Night Vision Goggle Simulation in a Mixed Reality Flight Simulator with Seamless Integrated Real World

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Night Vision Goggle Simulation in a Mixed Reality Flight Simulator with Seamless Integrated Real World

The thesis work carried out in Medieteknik

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Abstract

Night vision goggles (NVGs) are optical devices used to enhance human vision at low light conditions such as nighttime. The image seen through the goggles is brightened but with the consequence of introduced visual limitations and illusions. Because of this, fighter pilots need to undergo proper training with such equipment before operating with them in real-life. An NVG simulation within a Mixed Reality (MR) flight simulator can in theory be used to build the skills needed and directly translate them into real life. In this thesis, an NVG effect was added to a video see-through camera feed (VST) such that a whole NVG simulation could be experienced in an MR flight simulator. Furthermore, a method to seamlessly integrate the VST into the nocturnal virtual world was proposed. By conducting a semi-structured interview with an NVG expert, the experienced realism, presence, and training value of the implemented effects were measured. A thematic analysis of the gathered interview data provided insight into the most important themes regarding NVG simulations within an MR flight simulator. These together with related research were used to reach conclusions such as there exists a training need for simulating realistic light differences between NVGs and a low-lit cockpit, Reinhard’s color transfer algorithm with CIELAB color space is a viable method to seamlessly integrate the VST into the nocturnal virtual world, and finally, the vertical field-of-view of the head-mounted display must allow the user to glance down into the cockpit with a head level to the horizon for tactile training.
Acknowledgments

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Using night vision goggles (NVGs) comes with visual limitations and illusions that are difficult to interpret correctly. This is why fighter pilots need to undergo proper training with such equipment before using it in real-life situations that call for expert execution. In theory, there is a potential to use simulators as a tool for fighter pilots to practice with NVGs without any hazards and then translate the skills to the real world\cite{1,2}. At Concept and Marketing Simulators at Saab Aeronautics, an NVG simulation has been implemented in a virtual reality (VR) flight simulator, but it remains to be seen how it should be implemented in their mixed reality (MR) flight simulator. The distinction between the VR and MR flight simulator lies in the fact that in the MR flight simulator, elements from the real world are integrated into the virtual world such as parts of the real cockpit and the pilot’s own body. This creates a question of how the real world should be seamlessly integrated into the virtual world and how it will affect the realism of an NVG simulation.

1.1 Background

The MR flight simulator used during this thesis was made to replicate the experience of flying a fighter jet. The user sits in a simple setup and experiences the real and virtual world as one by wearing a head-mounted display (HMD). To simulate NVGs, an effect replicating NVG characteristics is post processed into the view.

1.1.1 The MR Flight Simulator

The MR flight simulator used during this thesis is designed together with the Varjo XR-3\cite{3} HMD and Unreal Engine 5.2 (UE5)\cite{4}. The HMD provides a stereoscopic display with a horizontal field-of-view of 115° at a refresh rate of 90 Hz. Two cameras, one for each eye, are mounted at the front of the HMD. They record in real time a video see-through camera feed (VST) at 90 Hz that can be mixed with the virtual world by using masking. Masking is when an object in the virtual world is chosen to act like a window to the real world where the user sees the direct camera feed. The VST is never read into UE5 instead an alpha value layer within UE5 decides what should be see-through\cite{5}. This method is used to create the MR flight simulator. Polygon meshes for various parts of the cockpit are used as masks, replacing them with the real-life parts of the cockpit that the user sits in as well as the user’s body itself.
The result is an experience where the user can navigate the real-life cockpit while also being submerged in the computer-generated world. However, this method might combine the two video streams but it does not seamlessly integrate them. The dissimilarity between the color characteristics becomes apparent when the virtual world simulates a nocturnal scene and the VST is recorded in a brightly lit room. By addressing the VST’s color and brightness it could be seamlessly integrated it into the virtual world.

1.1.2 The NVG Effect

The NVG effect was first implemented for VR and in this thesis will be implemented for MR. The implementation for the VR flight simulator has the standard NVG characteristics of being chromatic green and grainy, has halo effects, reflections of chlorophyll, and a reduced resolution in near objects. The field-of-view is limited in a circular fashion, typical for binoculars. This imply that the peripheral vision is occluded by the binoculars, and is therefore set to black. The lower bottom of the view is left as visible area to simulate looking under the goggles and down at the flight instruments. We call this area the look down effect. The layout of the NVG effect can be seen in figure 1.1. When the NVG effect is active in the MR flight simulator before any work, the VST is left without the effect, see figure 1.2a. Figure 1.2b visualizes with colors the NVG layout and the VST within the HMD. The hand, lined with white, is a part of the VST and overlaps the NVG area which is lined with blue. The hand should adapt the NVG color when within this area but does not. Moreover, the wrist and half of the area for the wide-area display should be occluded and in other words, adapt the black color.

1.2 Aim

The aim of this thesis is to propose a method to address the colors and brightness of the VST to suit the virtual world’s nocturnal scene. The NVG effect will be added to the VST such that both video streams within the MR flight simulator have the same NVG characteristics. The MR flight simulator with and without the applied NVG effect will be analyzed to evaluate if the two streams can be perceived as part of the same world when the VST is seamlessly integrated. Finally, the effects will be used to evaluate the experienced realism, presence, and training value from the perspective of a fighter pilot to find what is most important in the design of an NVG simulation within an MR flight simulator.

1.3 Research questions

- How does the light setting in the simulator room affect the overall experience of an NVG simulation within an MR flight simulator and is it a crucial factor to consider when implementing it?
- How can the color and brightness of a VST captured in a bright room be addressed to seamlessly integrate it into a virtual world that simulates a nocturnal scene?
- What is important to include in an NVG simulation experienced in an MR flight simulator for it to reflect real life and have a training value for fighter pilots?

1.4 Delimitations

The implemented NVG effect applied to the VST will have the same NVG characteristics as the NVG effect implemented for the virtual world. It will not be implemented for dynamic foveated rendering. No new visual limitation or illusion that occurs during the use of NVGs
will be added and the NVG effect within UE5 will remain unchanged. The method used to
seamlessly integrate the VST will only be tested for nocturnal scenes.

Figure 1.1: Illustration of the NVG effects layout. The green circle is where the user looks through the goggles. Limited field-of-view is the occluded peripheral vision because of the goggles. The look down effect is the area where the user can look down under the goggles.

Figure 1.2: Two images showing the NVG effect active within the MR flight simulator before any work. (a) show the original view and (b) has been edited to visualize the various parts of the effect.
To design a realistic night vision goggle (NVG) effect, it is essential to comprehend NVG technology and its image characteristics. Also, it is good to know how NVGs are used, and the training pilots need to go through to use them. To understand the reasoning behind specific decisions during the implementation of the NVG effect for the video see-through camera feed (VST) as well as the seamless integration of the VST, an understanding of development for mixed reality (MR) is needed. This background information is provided within this chapter. Lastly, an overview of related work regarding NVG simulations is provided.

2.1 Night Vision Goggles

Night vision goggles (NVG) are optical devices used to enhance human vision at low light conditions such as nighttime. An objective catches incoming light rays, photons, and directs them to an image intensifier tube within the goggles. The first thing the photons hit within the tube is a photocathode. This material is sensitive to the lower range of visible light and infrared light and as a result, emits electrons when hit by this kind of light rays. As a consequence, a level of noise is created at this stage. The emitted electrons are directed to a small conductive glass disk called a microchannel plate. This disk is covered by tiny holes, fiber optics, that the electrons pass through. Each time an electron bounces against a wall it multiplies, creating a second electron that behaves in the same way. The multiplication is powered by an added voltage from a battery. The optical fibers preserve the enhanced electrons’ pattern, which is then finally guided to a phosphor screen at the back of the image intensifier tube. This screen turns the enhanced electrons back into photons which results in a monochromatic image with a color depending on the kind of phosphor used, usually the result is green. The image is magnified and viewed by the user with an ocular lens. An illustration of NVG technology can be seen in figure 2.1.

In aviation, pilots use NVGs by having them mounted on their helmets such that they can be flipped down to cover the eyes. A small gap between the goggles and the eyes allows the pilot to glance around the cockpit without night vision. We call this the look down effect.
2.1. Night Vision Goggles

Figure 2.1: Illustration of NVG technology. The incoming light, photons, hits the photocathode creating electrons. The electrons are multiplied, enhanced, by traveling through the microchannel plate and then converted back to photons by hitting the phosphor screen. The observed monochromatic image is viewed through an ocular lens.

2.1.1 Important NVG Image Characteristics to Replicate in Simulations

The characteristics of an NVG image diverge from the same scene observed with the naked eye. According to Kooi and Toet (2005)[1], the most important characteristics to replicate when creating an NVG simulation are:

- **Reduced resolution and contrast**
  According to Brickner (1989), the resolution and contrast of the night vision image depend on the design and quality of the components within the NVGs and also the characteristics of the scene. Low ambient lightning will result in low resolution because of the overpowering noise created by the photocathode[7]. Low-contrast scenes such as fog-covered landscapes will lose details even if they could be correctly interpreted by the naked eye. In other words, the area loses even more contrast making objects indiscernible[1].

- **Limited field-of-view**
  NVGs used by pilots are designed as binoculars and have a standard circular field-of-view around 40°.

