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Ghost Injection Attack on Automatic Dependent Surveillance-Broadcast Equipped Drones Impact on Human Behaviour

Master's thesis

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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

Automatic Dependent Surveillance-Broadcast (ADS-B) is a communication protocol used in aviation for situational awareness by sending out own position and altitude data. ADS-B IN devices can receive ADS-B messages. The ADS-B protocol is known to be vulnerable to a variety of cyber attacks. Our work simulates a ghost injection attack on drones equipped with ADS-B IN equipment to identify its effect on human behaviour. We aim to study how users and drone pilots will react while under attack. To investigate this, we conducted an experiment with 50 participants who were asked to operate a drone simulator and fly a time critical mission. An attacker fakes a nearby aircraft during the mission by sending out spoofed ADS-B OUT messages to alter the drone's flight path. We monitored participants by analysing their flight behaviour, brain activity measurements and receiving feedback after the experiment. Our research focuses on human behaviour during realistic cyber attacks on drones: "are people recognising a cyber attack or not" and "how might such an attack change their behaviour". In this specific experiment, with one cyber attack repeated three times, the focus went on whether to land a drone prematurely or not. Surprisingly, the experiment discerned a considerably large diverge between participants native to Estonia and participants from other countries. About 40% of the participants were Estonian, and they complied with the message from the ghost injection attack and landed the drone. On the contrary, the vast majority of non-Estonian participants continued the mission.

This thesis is written in English and is 46 pages long, including 7 chapters, 22 figures and 8 tables.

List of abbreviations and terms

AAI	Airports Authority of India
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-B IN	ADS-B Receiver
ADS-B OUT	ADS-B Transmitter
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
BVLOS	Beyond Visual Line of Sight
CNS	Communication, Navigation and Surveillance
CogSIMA	IEEE Conference on Cognitive and Computational Aspects of Situation Management
CPU	Central Processing Unit
CSV	Comma Separated Value file
DAA	Detect And Avoid
EASA	European Union Aviation Safety Agency
EAVA	Estonian Aviation Academy
EECL	Tallinn City Hall Heliport
EEG	Electroencephalography
ERP	Event-related Potential
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GOF	Gulf of Finland
GPS	Global Positioning System
GPU	Graphics Processing Unit
ICAO	International Civil Aviation Organization
ICT	Information Communication Technologies
IFF	Identification Friend or Foe System
OS	Operating System
PPG	Photoplethysmogram
PSR	Primary Surveillance Radar

RAM	Random Access Memory
RC	Remote Controlled
SES	Single European Sky
SESAR	Single European Sky ATM Research
SESAR JU	Single European Sky ATM Research Joint Undertaking
SSR	Secondary Surveillance Radar
TCAS	Traffic Collision Avoidance System
U-Space	SESAR JU Project
VR	Virtual Reality

Table of Contents

List of Figures

List of Tables

1. Introduction

Single European Sky Air traffic management Research Joint Undertaking (SESAR JU) was selected, by the European Commission, in 2015 to produce a new generation of the European air traffic management system [1]. SESAR JU then created the innovative project of U-Space to regulate the airspace which now encompasses a large number of drones aside from regular aircraft. As the project is still being developed, it will start offering different types of digitalised and automated services to enable a framework that supports both manned aviation routine operations and drone pilots [1]. Some of those functions can either be equipped in drones or installed in ground base stations [1].

The number and usage of drones are increasing rapidly, and the forecast is that this tendency will not change in the near future. According to the Single European Sky Air traffic management Research (SESAR) European Drones Outlook Study "European demand suggestive of a valuation in excess of EUR 10 billion annually, in nominal terms, by 2035 and over EUR 15 billion annually by 2050" [2]. It is expected that by the year 2050 there will be around 7 million drones used in governmental and commercial missions [2]. SESAR started a project called U-Space to assist the development of the drone services in Europe while taking both safety and security into consideration [1].

U-Space provides a framework with specific procedures designed to support the safe, efficient, and secure access to airspace for large numbers of drones in Europe [3]. U-Space aims to create safe airspace for flying both drones and aircraft. As the airspace gets increasingly congested with rising numbers of both manned and unmanned aircraft, the chances of air collision ascend. One potential solution to reduce the possibility of in-air collisions is using the Automatic Dependent Surveillance-Broadcast (ADS-B) messages. Aircraft transmitting ADS-B messages gives the drone pilot additional situational awareness. A potential feature in a drone's remote control software is a proximity warning based on received ADS-B messages. Since ADS-B was not designed with security in mind and no encryption is used, hackers can easily spoof the unencrypted messages. One of the numerous types of attacks to which drones are potentially vulnerable is the ghost injection attack. A ghost injection attack is when an attacker uses a radio transmitter to broadcast fake ADS-B messages similar to an actual message which can be seen by aircraft and Air Traffic Controller (ATC) as a real aircraft [4]. (see 2.5 for detailed definition of ghost injection attack)

In this work, the author focus on the behaviour of a drone pilot under a ghost injection attack to determine if there are socio-demographical factors that enhance or reduce compliance with regulations under an ethical dilemma. We hypothesis that ghost injection attack on ADS-B equipped drones will not have an effect on human behaviour.

