilots stated that the MR headset in combination with a helicopter mock-up carries potential for helicopter pilot training.

**Findings of Virtual Reality Configuration**

In this study, a fully virtual cockpit is provided with an avatar that is animated according to the control inputs. In addition, the configuration also required head tracking. Since the pilots did not have to interact with the cockpit during the maneuver, the configuration is sufficient to gather initial insights. One advantage of the VR configuration in contrast to the MR configuration is, that the flights instruments were better readable. The VR configuration can be improved by animating the avatar with body tracking. Another challenge is the haptic feedback when the pilots have to interact with buttons in the cockpit. It could be beneficial to use a physical helicopter cockpit or utilize haptic gloves to enhance the immersive experience. A more detailed virtual cockpit with fully equipped flight instruments would be essential for helicopter flight training. Also, as for the MR configuration, a motion platform could contribute to improve the realism of the simulation. Pilots pointed out that the VR configuration, as the MR configuration, has the potential for helicopter pilot training, although the MR configuration felt more immersive to them.

**Findings of Augmented Reality Configuration**

For this study, the JVC headset was used for the AR configuration. The pilots reported that the virtual world did not completely overlay the real world so that the real world is much more present than the virtual world. In addition, the opinions regarding the readability of the displays spread among the pilots. The readability depended also on the brightness of the environment.

To optimize this AR configuration a closed mock-up with non reflective texture could avoid unwanted reflections and objects of the real world blended in the image. Also the illumination has an impact on the readability of the cockpit instruments. Another topic is the small vertical field of view of the JVC headset. The limited view reduced the presence ratings of this configuration. All pilots stated that the JVC headset is less immersive and less suitable for the conduction of the test maneuver compared to the Varjo headset. A motion platform for the helicopter simulator could be beneficial for this configuration as well.

## CONCLUSIONS

This paper presented the findings of a piloted campaign, where an AR, MR and VR configuration have been compared to conventional helicopter simulation at a research simulator. Three helicopter pilots have been participated in the campaign. For the subjective assessment, the PQ from Wittmer and Singer and the SSQ from Kennedy et al. have been used. In addition, the flight performance for each pilot has been evaluated. The results are regarded as first findings and trend indicators.

Within this study

- the MR configuration with the Varjo XR-3 is the preferred configurations by the pilots, closely followed by the VR configuration.
- the different configurations did not have an significant impact on the flight performance of the hover and slalom maneuver.
- more head movement is necessary to compensate for the lack of peripheral vision due to the limited field of view of the headsets.
- one out of three pilots experienced slightly symptoms of simulation sickness during one maneuver, while the other two pilot reported no symptoms.
- no physical discomfort occurred by wearing the headsets.

The findings show, that there is potential to optimize each configuration. Both headsets and the associated configurations carry the potential to be used for helicopter pilot training. The next steps will be to integrate the Varjo XR-3 headset into a full flight simulator to investigate the interaction within the cockpit.

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## APPENDIX A

**Table 7. Simulation Sickness Questionnaire and the calculation of nausea (N), oculomotor disturbance (O) and disorientation (D) based on (Ref. 22) and for calculation clarification (Ref. 29).**

| SSQ Symptoms | N | O | D |
|---|---|---|---|
| General Discomfort | 1 | 1 | |
| Fatigue | | 1 | |
| Headache | | 1 | |
| Eyestrain | | 1 | |
| Difficulty focusing | | 1 | 1 |
| Increased salvation | 1 | | |
| Sweating | 1 | | |
| Nausea | 1 | | 1 |
| Difficulty concentrating | 1 | 1 | |
| Fullness of head | | | 1 |
| Blurred Vision | | 1 | 1 |
| Dizzy (eye open) | | | 1 |
| Dizzy (eye closed) | | | 1 |
| Vertigo | | | 1 |
| Stomach awareness | 1 | | |
| Burping | 1 | | |
| Total | [1] | [2] | [3] |

N = [1] x 9.54
O = [2] x 7.58
D = [3] x 13.92
TS = ([1]+[2]+[3]) x 3.74

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