- **Absence of color**
  Due to NVGs being less sensitive to the upper part of the visible light spectrum, objects with colors such as green/blue will sometimes not show on the resulting image. For example, a spotlight emitting a blue-colored light would not be visible through NVGs.

- **High reflection of chlorophyll**
  Chlorophyll in plants absorbs visible light for photosynthesis but also reflects near-infrared light. The photocathode within NVGs is most sensitive to the near-infrared light making vegetation shine bright in the resulting night vision image.

- **Shading**
  If objects within the shade are not well-lit, they will not show in the night vision image even if visible to the naked eye. This is due to NVGs not being good at recreating low-contrast scenes.

- **Halos**
  In a night vision image, light sources become surrounded by bright circles of light called
halos, also called blooming. Brickner (1989) means that this effect can sometimes become bright enough that the remaining image loses contrast due to the drastic difference between the bright light and the remaining colors which flattens\[7\].

Martin and Howard (2001) further add that the viewing distance should be around 100 nautical miles where 30 nautical miles is the minimum\[2\]. According to Brickner (1989), the focal distance on helmet-mounted ANVIS, aviators night-vision-imaging system, is usually set to infinity\[7\].

### 2.1.2 Training with NVGs

Because of the large difference between NVG imagery and the naked eye, pilots must practice with the goggles before operating with them. According to Martin and Howard (2001), an NVG user needs to be taught a basic understanding of the device such as operational procedure, proper scanning and cross-check technique and the overall altered task management and tactics. The goggles are often adjusted such that the focal point is set to infinity which requires the pilot to glance under the goggles into the cockpit to read the flight instruments. The regular scanning pattern is therefore changed to accommodate this which changes the overall work procedure within the cockpit. The different luminance levels in the NVG image compared to the cockpit itself, even if turned down low, require the eyes to adapt. The time it takes depend on age and the acuity required to read a certain instrument but usually it takes several seconds\[2\].

### 2.2 Extended Reality and Head-Mounted Displays

Extended reality is an umbrella term for extending or enhancing the perceived reality with computer-generated imagery. The technologies that make the extended reality continuum are Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR). VR immerses the user fully by submerging them in a fully computer-generated simulation. AR lets the user experience the real world but enhances it with bits of computer-generated elements. MR allows the user to experience a world where reality and the virtual reality are seamlessly integrated\[8\]. Head-mounted displays (HMDs) are the medium that lets the user experience extended reality. The housing contains a liquid crystal display and an optical system for displaying the image to the user’s eyes. MR requires a captured video feed to create a mix between the real and virtual world. Video see-through HMDs have cameras integrated into the housing and are used for this purpose\[9\]. We call the captured video, a video see-through camera feed (VST) and it is integrated into the virtual world.

#### 2.2.1 Foveated Rendering

For all extended reality experiences, there is a need for displays that can provide a wide field-of-view in high resolution and frequency. This requires high-rendering resources that are seldom met by the hardware. To save computation time, foveated rendering is used which uses the human visual system to its advantage. Only a small fraction of the human visual system called the foveal region allows a person to see in fine detail. This region is placed at the center of the eye which covers about 2.5° of the field-of-view. The remaining regions are called the peripheral vision where the visual acuity, a measure of the ability to observe fine details, drops off drastically. The foveated rendering method saves a lot of computational time by rendering the peripheral region in lower detail and it works because the human visual system will not perceive the quality of the image as less provided that the foveal region follows the gaze. Dynamic foveated rendering is when the user’s gaze position is tracked in real-time and the focal area is adjusted to said position. If gaze tracking is not available, static

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\[\text{footnotes}\]


foveated rendering can be used where the gaze position is estimated which is usually the center of the screen[10].

2.2.2 Presence

The term Presence in VR has many interpretations and according to Murphy and Skarbez (2020), the prevailing ones are the sense of Being there and Nonmediation. Being there refers to the feeling of being within the virtual environment while Nonmediation refers to not noticing the technology as part of the experience [11]. We will be using the term in the sense of Being there in an MR experience.

2.2.3 Developing for Mixed Reality HMDs

Multiple platforms can be used to develop MR projects and Unreal Engine is one of them. There are also multiple HMDs provided by different companies on the market and to create an industry standard for developing to them, OpenXR was founded. With the OpenXR API, Unreal Engine can be used to create MR projects for a wide set of HMDs that support the API[12][13]. Due to openXR not having implemented support for VST-post processing shaders, the VST does not blend with any post processing effect in Unreal Engine 5.2 (UE5)[14].

2.3 Related Work

For perspective, it is important to know about prior work that is related to the aim of this thesis. There have been earlier implementations of NVG simulations within the extended reality continuum and their previous work can set the foundation for our work.

2.3.1 NVG Simulation in Chroma-keyed Flight Simulator

Beilstein (2003) examined the potential of using a chroma-keyed AR environment, also called chrAVE, as an NVG training device. He also investigated if the NVG simulation needed to be based on physical light calculations. The ChrAVE used blue chroma-keying for composing the foreground, the real-life cockpit, together with the virtual world. The AR scene was experienced through an HMD with a camera mounted on top that captured both the cockpit and the blue material. The NVG simulation was made by making calculations based on the position and angle of the moon, the atmospheric conditions, the geographical location, and the time of day. The NVG characteristics that the NVG effect included were the chromatic green color, fixed pattern, variable noise, light blooming, obscuration, and scintillation. The user tests made with military helicopter pilots showed that having physics-based calculations to achieve the NVG imagery had the potential to be used in training. The future work highlighted that some pilots had difficulty looking down into the cockpit through the head-mounted camera. In real-life they would look under the goggles into a low-lit cockpit and some found it difficult to adjust their regular scanning technique. Beilstein also recommended that a viable method for creating a dark cockpit should be found as it would lead to higher fidelity as well as a greater insight into more NVG training possibilities. For the ChrAVE, back-lit chroma-key material could be a possible method [15].

2.3.2 NVG Simulation in VR Flight Simulator

The NVG effect we will implement for MR was originally built by Palmqvist (2020) for a VR flight simulator that used Unreal Engine 4. The NVG characteristics included in the effect were the monochromatic green, limited field-of-view, reduced resolution because of grain and the set focal point, blooming, and the look down effect. Post processing effects in Unreal
Engine 4 were used to achieve the NVG characteristics and the result showed that it performed with a frame rate matching the industry standard [16]. The NVG effect we used in the MR flight simulator had evolved since then and the values used by Palmqvist to implement the NVG characteristics were therefore not used in this thesis.
The NVG effect would most likely be used during a simulation with a nocturnal scene and the VST should have the same color characteristics if the two streams are to be perceived as one. The light sources in the simulator room could be turned off during use to counter this problem but that would instead result in a dark video feed that cannot be correctly displayed in MR due to the lack of information. Some light is therefore required, and to create a seamless integration, the VST could instead simulate darkness. In this chapter, Reinhard’s color transfer algorithm[17] was preliminarily assessed as a method to change the color characteristics of a VST to seamlessly integrate it into a nocturnal scene.

3.1 Different Methods for Simulating Darkness in a VST

There are various approaches for addressing the VST and one of them is to use the camera settings provided for the Varjo XR-3 headset. The functionality is meant to be used as a way to compensate for bad lighting in the physical room and the settings should be adjusted each time the light conditions change. For the cameras to perform at best it is recommended that the room is well and evenly lit and it is for this reason the lights in the simulator room can not be simply turned off. While it’s technically possible to change the brightness, exposure, and ISO of the camera to simulate darkness this also has a large drawback which would be a substantial loss in image quality[18]. Another method that could be used is a movie technique called Day for Night. Most cameras perform badly during low lighting conditions and as a consequence, the night scene has to be shot in bright conditions such as daylight. To simulate a night scene the cameras record with filters and by using video post processing, the colors are turned dark and cold. As a result, the scene looks nocturnal where the sunlight can be interpreted as moonlight[19]. This technique is useful when the characteristic of the scene is known but it is less useful in real time since the scene’s overall brightness and hue might continuously change. In the MR flight simulator, the positioning of the aircraft will continuously change, and therefore also the light setting. This is why Day for Night is not a viable method to seamlessly integrate the VST into the virtual world. A method that can adapt the brightness and colors of the VST depending on the virtual world without prior knowledge of its characteristics is Reinhard’s color transfer algorithm[17].
3.2 Reinhard’s Color Transfer Algorithm

Reinhard et al. (2001) created a color transfer algorithm that uses statistical analysis to transfer the color traits of a source image onto a target image. The result is a synthetic image with the composition of the target image but with a color theme from the source image [17]. The algorithm can theoretically turn day images into night images without prior knowledge of the color characteristics. If each frame in the VST is used as the target image and the virtual world as the source image, the algorithm could be used to seamlessly integrate the two continuously for any light setting in the virtual world. The algorithm can be summarized in four steps:

1. Convert the source and target image from RGB color space into \( l\alpha\beta \) color space.
2. Calculate mean and standard deviation for each channel separately for both source and target image.
3. Perform color correction.
4. Convert the synthetic image back into RGB color space.