1.1 Motivation

Cybersecurity in aviation is of paramount importance. This is because, as great new technology or innovation emerges, it brings tremendous value to the sector, but it can get undermined and scrutinised later on from the criminals due to our inability to maintain them safely and securely.

Whether it is a social media giant facing privacy and security threats, cryptocurrencies facing numerous cyber attacks, or drone manufacturers getting their drones hacked into, those obstacles, if not addressed quickly and adequately, would result in the loss of trust in those innovations. Most importantly, they can steer away from significant innovations into becoming irrelevant or even obsolete.

In a world full of drones, and with U-Space advancing day after day, the safety of our sky and airspace lies in the hands of securing these innovations.

1.2 Novelty and contribution

ADS-B has recently become a much discussed topic in academic literature. Several researchers have proved how simple it is to launch a cyber attack while using only easy to access hardware and software. Those kinds of cyber attacks can be perilous for aviation and drone industries.

The research will mainly focus on human behaviour, user performance during an experiment, and pilots' overall indicators and cognitive performance facing a cybersecurity attack, such as the ADS-B ghost injection attack, while delivering an organ to a hospital.

There has not been any study combining ADS-B IN equipped drones and ghost injection attack and their impact on human behaviour. Section 3 covers related studies. As ADS-B IN is one of the required options for U-Space Detect And Avoid system (DAA) and air collaborative conflict avoidance for all drones above 250 grams [5]. Therefore, the results of the research could affect the use of ADS-B IN equipped drones in U-Space.

1.3 Scope

The problem will arise when U-Space implementation starts to take action while at the same time companies are equipping ADS-B IN to their drones. The drone pilot's decision can be affected by this type of attack. The objective or the reason of the research will be necessary for SESAR and drone manufacturers. The problem can also give insight into whether users would comply or not when facing a system prompted warning message.

1.4 Limitations and challenges

The experiment will be conducted in a simulated environment, with voluntary participation and signed consent to avoid common ethical concerns. As mentioned in [6], under surprise conditions, pilots struggled to succeed following basic operations. Considering the reasons mentioned earlier and the risk of losing a drone or damaging anything, we will use a simulation software to implement the experiment.

One of the greatest challenges will be to find enough participants with the current COVID-19 restrictions.

1.5 Research methods

We will use different methods for our research:

- Experimental
- Interviews
- Observational

1.6 Research problem

Hypothesis: Ghost injection attack on ADS-B equipped drones will not have an effect on human behaviour.

1.7 Chapters summary

The thesis consists of seven chapters:

- Chapter 1 presents an introduction with the problem statement and research design of our research.
- Chapter 2 provides a look at the study background.
- Chapter 3 explains related work.
- Chapter 4 explains the experimental setup, the tools that we used and how we implemented the attack. More technical details were explained in 4.1.1 and 4.3.1
- Chapter 5 shows the results of the experiments in our research.
- Chapter 6 defines our conclusion.
- Chapter 7 include our future work and recommendations.

1.8 Publication and conference presentation

This work "Ghost Injection Attack on Automatic Dependent Surveillance-Broadcast Equipped Drones Impact on Human Behaviour" was accepted for the Focus Session: Psychological Dimensions of Cognitive Situation Management for the 11th IEEE Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA 2021) [7].

2. Background

2.1 History of air traffic control

Air Traffic Control or ATC is the terrestrial part of air traffic. The primary purpose of it is to prevent in-air collisions by directing aircraft through controlled airspace [8]. In 1936 the first generation of ATC originated in Newark, Chicago, and Cleveland [9]. At that time, it did not have any automation and almost no radar coverage. By the end of the 1940s, the second generation of ATC started implementing the ground-based radar system, and began the age of using computers for processing flights [10]. In 1961, the Federal Aviation Administration (FAA) took over the project and added devices to interrogate transponders on aircraft [10]. The Identification Friend or Foe System (IFF) is a device that was developed during World War II for military applications to identify aircraft [10, 11].

The FAA provided the Third generation in the 1970s [10, 12]. It was a significant upgrade towards automating tasks and adding real-time capabilities of aircraft such as location, identity, altitude, direction, and speed [10].

NextGen was the following step for the FAA to increase "Capacity and Safety" in air space operations, and the main component of NextGen is automatic dependent surveillance-broadcast [10]. ADS-B accuracy can get to 20 meteres while ground-based radars can get approximately to 450 meters [13]. ADS-B made aviation step into cyberspace and become a potential target for cyber attacks when it was introduced in NextGen [14]. FAA required all aircraft flying in the US airspace to have an ADS-B transmitter by the 01st of January 2020 [15, 16]. According to SESAR, Single European Sky (SES) and European Union Aviation Safety Agency (EASA), the EU airspace target date was the 07th of December 2020 [17, 18]. Moreover, the Airports Authority of India (AAI) set the deadline for the 01st of January 2019 [19].

The aim of ADS-B is to replace Primary Surveillance Radar (PSR) and Secondary Surveillance Radar (SSR) [15, 20]. Both radars are part of the Air Traffic Control Radar Beacon System (ATCRBS). PSR sends out a pulse 'Bang' from the ATC ground-based station and listens to the echo from the pulse hitting an aircraft and returning; and then measures the time difference to find the range of the aircraft [14, 21]. It also measures size, shape, and velocity [14, 21]. SSR (such as IFF) are part of a ground-based station that transmits an interrogation signal and waits for transponders of aircraft that receive the interrogation and return a response [14, 21].

Flightradar24 is a real-time commercial aircraft flight tracking service [22]. The website shows the world map with real time tracking of the flights [22]. Flightradar24 does not only disclose the location of the aircraft, but indicates more detailed information which can be viewed on their website [22], such as:

- Current position
- Route with origin and destination
- Estimated time of arrival and actual time of departure
- Flight number
- Aircraft types
- Speed, altitude, ...

Figure 1 shows a screenshot of Flightradar24 taken on the 06th of June 2020, wherein yellow-coloured aircraft are broadcasting information using ADS-B while blue aircraft are located using satellite data [22].

Figure 1. *FlightRadar24.com real-time aircraft flights [22]*

2.2 ADS-B overview

ADS-B is a communication protocol, which stands for Automatic Dependent Surveillance-Broadcast [10, 20]:

Automatic: no need for any intervention (pilot or controller).

Dependent Surveillance: receives data from the Global Positioning System (GPS) and flight controller.

Broadcast: repeatedly and periodically (twice per second) broadcast the information using Mode S with Extended Squitter.

M.Strohmeier *et al.* [4] describes ADS-B as the 'Heart of modern air traffic control'. It provides the same functionality as a PSR but with better precision. The aircraft calculates the required information from a Global Navigation Satellite System (GNSS) or an inertial navigation system [10]. The aircraft sends out automatically and periodically ADS-B messages containing its position, altitude, speed, identity (tail number), squawk code, airport of departure and arrival and other relevant information [14, 21].

There are two types of ADS-B services: ADS-B IN receives ADS-B messages, and ADS-B OUT transmits ADS-B messages. There are different hardware for both services. ADS-B OUT is mandatory in Europe for new aircraft certified with a take-off mass exceeding 5700 kg or having a maximum cruising true airspeed capability above 250 knots [23]. Under similar altitude or speed, older aircraft have until mid-2023 to comply with this legislation [23].

As shown in Figure 2 ADS-B OUT primary function is to collect GPS data and information from the flight controller, encode it and transmit it through 1090MHz and broadcast it [4, 10]. At the same time, ADS-B IN receives the interrogation and displays it in human readable data. Both ATC and aircraft can install ADS-B IN receivers [10]. Adding the ADS-B IN to an aircraft will allow it to receive the information provided by ATC and other aircraft.

Although it is not mandatory, drone manufacturers are starting to install ADS-B IN to a wide range of drones. In contrast, this capability was previously only available for professional grade drones. One of these features includes a warning alerting the remote drone pilots if their drone appears to be on a collision course with another aircraft transmitting ADS-B messages.

A study to measure the impact of ADS-B accidents rate for 5 years (2013 - 2017) in aircraft found that ADS-B IN decreased the fatal accident rate by 89% [24].