3.2.1 \( l\alpha\beta \) Color Space

Reinhard et al. (2001) describes how the source and target image are converted from RGB color space into a color space called \( l\alpha\beta \)[17]. RGB is an additive color model where modifying one channel affects the other channels significantly whereas \( l\alpha\beta \) has little dependencies between its three channels viewed as orthogonal axes. \( l\alpha\beta \) is designed to replicate the human visual system where \( l \) is brightness, \( \alpha \) is yellow-blue and \( \beta \) is red-green. The RGB color space is first converted into LMS cone space which is done in two steps. The values are first converted into XYZ tristimulus values, see formula (3.1), where the conversion is device-independent. From XYZ to LMS space, the matrix in formula (3.2) is used. To save one operation the two matrices are combined such that RGB can be directly converted to LMS, see formula (3.3). Each data point within the images is converted from RGB to LMS using this matrix.

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
= \begin{bmatrix}
0.5141 & 0.3239 & 0.1604 \\
0.2651 & 0.6702 & 0.0641 \\
0.0241 & 0.1228 & 0.8444
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\quad (3.1)
\]

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
= \begin{bmatrix}
0.3897 & 0.6890 & -0.0787 \\
-0.2298 & 1.1834 & 0.0464 \\
0.0000 & 0.0000 & 1.0000
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\quad (3.2)
\]

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
= \begin{bmatrix}
0.3811 & 0.5783 & 0.0402 \\
0.1967 & 0.7244 & 0.0782 \\
0.0241 & 0.1288 & 0.8444
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\quad (3.3)
\]

The data points are then turned into logarithmic space to compensate for the skew that is introduced during the conversion, see formula (3.4)

\[
L = \log L
\]
\[
M = \log M
\]
\[
S = \log S
\quad (3.4)
\]

The axes are then decorrelated by turning them into an orthogonal system, \( l\alpha\beta \) color space, see formula (3.5)

\[
\begin{bmatrix}
l \\
\alpha \\
\beta
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{\sqrt{3}} & 0 & 0 \\
0 & \frac{1}{\sqrt{6}} & 0 \\
0 & 0 & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & -2 \\
1 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
\quad (3.5)
\]
After this operation, the images are ready for the next step in the color transfer algorithm. With formula 3.6 and 3.7, the resulting synthetic image can be turned back into RGB color space for viewing.

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & -1 \\
1 & -2 & 0
\end{bmatrix} \begin{bmatrix}
\frac{\sqrt{3}}{3} & 0 & 0 \\
0 & \frac{\sqrt{6}}{6} & 0 \\
0 & 0 & \sqrt{2}
\end{bmatrix} \begin{bmatrix}
I \\
\alpha \\
\beta
\end{bmatrix}
\]

(3.6)

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} = \begin{bmatrix}
4.4679 & -3.5873 & 0.1193 \\
-1.2186 & 2.3809 & -0.1624 \\
0.0497 & -0.2439 & 1.2045
\end{bmatrix} \begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
\]

(3.7)

### 3.2.2 Mean and Standard Deviation

The mean intensity value \( \mu \) is gained by summing the pixel values of an image \( I \) of size \( M \times N \) and dividing by the number of values, see formula 3.8. The standard deviation \( \sigma \) is acquired by using formula 3.9\[20\]. The value is used to measure how far a group of data points varies from the mean. If the standard deviation is small, the data points are close to the mean and if it is larger, they are more dispersed\[21\]. Therefore, the standard deviation calculated for each channel for the source and target image conveys the amount of variation in the colors and brightness.

\[
\mu = \frac{1}{MN} \sum_{u=1}^{M} \sum_{v=1}^{N} I(u, v)
\]

(3.8)

\[
\sigma = \sqrt{\frac{1}{MN} \sum_{u=1}^{M} \sum_{v=1}^{N} [I(u, v) - \mu]^2}
\]

(3.9)

### 3.2.3 Color Correction

The color correction is made by first removing the target images mean from the target images data points for each channel separately \[17\]. See formula 3.10, note that the variable names differentiate from the original conference paper.

\[
I^* = I_{\text{target}} - \mu_{\text{target}, I}
\]

\[
\alpha^* = \alpha_{\text{target}} - \mu_{\text{target}, \alpha}
\]

\[
\beta^* = \beta_{\text{target}} - \mu_{\text{target}, \beta}
\]

(3.10)

The data points are then scaled with a factor for each channel separately. Reinhard together with varying researchers wrote two conference papers on the color transfer algorithm, the original conference paper from 2001\[17\] and another from 2004 that further developed it to work better for a continuous video feed\[22\]. The color correction method was described similarly in both conference papers but with one discrepancy. The numerator and denominator of the scaling factor had switched places. In the original conference paper the target’s standard deviation was divided by the source’s standard deviation whereas, in the conference paper from 2004, the source’s standard deviation was divided by the target’s standard deviation. This discrepancy was investigated in the preliminary assessment of the color transfer algorithm and it was deemed that the correct order was within the conference paper from 2004. The formula 3.11 shows how the factor is calculated for each channel separately and multiplied with the result from formula 3.10. The mean calculated from the source image is then added to each channel of the data points, see formula 3.12. When the data points have been turned back into RGB, using formula 3.6 and 3.7, the resulting synthetic image can be viewed.
3.3 Preliminary Assessment of the Color Transfer Algorithm

A preliminary assessment of the color transfer algorithm’s usability was conducted using MATLAB. In the MR flight simulator, the masked areas were the throttle, joystick, area for the wide-area display, and the pilot’s own body. The remaining parts of the view, the nocturnal scene surrounding the aircraft and the cockpit itself, would act as the reference for the color correction of the VST. Source images with these color characteristics was therefore used in the tests to ensure that the algorithm would show potential for this purpose. In some cases, the resulting images had too strong contrast and saturation. According to Reinhard et al. (2001), the quality of the result depends on the similarity of the composition in the two images. For example, if the target image contained more grass and the source image contained more sky, the result would be less satisfactory. The solution would be to extract multiple swatches and use their statistics as clusters in the color correction step [17]. This might have been a solution to the less satisfactory results. However, it was not implemented since it would require a method in itself to separate the images in areas according to appropriate color characteristics. The color transfer algorithm was therefore used in its simpler form. To investigate if it was possible to remedy the unsatisfactory results, the tests were also made with RGB converted into CIELAB instead of \( l_{\alpha\beta} \).

### 3.3.1 CIELAB Color Space

CIELAB or \( L^*a^*b^* \) is a color space created to linearize color representation according to the human visual system [20]. \( L^* \) represents luminosity and is within the range of \([0,100]\) where 0 is black and 100 is white. \( a^* \) represents the value for green-red and \( b^* \) represents the value for blue-yellow. Both are typically within the range of \([-127,+127]\) but could extend beyond. The three values for each channel are relative to the reference white point \((X_{ref}, Y_{ref}, Z_{ref})\) which is usually set as the standard illuminant D65 and also used in this implementation, \((X_{ref} = 0.95047, Y_{ref} = 1.0, Z_{ref} = 1.08883)\). The conversion is made in floating point values and RGB values within the range \([0,255]\) are therefore divided by 255 to be within the range of \([0,1]\). It is also important to note that the conversion needs to be done with linear RGB color mapping. If the values are given in sRGB they need to be converted with formula (3.14) where \( c \) is each separate sRGB color value. To turn into gamma-corrected values again, sRGB, use formula (3.13). To convert RGB into CIELAB color space the values are first converted into XYZ tristimulus values with formula (3.15). To convert them back, the formula (3.16) is used.

\[
f_1(c) = \begin{cases} 12.92 \cdot c & \text{for } c \leq 0.0031308, \\ 1.055 \cdot c^{1/2.4} - 0.055 & \text{for } c > 0.0031308 \end{cases}
\]

\[
f_2(c') = \begin{cases} \frac{12.92}{c'} & \text{for } c' \leq 0.04045, \\ \left(\frac{c' + 0.055}{1.055}\right)^{2.4} & \text{for } c' > 0.04045 \end{cases}
\]
3.3. Preliminary Assessment of the Color Transfer Algorithm

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.35758 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$ (3.15)

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.240479 & -1.53715 & -0.498535 \\ 0.212671 & 1.875992 & 0.041556 \\ 0.055648 & 0.204043 & 1.057311 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$ (3.16)

The XYZ tristimulus values are then converted into CIELAB using formula 3.17 with 3.18, 3.19, 3.20, 3.21.

$$L^* = 116 \cdot Y' - 16$$
$$a^* = 500 \cdot (X' - Y')$$
$$b^* = 200 \cdot (Y' - Z')$$

$$X' = f_1\left(\frac{X}{X_{ref}}\right)$$
$$Y' = f_1\left(\frac{Y}{Y_{ref}}\right)$$
$$Z' = f_1\left(\frac{Z}{Z_{ref}}\right)$$ (3.18)

$$f_1(c) = \begin{cases} c^{1/3} & \text{for } c > \epsilon, \\ \kappa \cdot c + \frac{16}{116} & \text{for } c \leq \epsilon \end{cases}$$ (3.19)

$$\epsilon = \left(\frac{6}{29}\right)^3 = \frac{216}{24389} \approx 0.008856$$ (3.20)

$$\kappa = \frac{1}{116} \left(\frac{29}{3}\right)^3 = \frac{841}{108} \approx 7.787$$ (3.21)

The values can be converted back into XYZ tristimulus values using formula 3.22 with 3.23.

$$X = X_{ref} \cdot f_2\left(\frac{L^* + 16}{116} + \frac{a^*}{500}\right)$$
$$Y = Y_{ref} \cdot f_2\left(\frac{L^* + 16}{116}\right)$$
$$Z = Z_{ref} \cdot f_2\left(\frac{L^* + 16}{116} - \frac{b^*}{200}\right)$$ (3.22)

$$f_2(c) = \begin{cases} c^3 & \text{for } c^3 > \epsilon, \\ \frac{c^3 - 16}{\kappa} & \text{for } c^3 \leq \epsilon \end{cases}$$ (3.23)

The color correction step with CIELAB as the color space was done with $L^*$ instead of $l$, $a^*$ instead of $a$ and finally, $b^*$ instead of $b$.