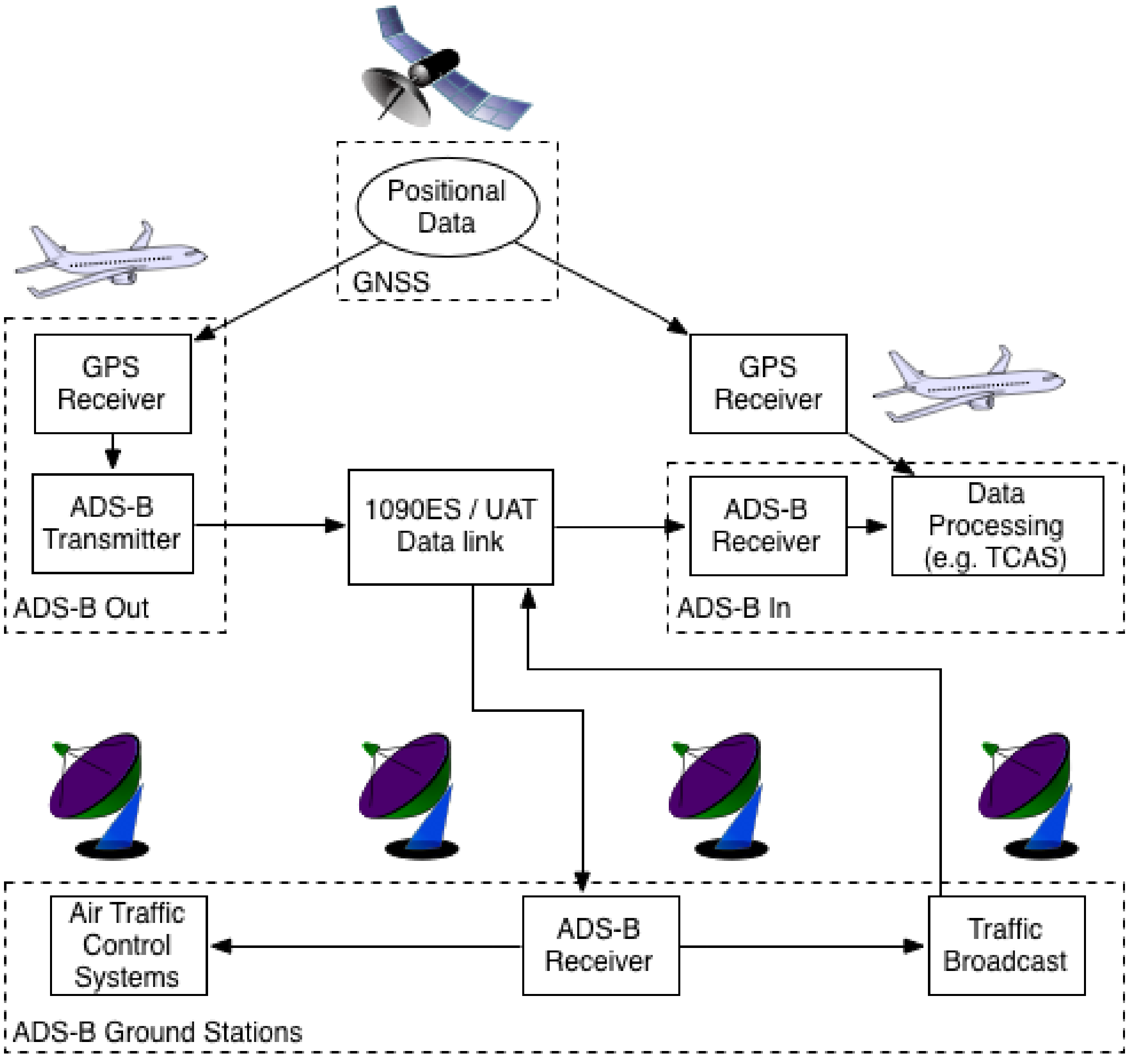


Figure 2. *ADS-B IN and ADS-B OUT function with aircraft, GNSS and ground station [4]*

2.3 ADS-B packets

ADS-B messages are transferred as plain text, unencrypted [25], as shown in Figure 3 [26]. The 1090 Megahertz Riddle book offers a thorough description of the packet's content [27].

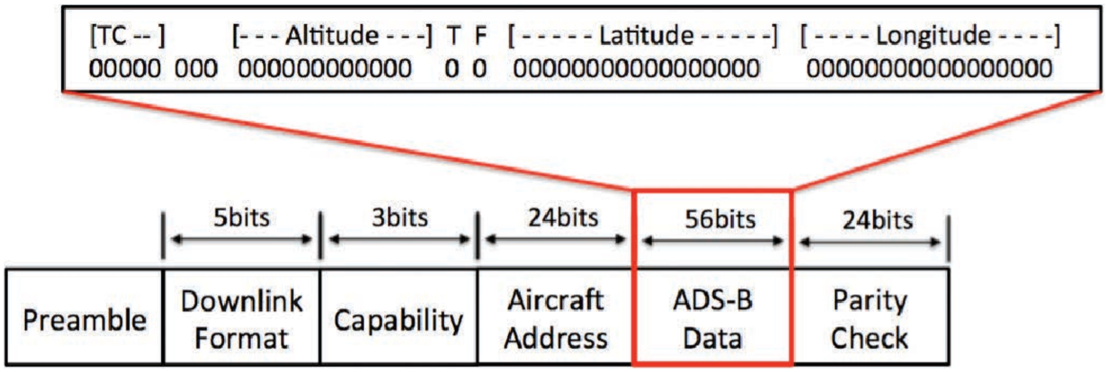


Figure 3. *ADS-B Message Sample [26]*

2.4 ADS-B vulnerabilities

Unencrypted messages are a critical security issue in Information Communication Technologies (ICT) [28]. "Attacks on ADS-B, can affect the information's confidentiality, integrity, and availability" [28]. ADS-B was developed and implemented, focusing mostly on safety, not security [14], therefore, it lacks authentication, message signatures, encryption, challenge-response mechanism or other ephemeral identifiers [25].

M. Strohmeier *et al.* gives an overview of ADS-B vulnerabilities [4]. These vulnerabilities can be exploited to launch cyber attacks such as [10, 13, 29, 30, 31, 32]:

- Aircraft reconnaissance;
- Ground station flood message denial of service attack;
- Aircraft flood message denial of service attack;
- Ground station ghost injection attack;
- Aircraft ghost injection attack;
- Aircraft spoofing attack;
- Virtual aircraft hijacking attack;
- Virtual trajectory modification attack;
- Aircraft disappearance.

2.5 Ghost injection attack

During a ghost injection attack, the attacker transmits well-crafted spoofed ADS-B messages, including fundamental properties and information that make its appearance identical to genuine messages received from real aircraft. Receiving these spoofed ADS-B messages has the potential to cause air traffic controllers or pilots of aircraft or drones equipped with ADS-B IN to become distracted and confused. Consequently, forced or denied landings, changes to flight paths or instructions to other aircraft to change their course, velocity, altitude (etc.) can occur. In some cases, a ghost injection attack could even result in life-threatening decisions made by pilots and controllers [29].

2.6 U-Space

SESAR vision is to provide a fully functional traffic management system that can handle the growing air traffic and to connect European aviation under one network [33]. U-Space is a framework with specific procedures designed to support safe, efficient, and secure access to airspace for large numbers of drones [33].

U-Space is based on several essential principles. To name a few, providing access to different users, ensuring their safety (either on ground or in airspace), high-density operations with multiple automated drones, and adopting new technologies in different sectors [1]. In order to develop such framework, appropriate measurements of cybersecurity, privacy and data protection are essential [1].

With the U-Space coming, thousands of drones will be flying Beyond Visual Line of Sight (BVLOS). Drone pilots and operators will have a struggle flying drones inside and outside of urban areas. Currently, ADS-B IN in drones is not activated in Europe, which undermines the drones' safety. Threod Systems and EANS covered a scenario of BVLOS by installing an ADS-B to track a drone's flight route. The successful trial over the Gulf of Finland (GOF or GOF U-Space) in 2019, a collaboration between Estonia and Finland under the umbrella of U-Space [34], showed that it was possible to track a drone throughout the whole flight from Estonia to Finland while delivering a parcel [35].

The SESAR U-Space Communication, Navigation and Surveillance (CNS) has ADS-B as one of the bases of its backbone infrastructure [36]. The CNS roadmap shows that ADS-B IN implementation will start around the year 2025 [36]. The SESAR "pays special attention to cybersecurity resilience considerations while still ensuring interoperability for civil-military CNS in current and future CNS infrastructure services and performance equivalence" [37].

Currently, two companies provide drones equipped with ADS-B IN DJI and Yuneec. DJI is the world-leading company for the commercial drone market. DJI installs ADS-B IN receivers starting from the 01st of January 2020 with the AirSense Technology [38]. AirSence is a system that uses ADS-B to alert pilots from aircraft flying near the drone [38].

3. Related work

Manesh *et al.* [15] simulated a ghost injection attack on an aircraft using a drone. The paper concluded that a ghost injection attack can distract pilots and air traffic controllers and force them to change course or execute unplanned manoeuvres which can threaten the security and safety of airspace [15].

Smith *et al.* [39] stated that cybersecurity in aviation is a recent concern. They identified how pilots reacted to different wireless communication attacks [39]. One of the communication protocols that the authors covered in the paper [39] is the Traffic Collision Avoidance System (TCAS), similar to the ADS-B DAA. Thirty pilots participated in their experiment [39] which consisted of being placed in an aircraft simulator that underwent cyber attacks on the TCAS system. The attack aimed to cause the pilots to burn extra fuel and affected situational awareness [39]. According to participants, injecting spoofed aircraft into the system was the most concerning attack, with 86.7% of the pilots reducing the sensitivity of TCAS and 36.7% of the pilots switching the TCAS system off entirely [39]. Both result in reducing the pilot's situational awareness [39]. After the flight, the participants answered the following questions [39]:

- "Would you trust systems under cyber-attack in flight?" 73.4% responded "No" [39].
- "Does the cyber-attack put the aircraft in a less safe situation?" 93.3% responded "Yes" [39].
- "If participants would respond the same way in a real aircraft?" 100% Responded "Yes" [39].

The above results show how an experimental attack on well-trained pilots can endanger the safety of a flight and lessen the pilots' trust towards a system.

Moreover, in a different experiment that tested the performance of 20 pilots in 2 scenarios: anticipated condition and surprise condition; shows that even skilled pilots could not follow well-known procedures when an unexpected attack occurred [6].

4. Experimental setup

The experiment makes use of a flight simulator. After a market survey, the software RealFlight 9.5 (see Appendix 1) was selected because it can support drones, offers good capabilities and a realistic environment. Each drone comes with its own controller [40] and to give a better flying experience. The participants used an Xbox One Wireless Controller [41] similar to the one in Figure 4 to control the drone. The simulation used the hardware, including the controller, of the Augmented Reality lab located in Tallinn University of Technology (Mektory XR Centre [42]).