### 3.3.2 Test Cases

Two cases were tested. The first was how the algorithm would perform when the source image was a nature image seen at nighttime and the other when the source image was a picture taken within a cockpit with the flight instruments lit at night. The target image used was always a picture of a hand with an arbitrary background reflecting an uncontrolled environment, see figure 3.1. During the research of the color transfer algorithm, a discrepancy in one of the formulas was found when cross-referencing the original conference paper from 2001[17] and a continuation from 2004[22], both written by Reinhard together with varying
3.3. Preliminary Assessment of the Color Transfer Algorithm

Researchers. The formula [3.11] used in the color correction step showed two versions where the order of the numerator and denominator had been switched. To decide which order to use in the future, formulas [3.24] and [3.25] were both tested in the color correction step.

\[
factor = \frac{\sigma_{\text{source}}}{\sigma_{\text{target}}} \quad (3.24)
\]

\[
factor = \frac{\sigma_{\text{target}}}{\sigma_{\text{source}}} \quad (3.25)
\]

Figure 3.1: The target image used in the preliminary assessment of the color transfer algorithm.

3.3.3 Result

The two cases were tested and are shown in this section. The target image used during each test can be seen in figure 3.1. Each figure contains the result images for each combination of color space and formula variation with the used source image included, see figure 3.2, 3.3, and 3.4.

3.3.4 Discussion

The algorithm combined with formula [3.25] the formula from the original conference paper from 2001, and laβ color space can be disregarded with confidence as the results are too dark, see figure 3.2c, 3.3c and 3.4c. The same formula used together with CIELAB is a little more believable but comparing it to its adversary, especially in result 3.3, shows that formula 3.24 is preferred.

The images generated with the laβ color space sometimes resulted in unwanted effects such as too strong contrast and saturation. It could be debated that it performed better than CIELAB when the source images in figure 3.3a and 3.4a were used but the color space also showed its unpredictability in figure 3.2c. A quick look at the images generated by using CIELAB, figure 3.2b, 3.3b and 3.4b, show consistent results with believable colors. Figure 3.2b might have resulted in more red hue than is believable but it would still be preferred to the result generated with laβ, see figure 3.2c. An important question to ask is for what purpose the final implementation will be used. The MR flight simulator will be used for training purposes and it will furthermore be experienced in an HMD. It is therefore important that the resulting image in the HMD does not strain the eyes of the user because of a strong color difference between the real and virtual world. For training purposes, the pilot is supposed to
3.3. Preliminary Assessment of the Color Transfer Algorithm

(a) Source image

(b) Result using CIELAB and formula 3.24

(c) Result using $l\alpha\beta$ and formula 3.24

(d) Result using CIELAB and formula 3.25

(e) Result using $l\alpha\beta$ and formula 3.25

Figure 3.2: Result from testing the color transfer algorithm. The source image depicts a lake seen at nighttime with aurora borealis in the sky.

... work where the hands are an instrument to interact with the various parts of the cockpit. It is therefore important that the VST does not unexpectedly have intruding colors that might distract the pilot from the simulation. If the simulator is to be used in almost any room, it is also important that the color correction of the VST does not act unpredictably as the $l\alpha\beta$ color space has shown to be. With this reasoning, it is a much safer choice to use the color transfer algorithm with CIELAB as it leads to less unpredictability in the result. Moreover, in a conference paper written by Reinhard and Pouli (2011), they reached the conclusion that CIELAB with illuminant E as reference white point in average performed best for varying images when compared to multiple color spaces\[23\]. Since the conference paper was discovered at later stages of the thesis, D65 was still used as the reference white point in the implementation but it further strengthened the decision of using CIELAB as the color space.

The preliminary assessment proved that the color transfer algorithm showed to have potential for the intended purpose, and it is for this reason that the algorithm together with CIELAB and formula 3.24 was used in the implementation of the seamless integration between the real and virtual world.
3.3. Preliminary Assessment of the Color Transfer Algorithm

(a) Source image
(b) Result using CIELAB and formula \(3.24\)
(c) Result using \(l\alpha\beta\) and formula \(3.24\)
(d) Result using CIELAB and formula \(3.25\)
(e) Result using \(l\alpha\beta\) and formula \(3.25\)

Figure 3.3: Result from testing the color transfer algorithm. The source image depicts a dark scene with only the moon as a light source.
3.3. Preliminary Assessment of the Color Transfer Algorithm

(a) Source image

(b) Result using CIELAB and formula 3.24

(c) Result using $l\alpha\beta$ and formula 3.24

(d) Result using CIELAB and formula 3.25

(e) Result using $l\alpha\beta$ and formula 3.25

Figure 3.4: Result from testing the color transfer algorithm. The source image depicts a low-lit cockpit at dawn with its flight instruments lit.
4 VST Post Processing and Seamless Integration between the Real and Virtual World

The seamless integration between the real and virtual worlds and the NVG effect had both in common that it would require modifications of the VST. This would naturally be done with post processing shaders within UE5 but due to OpenXR not having support for VST-post processing shaders, see section 2.2.3, this had to be implemented with an additional application. To implement the seamless integration between the real and virtual world with the color transfer algorithm, see section 3.2, the UE5 project and the application also needed to be able to communicate.

4.1 The VST Post Processing Tool

The requirement for the VST post process application was that it needed to allow toggling effects in real time and complement the final view in the HMD. Varjo had previously created a post processing tool with their experimental native developer asset Varjo Experimental SDK for Custom Engines[24]. The application written with C++ had a post process API that let the user toggle implemented effects in real time. This was done by pre-defining the effects in an HLSL shader and updating them with parameters that could be changed within a GUI. To post process the VST and complement the resulting view in the HMD, the additional application could be run in the background. This worked because of the predefined alpha layer that was defined within UE5. The layer set pixels within the virtual world to be see-through directly to the VST, see section 1.1.1.

4.2 Implementation of the Seamless Integration between the Real and Virtual World

In the preliminary assessment of the color transfer algorithm, see chapter 3.3, it was shown that the method had the potential to simulate darkness and therefore be able to seamlessly integrate the VST into the virtual world. It was also shown that the method should be used with the CIELAB color space for the intended purpose. To implement it such that the VST was post processed based on the UE5 project, the two applications needed to share data. The mean and standard deviation of the camera within UE5 needed to be calculated and sent to the VST post process tool to act like the source values. The same values needed to be
4.2. Implementation of the Seamless Integration between the Real and Virtual World

calculated for the VST to act like the target values before finally calculating the new color for each VST pixel within the shader. Each frame seen from the viewer’s perspective in the UE5 project was therefore seen as the source image and each frame from the VST captured with the HMD was seen as the target image. The application structure for seamlessly integrating the VST according to UE5 can be seen in figure 4.1.

![Figure 4.1: The application structure for post processing the VST with regard to the UE5 project](image)

4.2.1 Source Image from UE5

Within the UE5 project, during run time, each frame of the viewer’s perspective that is rendered to the HMD was captured. The function used for accessing the pixel data for each frame was, `Read Render Target` [25]. The captured frames were to have no MR parts present and no NVG effect influencing the colors. If the NVG effect influenced the calculated values, the VST would adapt the green tint. If parts of the VST was present in the frame, the VST would partially adapt to itself. It was therefore most important that the frame only included the view of the virtual world. For each frame, the pixels were looped through and converted into CIELAB color space. The mean and standard deviation were calculated from the pixels within this color space. This resulted in two vectors of three values. The mean values as in \((L_{\text{mean}}, a_{\text{mean}}, b_{\text{mean}})\) and standard deviation values as in \((L_{\text{std}}, a_{\text{std}}, b_{\text{std}})\). The values were then converted into a JSON string and written to a JSON file that was stored within the project folder. This file could then be opened from the VST post process application and use the values, see figure 4.1. During runtime, there were issues in performance and the calculation of mean and standard deviation for UE5 was therefore also tested by tying it to a specific key.

4.2.2 Target Image from the VST and Color Correction

In the VST post processing application the mean and standard deviation of each VST frame needed to be calculated before post processing each pixel. Within the application, there was a predefined data stream API [26]. By using this API, a data stream of a chosen type could be opened, subscribed to, and therefore accessed. Two streams captured from the cameras on the headset, left and right eye, were available. Both frames were nearly identical with only a small difference in perspective. The color characteristics were the same and it was therefore deemed acceptable to only subscribe to one of them. Each frame of the left stream was chosen to act like the target image. During runtime, if a checkbox for adapting the VST was marked in the GUI, a data stream was opened and subscribed to. When the pixel values were acquired for a frame, the mean and standard deviation could be calculated in the same way as for each UE5 frame. The values were calculated for each frame and to save computation time, each frame could be down sampled by an arbitrary number. The values were then sent to the post processing shader together with the source image values read from the JSON file stored in
4.3 Result

Each image in the result was taken while using the same setup. The view in the virtual world was a nocturnal scene on a runway seen from a cockpit. The real world was a room with multiple spotlights in the ceiling with floor and walls in a dark color. See figure 4.2 for the result when the VST was not seamlessly integrated into the virtual world. A direct comparison can be made with figure 4.3 where the same light setting was used but with a seamlessly integrated VST. Figure 4.4 shows the result when some light sources are present in the virtual world and the VST is seamlessly integrated into it. Figure 4.5 shows a seamlessly integrated VST where the cockpit is low-lit. The hand is much brighter compared to the surrounding virtual world.