Figure 4. *Xbox One Wireless Controller [41]*

Figure 5 shows a screenshot of the simulator. The participants got parameters such as speed, altitude, battery remaining, rotation speed of propellers, wind speed, GPS coordinates, time flown, and a video stream from the onboard camera.

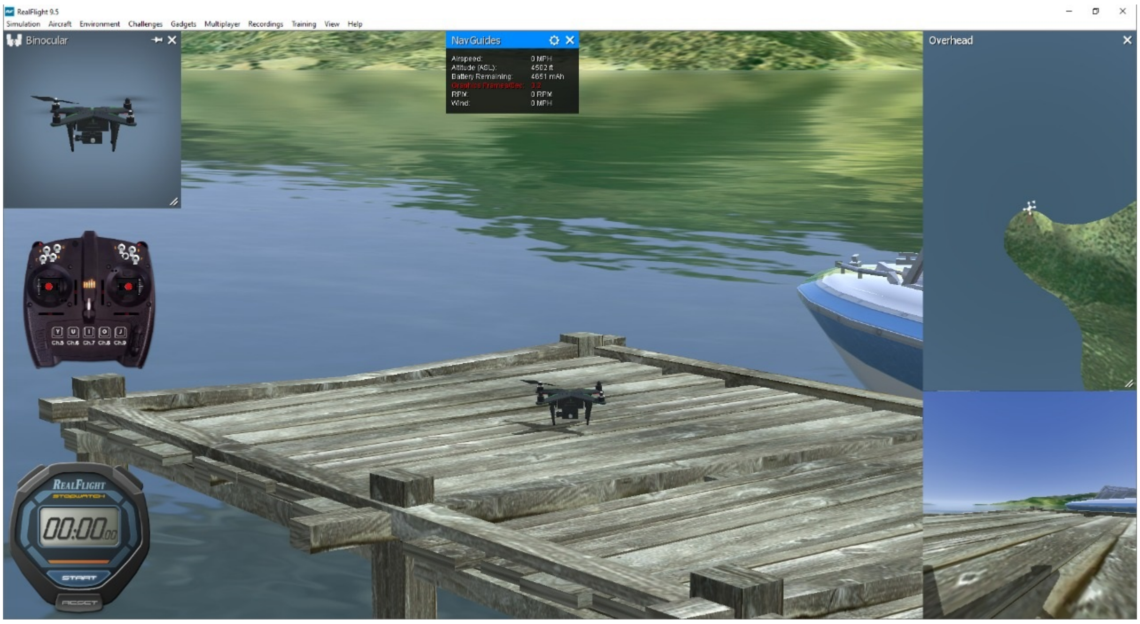


Figure 5. *Screenshot of RealFlight 9.5 flight simulator*

The Table 1 depicts the recommended optimal performance system for RealFlight 9.5 according to RealFlight official website [43] and the computer used for the experiment. The high-end computer power ensured a sufficient performance level. The computer used for the experiment covers all the requirements of RealFlight 9.5.

Table 1. *Recommended optimal performance system for RealFlight 9.5 VS the computer that was used for the experiment*

Hardware requirements	**Recommended optimal performance system for RealFlight 9.5 [43].**	**Computer used for the experiment**
Operating system (OS)	Windows 7 or Windows 8 or Windows 10	64-bit Windows 10 operating system
Central Processing Unit (CPU)	Dual Core 2.4GHz CPU	Intel® Core™ i7-9700KF Processor 3.6GHz
Random Access Memory (RAM)	2 GB RAM	32 GB RAM
Graphical performance/ Graphics Processing Unit (GPU)	3D Accelerated Video with: 512 MB dedicated video memory	NVIDIA RTX 2080Ti graphic card
Controller	USB 2.0 Port or Compatible FM	Xbox One wireless Controller

Continues...

Table 1 – *Continues...*

Requirements	Recommended optimal performance system for RealFlight 9.5 [43].	Computer used for the experiment
Virtual Reality (VR) capabilities	Compatible with some VR sets	Valve Index

4.1 Brain sensing headband

Participants were connected to the headband Muse 2 [44], similar to the one shown in Figure 6 [45], to record their brain activity. The sensor utilises electroencephalography (EEG), photoplethysmogram (PPG), accelerometer, and gyroscope [44].

Figure 6. *Muse 2 brain sensing headband [45]*

Muse 2 EEG sensors are focused on four parts of the brain: AF7, AF8, TP9, and TP10. As described in [46, 47, 48, 49]: Odd numbers stand for the left side of the brain, while even numbers are for the right side. "AF" stands for pre-frontal lobe and frontal lobe. This part of the brain is responsible for reasoning, judgment, creativity, planning and impulse control. "TP" stands for temporal lobe, which is vital for hearing, memory, learning, and interpreting languages, and the parietal lobe, which is responsible for understanding senses from touch, taste, pain and pressure. Another possibility is to do the VP300 test using EEG-Notebooks [50] with the collected EEG data from participants.“The Visual P300 is a positive event-related potential (ERP) that occurs around 300ms after perceiving a novel or unexpected stimulus.” [51].

The Muse 2 was utilised in the experiment to analyse the reactions in the brain and impulse control when the attack is initiated; different data from other sensors was collected for further investigation.

4.1.1 Muse 2 technical details

Muse LSL created and recorded the data stream from the sensors of Muse 2. The source code is available on GitHub [52]. Muse LSL requires BlueMuse [53] to run on Windows, however, due to Bluetooth connection issues a Linux machine was used instead running Python 3.8 and a few other Python models and packages. A Bash script, as shown in Figure 7, collected the participants' data. The green comments describe the purposes of each command.

```bash
#!/bin/bash
# Initiate a terminal to run the command for collecting data
   from EEG sensors (AF7, AF8, TP9 and TP10) for 10 minutes (600
    seconds).
gnome-terminal -e "muselsl record --duration 600"
# Initiate a terminal to run the command for collecting data
   from accelerometer sensors for 10 minutes (600 seconds).
gnome-terminal -e "muselsl record --type ACC --duration 600"
# Initiate a terminal to run the command for collecting data
   from gyroscope sensors for 10 minutes (600 seconds).
gnome-terminal -e "muselsl record --type GYRO --duration 600"
# Initiate a terminal to run the command for collecting data
   from PPG sensors for 10 minutes (600 seconds).
gnome-terminal -e "muselsl record --type PPG --duration 600"
```

Figure 7. *Bash script content for recording Muse 2 data stream*

The script runs four different Linux terminals and records the data stream from the Muse 2 sensors for 10 minutes. Each terminal runs another Muse LSL command to collect data from various sensors in the headband. A computer program exported each command to a Comma Separated Value file (.CSV). Appendix 2contains a sample output data of the .csv files presented in tables that were generated by Muse LSL.

MatLab uses the EEGLAB package for analysing and visualising the EEG data. Figure 8 shows a 15 seconds sample of the EEG brain activity collected from Muse 2 and each sensor readings for testing.

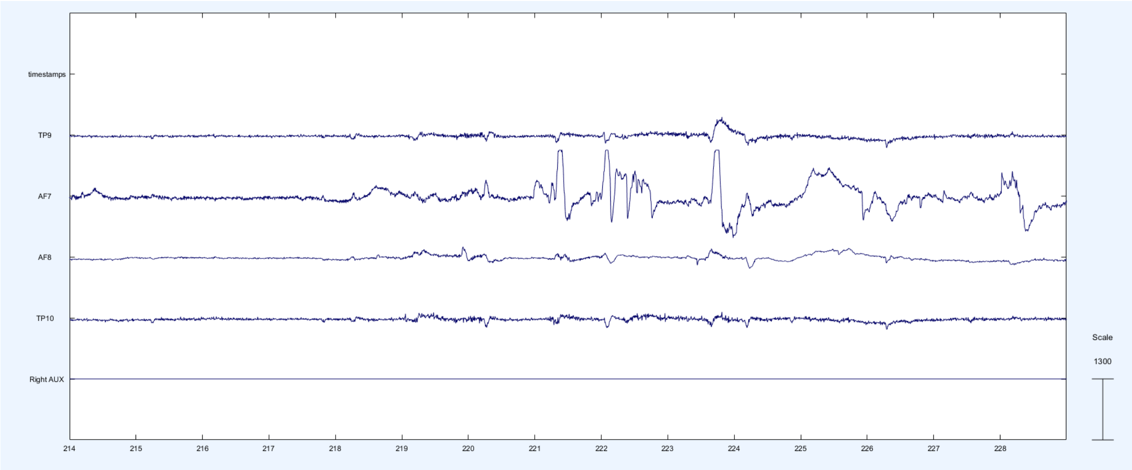


Figure 8. *MatLab EEGLAB 15 seconds recorded data from Muse 2*

4.2 Flight Scenario

The scenario is an emergency organ transport from a hospital in Helsinki to the East Tallinn Central Hospital. A crewed helicopter transports the organ to Tallinn City Hall Heliport (International Civil Aviation Organization (ICAO) identifier: EECL), and from there, a drone continues the transfer to the hospital (see Figure 9). The drone pilots are aware that the timing of the mission is of crucial importance and any delay in delivery might result in the death of the patient in question.