When the mean and standard deviation were updated for each frame in UE5, an error would occur in the VST post processing application because of read and write collision in the JSON file. See table 4.1 for measured frame rate (FPS) when the VST was seamlessly integrated and not.

---

**Application and Effects**

<table>
<thead>
<tr>
<th>Description</th>
<th>FPS</th>
<th>± %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both applications without seamless integrated VST (not updated UE5 values)</td>
<td>86.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Both applications with seamless integrated VST (not updated UE5 values)</td>
<td>84.5</td>
<td>1.2</td>
</tr>
<tr>
<td>The same instant that the values from UE5 are updated and the VST is seamlessly integrated</td>
<td>80</td>
<td>14.1</td>
</tr>
<tr>
<td>Constant updated values from UE5 and the VST is seamlessly integrated</td>
<td>&lt;30</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Table 4.1: Table containing measured FPS when seamlessly integrating the VST
4.3. Result

Figure 4.3: Result when the VST was seamlessly integrated into the virtual world when all light sources from the aircraft were turned off.

Figure 4.4: Result when the VST was seamlessly integrated into the virtual world with low lighting switched on within the cockpit and headlights turned on.
Figure 4.5: Result when the VST was seamlessly integrated into the virtual world with low lighting switched on within the cockpit. The hand was much brighter than the virtual world.
5 Design and Implementation of the NVG Effect

The NVG effect implemented for the MR flight simulator was to have the same characteristics as the NVG effect in the VR flight simulator. This included being chromatic green, grainy, reflecting chlorophyll, having halo effects, having reduced resolution in near objects, and having a limited field-of-view with a look down effect, see section 1.1.2. The characteristics needed to be post processed into the VST to make the effect complete. Due to the physical room lacking vegetation, a reflection of chlorophyll could be omitted. The effect was applied to the VST with the same post processing shader used for creating the seamless integration between the real and virtual world, see chapter 4.

5.1 The Limited Field-Of-View

The NVG effect, applied in the MR flight simulator before any work was incomplete. The VST had not adapted the NVG color characteristics and it was neither occluded such that the field-of-view was limited. The UE5 project used post processing effects to apply this but the VST remained unaffected because VST post processing effects were not supported by OpenXR, see section 2.2.3. This meant that the occlusion had to be implemented in the VST post process shader. With the formula of a circle, see formula (5.1), each pixel of the camera feed could be checked if they were to be occluded or not. If the current pixels’ length from the circle center (h,k) was larger than the radius with the power of two, the color was set to black which would simulate the same occlusion as in UE5. A GUI allowed changing the position and radius of the circle during run-time.

\[(x - h)^2 + (y - k)^2 = r^2\]

Because of foveated rendering, see section 2.2.1, 4 different textures of the VST were sent to the shader in slices. They were the left and right context view which was used as the peripheral vision and the left and right focus view which was placed according to the gaze tracking. This implied that the pixel coordinates within the focus view had to be recalculated to be within the context view if the edges of the circle would line up correctly. The coordinate conversion was not made, and the gaze tracking was instead set to static with a full-resolution view across the whole display to avoid low resolution in the peripheral vision. This placed the focus view in the middle of the screen and therefore within the circular field where it
came in no contact with the edges. Foveated rendering could not be turned off completely and this was therefore the trade-off.

A gradient to soften the edges of the circle was also added. To create the gradient, linear interpolation between the black color and each VST pixel was used. The weight was calculated from the pixel’s position within an area between the circumference and a bit inside the circle. The length of the gradient was controlled with a factor that could be adjusted from the GUI.

### 5.2 Night Vision Color

The area that was not occluded by the limited field-of-view and was not within the look down area was post processed to show the night vision. The method for creating the NVG color characteristics for the VST was based on the implementation in UE5. The effect within the two video streams was to be as similar as possible for them to blend. Each pixel of the VST was post processed to have the NVG color characteristics by the following 5 steps:

1. Apply box blur to the original color.
2. Create noise and add to the blurred original color.
3. Increase the brightness of the edited original color by multiplying each channel with a factor and then desaturate it.
4. Create a green color
5. Multiply the green color with the edited original color.
6. Compress the resulting color value to be within the allowed range for RGB.

#### 5.2.1 Blurring the VST with Box Blur

In real NVGs, the focal point is placed at a far distance before the aircraft making everything nearby out of focus, see section 2.1.1. The VST was masked to only be visible within close range of the user and could therefore be blurred when within the night vision area. This was done by using box blur, also known as moving average, which is a linear filter technique. A square kernel with each coefficient set to one is placed over each pixel in the image. All neighboring pixels, the pixels surrounding the center of the kernel, are summed together with the center value and then divided by the kernel size. The average is then set as the new pixel value which gives the blurred effect when done to each pixel in the image.[27, 28] Varjo had already implemented box blur which was repurposed to this effect. An option to change the size of the kernel had also been implemented in the GUI where a larger kernel results in more blur.[24] To implement the halo effects, the box blur complemented the brightened VST giving the impression that the extra bright objects bleed light into the surrounding areas.

According to Brickner (1989), the halo effect could bleed such excessively that the remaining image could lose its contrast, see section 2.1.1. This was not implemented because of how the post process shader processes the frame in slices where information was not possible to share between them. If it was implemented, unwanted effects on the edges of the slices could occur.

#### 5.2.2 Desaturation

The desaturation was done such that the color becomes a shade between black and white which allows for the final result to be chromatic green. This was done according to the human eye perception where the luminance level Y was calculated for each pixel and then set in each color channel, see formula 5.2[20].

\[
Y = Lum(R, G, B) = (0.299R + 0.587G + 0.114B) \tag{5.2}
\]
5.2.3 Generating the Noise

As light hits the photocathode within a pair of NVGs, electrons are emitted. As a consequence, a level of noise is created that is transferred into the viewed chromatic image, see section 2.1. The noise also called grain is what causes the low resolution in the NVG image, see section 2.1.1. To add noise in the VST, it had to be available in the shader. A single texture of noise would not be enough to mimic reality due to the noise continuously changing which meant that it had to be continuously generated. Varjo had already implemented a noise texture that was continuously generated on the GPU or CPU depending on preference. Each texel of the texture was a vector containing 4 randomly generated numbers between 0 and 1. The lack of correlation between the generated values created a texture with white noise. Within the shader, an intensity value could be extracted from the texture and added to each pixel, making the VST include noise.

5.3 Composing the NVG Layout with Seamlessly Integrated VST

In the NVG layout, there is a circle with night vision color and a look down area. When the NVG effect and the seamlessly integrated VST were both active, only the look down area would be color corrected. The reasoning was that the color correction could make the pixel values of the VST so dark that there would be no information to brighten when night vision color was applied. This would result in a flat brightened image which would not look realistic. The night vision area was therefore left without a seamlessly integrated VST.

5.4 Result

See figure 5.1 that shows the result of the implemented NVG effect in the MR flight simulator without the VST being seamlessly integrated. The VST has the chromatic green and grainy effect and is occluded because of the limited field-of-view. The resolution of the VST is lower within the goggles than in the look down area. The noise was generated continuously when the headset was held in the same position but would freeze when moved. This would only affect the noise and not the post processing of the VST overall. When the headset was held still again, the generation of the noise texture would be resumed. See table 5.1 for measured FPS when running the NVG effect with and without seamlessly integrated VST.

<table>
<thead>
<tr>
<th>Application and Effects</th>
<th>FPS</th>
<th>±%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both applications with active NVG effect and seamless integrated VST (not updated UE5 values)</td>
<td>80</td>
<td>1.4</td>
</tr>
<tr>
<td>Both applications with active NVG effect without seamless integrated VST</td>
<td>82.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Only UE5 with active NVG effect</td>
<td>86</td>
<td>1.2</td>
</tr>
<tr>
<td>Only VST application with active NVG effect without seamless integrated VST</td>
<td>83.9</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 5.1: Table containing measured FPS when running the NVG effect with and without seamlessly integrated VST.
Figure 5.1: Result when the NVG effect for MR was active and the VST was not seamlessly integrated into the virtual world.
User Study by Interviewing an Expert

The implementation of the NVG effect and the seamless integration of the VST were evaluated by conducting a semi structured interview with an NVG expert. The open-ended questions were meant to assess three main objectives: experienced realism, presence, and training value. A thematic analysis of the interview data was used to extract important themes for NVG simulations within MR flight simulators.

6.1 Semi Structured Interview

According to Gillham (2005), there are three common criteria for all interviewing methods, including the semi structured interview method used in this user study. The criteria are:

1. Questions asked are always open, giving the participant a chance to relay what they think is important. This allows for the researcher to gather unexpected data.

2. The interviewer adjusts to the participant’s responses and explores them by asking supplementary questions and or for clarification.

3. A structure is always present in the interview even if the questioning is informal and naturalistic.

A semi structured interview is highly rewarding due to its flexibility and underlying structure which awards rich qualitative data that is relevant to the objectives. The conducted semi structured interview was designed by following a protocol that has 5 stages:

1. **The preparation stage:** This stage is where the objectives are defined and the interview guide is written. Questions about the interview such as how much time will be available, how should the data be recorded and how will the procedure be carried out are also answered.

2. **The initial contact stage:** This stage is about the first impression the researcher makes of themselves. It is a purely social stage where the goal is to make the participant comfortable.

3. **The orientation stage:** This stage is where the interviewer establishes a report by explaining the interview structure, and what is to be researched and asks for consent.
4. **The substantive stage**: This is the main part of the interview where the topics are explored.

5. **The closure stage**: This is about closing the interview by asking the final questions, checking for feedback, reviewing the gathered data if wished, and make a social closure.

### 6.2 Objectives and Target Audience

The user study was designed such that three main objectives could be assessed. They were the realism of the NVG effect, the feeling of presence that the seamless integrated VST would evoke, and the overall training value of the NVG simulation within the MR flight simulator. The NVG effect was designed such that it simulated the use of NVGs within the cockpit of a fighter jet. The target audience of the final product was therefore fighter pilots who use NVGs in their work. One interview with a person of such background was conducted. The following information about the participant was gathered after a GDPR form was signed. His official job title was experimental test pilot and has worked as such for 10 years. He said that the role of an experimental test pilot is to be present and provide input during the whole product cycle for the development of an aircraft as a whole, not only by test-flying the final product. Before that, he worked as a pilot for 21 years at the Swedish Air Force. During that time, he was involved in developing NVGs at a concept level, creating regulations for their usage in the cockpit, and assembling a training program for pilots to learn how to use them. With this previous experience, the participant was credited with being an expert on NVGs and their usage of them within fighter jets.

### 6.3 Confidentiality and GDPR

According to Gillham (2005), it is most important that the participant know what they are participating in and feel comfortable doing so. A term he uses is *informed consent* where the interviewer informs the participant in a formal tone about the purpose of the research. Due to the subject being close to confidential matters, it was established early in the interview that the purpose was to use the given information for a public report. After the interview, a short discussion was conducted about the gathered data to affirm that it could be used. A GDPR notice was also signed for allowing the collected personal data to be used in a pseudonymized fashion in the report.

### 6.4 Test Setup

The setup of the MR flight simulator during the user test was with the Varjo XR-3 headset, an inclined chair, a joystick, and a throttle system with its control panel. The room had multiple spotlights in the ceiling with the floor and walls in a dark color. The simulation run was an open world with mountains, water, and forest with airstrips and cities. The aircraft’s initialized position when starting the simulation was at a runway, letting the user take off as the first thing. The participant was to restart from the runway for each tested effect and fly around the world to evaluate it. A colleague participated during the interview to control the effects and restarts in the simulation while the questions were asked and answers written down. When the interview guide had been written, a pilot interview was conducted. This was done to evaluate the interview guide and to rehearse with the colleague such that both understood who would do what. After the revision, a final pilot test was conducted.

### 6.5 Interview Structure

The whole interview was conducted in Swedish and translated into English afterward. It was opened with a welcome together with an expressed gratitude for the participant’s time.
Established rapport was made by giving a short explanation of the thesis and the interview structure. It was made clear that nothing would be a test of his abilities but a valuable insight into his work and that his opinions were important. After the GDPR notice had been signed, a few questions about his credentials and previous experiences were asked to establish credibility. When it was time for the user test, the setup of the MR flight simulator was explained and the participant got to make themselves comfortable with the system. The user test could be divided into three parts, usage of NVG without seamlessly integrated VST, only seamlessly integrated VST, and finally usage of NVG with seamlessly integrated VST. Open ended questions were asked that invited to discussion for each mode. Toward the end, questions about the training value of the NVG simulation were asked. The interview was concluded with a discussion about potential confidentiality and one more expression of gratitude for their time. To see the interview guide, see appendix A.

6.6 Thematic Analysis of Interview Data

The qualitative data gathered from the interview was then analyzed by using the thematic analysis method. The method lets the researcher identify reoccurring patterns and themes in large descriptive data with a six-step procedure provided by Naeem et al. (2023)\[30\]. These were:

1. **Transcription, familiarization with the data, and selection of quotations**: The researcher should engage with the data by multiple re-readings, extraction of significant quotes, identifying themes and discerning viewpoints closely tied to the research objectives.

2. **Selection of keywords**: The findings from the previous step are then encapsulated by using keywords that reflect the participant’s experiences and perceptions. By creating keywords the data becomes more comprehensible and manageable.

3. **Coding of the data**: The relevant portions of the data are then labeled with a word or two called codes. These are built upon the found keywords but grouped by relevancy. Codes are directly linked to the research questions.

4. **Development of themes**: The codes are then organized into groups to find relations and patterns. This is done by sorting the codes and data based on similarities. The data is converted from the detailed form into a more abstract representation.

5. **Conceptualization through interpretation of keywords, codes, and themes**: By reiterating the findings, the themes are reviewed and revised. If two themes are similar, they are combined and if they lack relevance to the research questions, they are removed. Through this process, concepts emerge.

6. **Development of a conceptual model**: The final part of the method is to create a conceptual model which is a representation of the data but in a conceptual way. It is used to answer the research questions and display the findings.

According to Gillham (2005), it is also important to be mindful of the researcher’s prior judgment to avoid interpreting the data in a preferred fashion. The researcher should ask themselves what they expect to find, what they prefer to find, and what they prefer not to find. If the researcher keeps these thoughts in mind while working with the data, interpretation can be made in a neutral opinion\[29\].
6.7 Results

The thematic analysis of the interview data resulted in three themes. These were *Practice scanning patterns, NVGs require low light within and outside the cockpit* and *MR should be used for low cost tactile training*. See figure 6.2 for the conceptual model that includes the complete thematic analysis with the statements, keywords, codes, and themes.

During the interview, the expert showed how fighter pilots sit in the cockpit at high G:s while wearing the NVGs. They sit straight in the seat with a locked head where the gaze is level with the horizon. This position is used to avoid putting strain on the neck which can lead to neck injury. Instead of turning their heads, they lower their eyes to check the flight instruments. The expert said that the pilot should be able to look down into the cockpit in the locked head position but that it was not physically possible due to the HMD limiting the aspect angle. Figure 6.1 shows what the expert saw when sitting with the described posture. The figure shows the active NVG effect and a seamlessly integrated VST. The image was taken after the interview by reenacting the posture. The visible angle stops halfway down the area for the wide-area display with only the top of the joystick visible. The expert also meant that the whole area that was covered by the black color should be visible peripheral vision since the goggles are positioned a finger away from the eyes.

![Figure 6.1: Result when the VST was seamlessly integrated into the virtual world together with active NVG effect. The user looks straight ahead](image-url)

Figure 6.1: Result when the VST was seamlessly integrated into the virtual world together with active NVG effect. The user looks straight ahead
Figure 6.2: A conceptual model showing the thematic analysis of the interview data. The statements, keywords, and codes used to extract the themes are included.
7 Discussion

The results showed a seamlessly integrated VST as well as an NVG effect applied on both video streams within the MR flight simulator. The two implementations were evaluated by interviewing an expert. The open-ended questions were made to target the experienced realism, presence, and training value where the gathered data was used to find important themes. The results together with the method and sources are discussed before discussing the entire work in a wider context.

7.1 Seamless Integration Between the Real and Virtual World

A comparison between figure 4.2 and 4.3 shows a significant difference in perceived realism when the VST has been seamlessly integrated into the virtual world. The VST in figure 4.3 has a low brightness that matches the pitch-black cockpit while the unadapted VST in figure 4.2 has color characteristics that make the integration seem harsh. Figure 4.4 shows how the seamless integrated VST is a little brighter when the lights within the cockpit and the head-lights of the aircraft are on. We can also see that the colors have adapted to the cold hue of the virtual world. This suggests that the color transfer algorithm works well in color correcting according to a nocturnal scene of varying character. However, some characteristics within the captured VST could not be color corrected to show a believable result. Figure 4.5 shows when the VST is seamlessly integrated but the hand is too bright to be realistic compared to the virtual world. When reenacting the figure by holding the HMD and a hand in a similar position with the same virtual scene and same position within the room, a matching result could be conjured. When moving the hand in a minute position, the result could turn believable again and vice versa. A theory that would explain the bad color correction, like in figure 4.5 could be because the hand was placed just under a spotlight which made the camera try to compensate and therefore create unexpected values. However, this would need further investigation. The research and assessment of the color transfer algorithm, see section 3.2, was not made at a greater depth due to lack of resources such as time. The conference paper describing the optimized version of the algorithm was solely used for understanding the color correction step. However, most of the optimization was made in the steps to convert RGB into $l\alpha\beta$ color space. Since $l\alpha\beta$ color space was disregarded after completing the assessment of the algorithm, delving deeper into the conference paper might not have made a difference. Furthermore, the original conference paper described with less detail how multiple swatches
of each image could be used to create a cluster of statistical values to compensate for a target and source image with too varying compositions, see section 3.3. This was not tested in the preliminary assessment which could be the reason for why some cases did not yield good results. However, to use the method in real time an automatic way to choose swatches would have been needed and the time for researching such a method was not available. Finally, Reinhard and Pouli (2011) compared multiple color spaces, two of them being CIELAB with illuminant D65 and E, and found that CIELAB with illuminant E performed best color correction for various images [23]. Since the conference paper was found late in the thesis process, illuminant E was never tested in the preliminary assessment of the color transfer algorithm but should be since it might lead to more believable results.

Receiving the new calculated mean and standard deviation for a frame in UE5 was very slow. The measured FPS in table 4.1 shows how the seamless integration with updated mean and standard deviation for each frame in both the VST and UE5 would result in a stream under 30 FPS. On the other hand, as soon as the values from UE5 were not continuously updated the stream would result in about 84.5 FPS. If the values from UE5 were updated by pressing an assigned key, a short drop to 80 FPS would occur before recovering to 84.5 FPS again. During the mentioned cases, the mean and standard deviation were calculated for each frame of the VST. This would suggest that the calculation heavy part was not from the color correction step or the CIELAB conversion as it was done with a high frame rate in the VST post processing application. In the UE5 documentation for the function that was used to extract the pixels of each frame, Read render target, it said that it was an "incredibly inefficient and slow operation" [25]. Additionally, opening and writing the values to a file for each frame could also be a reason for the large drop in frame rate. Furthermore, if the calculations within UE5 were made too frequently there was a risk of writing and reading in the file simultaneously from the two applications. This would cause an error in the VST post processing application which would make it stop working. To remedy both the slow computation and the risk of read and write collision, the mean and standard deviation from UE5 would only be updated manually by pressing the assigned key when the light setting changed significantly. The consequence of this was that the seamless integration would never be perfectly synchronized to the virtual world. This would be necessary when the positioning of the aircraft changes quickly, making the light reach the cockpit at a different angle. If there had been more time available, another method that would exclude the risk of read and write collision would have been researched and implemented. Read and writing to file was used since it made it possible to quickly implement the color transfer algorithm and see if it had potential.

### 7.2 Design and Implementation of the NVG Effect

In figure 5.1 the two implemented NVG effects in both streams complement each other. The box blur applied to the VST matches with the blur noticeable in the buttons on the flight instruments belonging to the virtual world. However, the halo effect on the bright hands pointed finger is noticeably clipped by the alpha layer. The light from the finger should bleed into the virtual world but is instead sharply cut. If a low resolution and halo effect should be possible to implement in the edges of the VST, the virtual world’s pixels need to be color corrected after the VST has been post processed. However, a statement from the thematic analysis data said that the light within the cockpit was always minimized as much as possible to maintain the eye’s night vision, see figure 6.2. By this reasoning, a strong halo effect implemented in the VST is unnecessary if strong lights are not going to be added for the sake of a realistic setting. The measured FPS from running an active NVG effect without seamless integrated VST could provide a frame rate of 82.4 FPS, see table 5.1. This shows that the effect does not require much computational power. However, the noise texture would not regenerate when the HMD would physically move. This caused the noise to be static and lessened the fidelity of the effect.
7.3. User Study by Interviewing an Expert

By avoiding implementing the NVG effect to work with dynamic foveated rendering, the solution was not run with as high optimization as it could have been. This was because full resolution across the whole display was used to counter the low resolution in the peripheral vision since the focus view could not be disabled, see section 2.2.1 and 5.1. The coordinate conversion between the focus view and the context view was not implemented because there was a lack of documentation on the two.

7.3 User Study by Interviewing an Expert

The three themes extracted from the thematic analysis of the interview data showed what was most important when simulating NVGs in an MR flight simulator. The first theme *Practice scanning patterns* was the theme that had most statements tied to it, see figure 6.2. It meant that the most important part of an NVG simulation used in training is that pilots should be able to practice scanning patterns. This refers to the fact that the goggles are only used for looking outside the cockpit and that the pilot keeps their head in a locked position at high G:s to prevent injury. The pilot scans across the horizon with a limited field-of-view and lowers their eyes to look under the goggles to operate the aircraft. Due to the restricted vertical field-of-view in the HMD, this kind of posture could not be held since the aspect angle did reach down into the cockpit. The human visual system has a vertical field-of-view with eye movement of 126° with 70° being downwards\[31\]. Varjo has not yet released the official value of the vertical field-of-view for the XR-3 headset but according to two headset comparison websites, it is between 78° and 90°\[32,33\]. The significant difference in the viewing angle implies that a proper scanning technique is not physically possible to practice with the current hardware. This can be seen in figure 6.1. The top of the joystick is barely visible when the HMD is held level to the horizon, but the aspect angle should reach even further down. This is even more important to point out when in real-life during flight, the goggles are never removed. The pilot must instead be proficient in navigating the flight instruments while wearing NVGs, see section 6.7. The vertical viewing angle downwards in an NVG simulation is therefore one of the most crucial factors for it to have training value. This could be remedied by using another HMD with a larger vertical field-of-view such as the Varjo XR-4 headset with 105°\[34\]. This is provided that the downward angle is improved. According to one statement in the thematic analysis, the positioning of the NVGs and the viewing angle is more important than implementing perfect graphics, see figure 6.2.

The second theme with the least statements attached to it was *NVGs require low light within and outside the cockpit*, see figure 6.2. One statement said that the light within and outside the cockpit is minimized as much as possible to maintain night vision in the eyes. This is closely related to the theory where Martin and Howard (2001) says that the differing luminance levels in the NVGs and within the cockpit itself are something that the pilot should learn to be accustomed to, see section 2.1.2. Additionally, Beilstein (2003) meant that making the cockpit dark would improve the fidelity of the NVG simulation and open up more training possibilities, see section 2.3.1. The seamless integration of the VST could therefore be seen as necessary for learning how to navigate the flight instruments correctly while using NVGs. However, it is more important that the vertical field-of-view in the HMD allows the user to glance down into the cockpit because, without such functionality, the seamless integration of the VST is not visible.

The third theme was that *MR should be used for low cost tactile training*. The numerous statements tied to this theme meant that MR should be utilized to train the tactile parts. This is once again tied to the theory where Martin and Howard (2001) says that a pilot needs to learn how to operate with the goggles, see section 2.1.2. To implement tactile training with NVGs in an MR flight simulator, the vertical field-of-view within the HMD needs to be improved for the pilot to be able to interact with the cockpit with proper posture.
7.4. Source Criticism

The experts’ credentials made the resulting themes carry weight but to avoid the possibility of missing important angles it would have been beneficial to interview multiple people. Unfortunately, it was difficult to arrange multiple interviews because of scheduling. A quantitative evaluation of experienced realism and presence could have been made but it also came with difficulties. The participants needed to have previous experience of using NVGs or have a reference to compare the implementation to if realism was to be measured. If NVGs were available during each test a large pool of people could have participated but this was not the case. Photos taken through NVGs could also have been used as a reference. However, acquiring NVG images from a trustworthy source was difficult. In other words, it was not possible to get multiple participants which would lead to trustworthy results and a qualitative evaluation had to be made instead.

Finally, the conducted interview and the gathered data was in Swedish and because of this, it had to be translated into English for the report. We must be aware that there is a chance of losing intricate details that exist within certain words when translating between two languages. The translation was therefore not made word for word, but to get the context.

7.4 Source Criticism

The sources used to describe NVG technology were peer-reviewed articles published in journals. The publication years spanned from 1989 to 2013, ensuring that both new and older technology was covered. The sources with user studies included both the methodology and the gathered data, making them credible because of the transparency. Some sources had stated fewer references in their bibliography which made them less trustworthy but the coverage of multiple sources providing the same information reinforced their reliability.

The related work relied on two thesis reports that were not peer-reviewed. Emphasis should be made on not letting non-peer-reviewed work carry too much weight in the research since no one with unbiased eyes has looked at the work. The report’s credibility lies within the included references and transparency of their gathered data. A finding in one of the thesis reports where used together with information gathered from peer-reviewed articles that stated similar information, making the piece of information reliable.

The sources used for the method varied in character. Chapter 3 and 6 relied on a range of credible sources that were published by journals and or publishers that focus on education. However, chapter 4 and 5 lacked sources because post processing VSTs is a fairly unknown subject. It therefore leaned heavily on documentation from Varjo and UE5.

The discussion of the thematic analysis of the interview data required information about the vertical field of view in the Varjo headset. This value could not be found within the Varjo documentation and was instead taken from websites that specialized in XR. To establish credibility, two sources were used.

7.5 The Work in a Wider Context

NVGs are hazardous to use during flight due to the visual limitations and illusions they introduce. Therefore, it is detrimental that an NVG simulation does not instill false confidence in a pilot because it was built in a way that does not reflect reality. In all research, we must be transparent with the gathered data and make conclusions that are true to it. This is to avoid misguided use of the information once it is published. The conclusions we made regarding NVG simulations within MR flight simulators can directly affect pilots’ learned skills in the future. The safety of the pilot is the priority, and the research has been done with care to uphold it even if it might not show favor to prior judgment.

The method used to seamlessly integrate the VST had previously been tested for nature images. We applied it for integration between a real and virtual world where the human body is a core part of it. However, the method was only tested on people with fair skin which
implies that there is great uncertainty about how it would perform with a user that has a different skin color. In the future, the method should also be tested on people with color to avoid exclusion. In the context of flight simulators, it is also important to remember that the tests were never made with proper flight gear. Pilots might use gloves and to reach high fidelity in a flight simulator, such gear should be used. It is therefore important to study how realistic the seamless integration of a VST is in this context both for experienced realism and safety aspects.
Conclusions and Future Work

A method to seamlessly integrate the VST into the nocturnal virtual world has been proposed and an NVG effect has been added to the VST making it possible to experience a whole NVG simulation within the MR flight simulator. The NVG simulation with and without a seamlessly integrated VST was evaluated by conducting a semi structured interview with an NVG expert. The questions targeted perceived realism, presence, and training value. This ensured that the extracted themes from the thematic analysis of the interview data were relevant to the research questions. These together with related research were then used to reach conclusions that could answer the following research questions.

The first was, "How does the light setting in the simulator room affect the overall experience of an NVG simulation within an MR flight simulator and is it a crucial factor to consider when implementing it?". A requirement for NVGs in real life is that the light within the cockpit must be as low as possible to avoid interfering with the goggles. The bright light within the goggles and the lack of light within the cockpit can be difficult for the eyes to adapt to and it is something fighter pilots need to be used to. A training need for this specific light setting does in other words exist. The fidelity of an NVG simulation would also be higher if the color characteristics between the virtual and real world were the same. The light setting in the simulator room is therefore a crucial factor to consider if fighter pilots should be able to translate the skills learned from NVG practice within an MR flight simulator into the real world.

The second research question was "How can the color and brightness of a VST captured in a bright room be addressed to seamlessly integrate it into a virtual world that simulates a nocturnal scene?". To seamlessly integrate a VST into a virtual world that simulates a nocturnal scene, Reinhard’s color transfer algorithm[17] could be used. Each frame in the virtual world is seen as the source image and each frame in the VST is seen as the target image. The algorithm together with CIELAB color space proved to be color correcting with believable results for varying degrees of brightness and hue in the nocturnal scene. However, some color characteristics within the VST have caused less satisfying results and these need to be identified in the future. Otherwise, since the algorithm requires few calculations, there is potential to color correct with a high frame rate.

The final research question was "What is important to include in an NVG simulation experienced in an MR flight simulator for it to reflect real life and have a training value for fighter pilots?". Fighter pilots must alter their task management and tactics when operating with
NVGs. The goggles require them to hold their heads level to the horizon for both personal safety at high G:s and also because the focal point of the goggles is set far before the aircraft. To manage the aircraft, the fighter pilot glances down into the cockpit. This highlights one of the most crucial factors when designing an NVG simulation for an MR flight simulator. The HMD must have a large enough vertical field-of-view to allow the fighter pilot to hold the correct posture while glancing down into the cockpit to see the flight instruments. The greatest training value an NVG simulation in MR can provide is tactical training with correct posture, and the hardware must support its physical elements.

For future exploration, the color transfer algorithm as a method to seamlessly integrate the VST into the virtual world should be further investigated. In some cases, the color corrected VST received too bright colors to be realistic compared to the virtual world. This could be because of the light characteristics within the simulator room but a definite cause should be identified to create the best conditions for success. The solution should also be tested for varying skin colors and by users who wear proper flight gear such as gloves. Furthermore, the algorithm was only tested with illuminant D65 as the reference white point in the conversion to CIELAB color space. However, illuminant E could lead to better color correction and should be assessed in the future. Finally, the color transfer algorithm should be assessed for any time of the day in the source image and not solely for nocturnal scenes. To make the color correction synced perfectly to the virtual world, an alternative way to send the mean and standard deviation from UE5 to the VST post processing shader needs to be found. Asynchronous messaging between the two applications could be the answer. Finally, a method to extract significant color swatches from the target and source image in real-time should be investigated to test the color transfer algorithm with clusters which could improve the realism. To develop an NVG simulation with high training value, an HMD with a large vertical field-of-view is needed and research should be done to find the required minimum.


A.1 Interview Guide in Swedish

Inledning och Välkomstfas:

- **Presentation:** Kort förklaring om exjobbet.
- **Förklara syftet med intervjun:** Syftet med detta användartest är att se hur väl effekterna är utformade men också för att se en pilots användarbehov. Förklara att deltagarens åsikter är värdefulla och att testet inte är en bedömning av deras prestation utan en utvärdering av systemet.
- **Samtycke:**
  - Informationen ska användas till offentlig rapport
  - Blir inskriven i rollen som expert men anonymt
  - Skriva på GDPR notis

Informationsfas:

- **Instruktioner:** Förklara testets struktur
  - Start med några frågor om tidigare erfarenheter
  - Testa MR simulatorn med olika effekter samt prata kring frågor
  - Runda av

Introduktion:

- **Frågor om tidigare erfarenheter:**
  1. Vad är din nuvarande jobbtitel? Vad innebär det? Hur länge har du arbetat som det?
  2. Har du några tidigare erfarenheter som pilot och vad var det och hur länge?
  3. Har du tidigare erfarenheter av att använda NVG i ditt arbete? Vad använde du dem till då?
4. Hur brukar ni träna med NVG, finns det simulatorer för det?
5. Har du använt ett VR eller MR headset tidigare?

**Intervju och användartest:**
Informera om att det är okej att avbryta när som av oavsett anledning! Genomgång av systemet.

**Test med NVG utan anpassad VST:**
Realism:
1. Tycker du att denna simulering känns lik verkligheten, i så fall vad?
2. Finns det något som skulle behöva förbättras?
3. Vi har lite olika väderförhållanden, har du flugit i några specifika som vi kan testa?
4. Hur är skillnaden mellan bakgrunden och händerna? Djupet i scenen?
5. Hur är det att bära headsetet jämfört med kikarna?
6. Man brukar prata om att piloten kan snegla ner i cockpit under kikarna, hur upplever du den funktionen i denna simulering?
7. Hur ljust är det inuti cockpit när NVG används?

**Test med och utan NVG med anpassad VST:**
Närvaro:
1. När du åter sneglar ner i cockpit, hur känns det nu?
2. Vilket av de två ljussättningarna föredrar du?
3. Vad är din åsikt om denna funktion (Anpassning av VST)? Ser du den som viktig, och i så fall, varför eller varför inte?
4. Brukar ni se väl inuti cockpit när ni är ute och flyger på natten?
5. Hur tycker du att ändringen av ljussättningen påverkade upplevelsen av NVG?

**Avslutande utan headset om önskat:**
Träningsvärde:
1. Från ditt perspektiv, vad skulle detta träningsverktyg kunna lära någon som är ny till NVG?
2. Finns det några ytterligare funktioner eller aspekter till denna simulering som skulle kunna förbättra utbildningsvärden?
3. Hur tycker du att användningen av VR eller MR-headset jämförs med mer traditionella träningsmetoder?

**Avslutning av Intervjun:**

- **Feedback:** Uppmuntra deltagaren att dela ytterligare feedback eller kommentarer de kan ha
- **Diskussion om sekretess:** Diskutera kring samlade datan och om något ska vara sekretess belagt
- **Tacka:** Tacka deltagaren för deras tid och vilja att medverka
A.2 Interview Guide Translated into English

Introduction and welcoming stage:

- **Presentation**: Short briefing about the master thesis.
- **Explain the purpose of the interview**: The purpose of this user test is to examine how well designed the effects are but also to see a pilot’s user needs. Explain that the participants’ thoughts are valuable and that the test is not an assessment of their performance but that it is an evaluation of the system.
- **Consent**:
  - The information is to be used in a public report
  - The participant is to be written within it as an expert but anonymously.
  - Sign a GDPR notice.

Information phase:

- **Instructions**: Explain the test structure
  - Begin with some questions about prior experiences
  - Test the MR simulator with the different effects while discussing around questions.
  - Bring the interview to a close

Introduction:

- **Questions about past experiences**:
  1. What is your current job title? What does that mean? How long have you worked with it?
  2. Do you have any previous experience as a pilot? What was it and for how long?
  3. Do you have previous experience of using NVG in your work? What did you use them for then?
  4. How do you usually train with NVGs, are there simulators for that?
  5. Have you used a VR or MR headset before?

Interview and user test:

Communicate that it is okay to stop the user test at any moment for any reason! Provide overview of the system.

Test with NVG without adapted VST:

Realism:

1. Do you think this simulation feels like reality, if so what?
2. Is there anything that could be improved?
3. We have slightly different weather conditions, have you flown in any specific ones that we can test?
4. How do you perceive the difference between the background and the hands? How is the depth in the scene?
5. How is it to wear the headset compared to the binoculars?
6. It is often talked about that the pilot is able to look down into the cockpit under the binoculars, how do you experience that functionality in this simulation?

7. How bright is it inside the cockpit when NVGs are used?

**Test with and without NVG with adapted VST:**

**Presence:**

1. When you look down into the cockpit again, how does it feel now?

2. Which of the two light settings do you prefer?

3. What is your opinion about this feature (adaptation of the VST)? Do you see it as important and if so why, why not?

4. Do you usually see well inside the cockpit when you are out flying at night?

5. How do you think the change in lighting affected the experience of NVG?

**Closing without the headset if desired:**

**Training value:**

1. From your perspective, what could this training tool teach someone new to NVG?

2. Are there any additional features or aspects to this simulation that could enhance the educational value?

3. How do you think using a VR or MR headset compares to more traditional training methods?

**Conclusion of the interview:**

- **Feedback:** Encourage the participant to share any additional feedback or comments they may have

- **Discussion about confidentiality:** Discuss the collected data and whether something should be kept confidential

- **Express gratitude:** Thank the participant for their time and willingness to participate