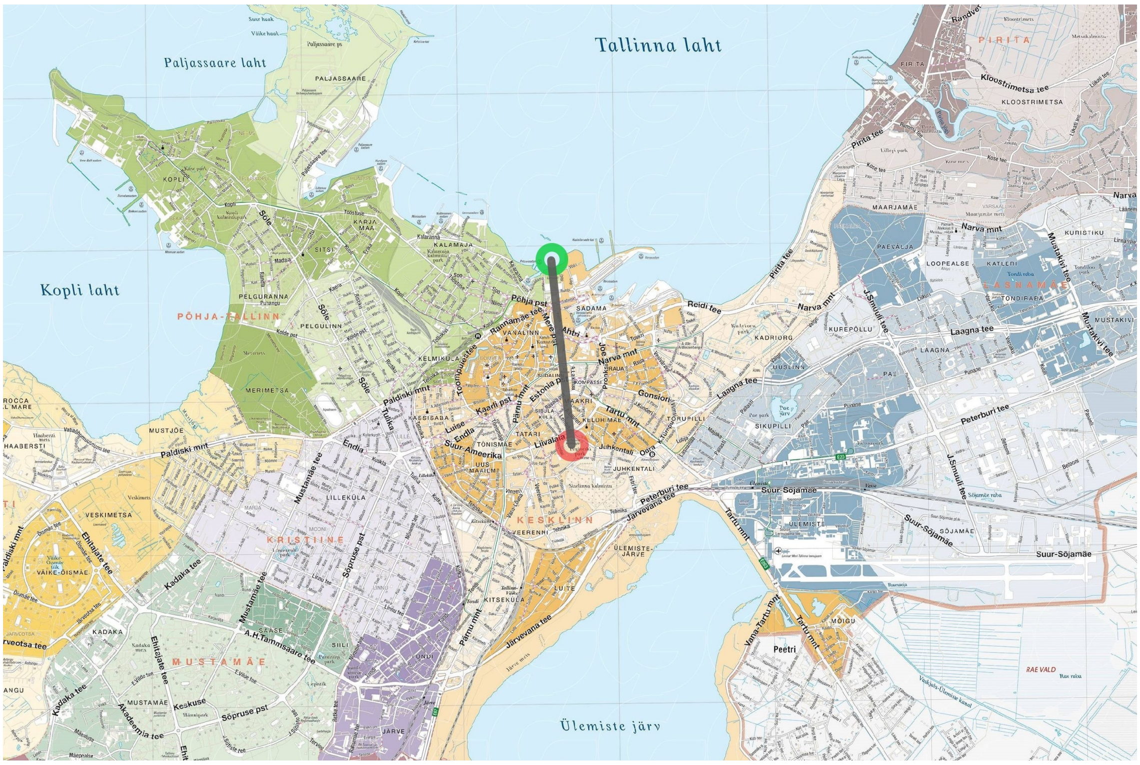


Figure 9. *Flight EECL to East Central Hospital Tallinn [54]*

4.3 Attack Scenario

The attacker spoofs ADS-B messages by indicating a fake aircraft close to the drone's position. The drone's software analyses the captured ADS-B messages received from the ADS-B IN sensor. If the decoded message indicates an imminent threat of an in-air collision, the drone operator will get a message on the screen. The participants were not aware that a cyber attack would be launched during the mission until the debriefing afterwards.

Three iterations of a simulated ghost injection attack were implemented, with the first appearing three and a half minutes after take-off. The second attack takes place thirty seconds after the first one, and finally the last one also appears after an interval of thirty seconds. The drone pilot sees the message in Figure 10 when an aircraft is in close vicinity.

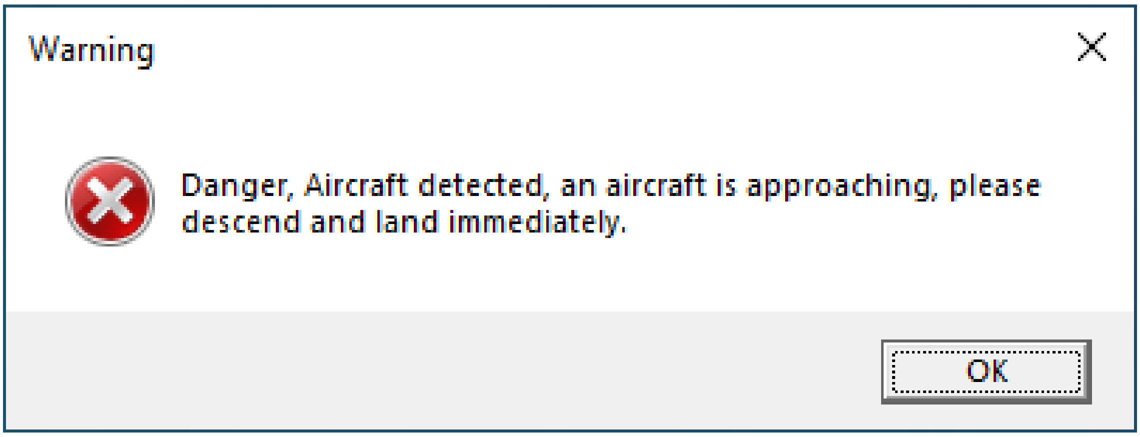


Figure 10. *Warning message for imminent danger*

4.3.1 Simulated attack implementation

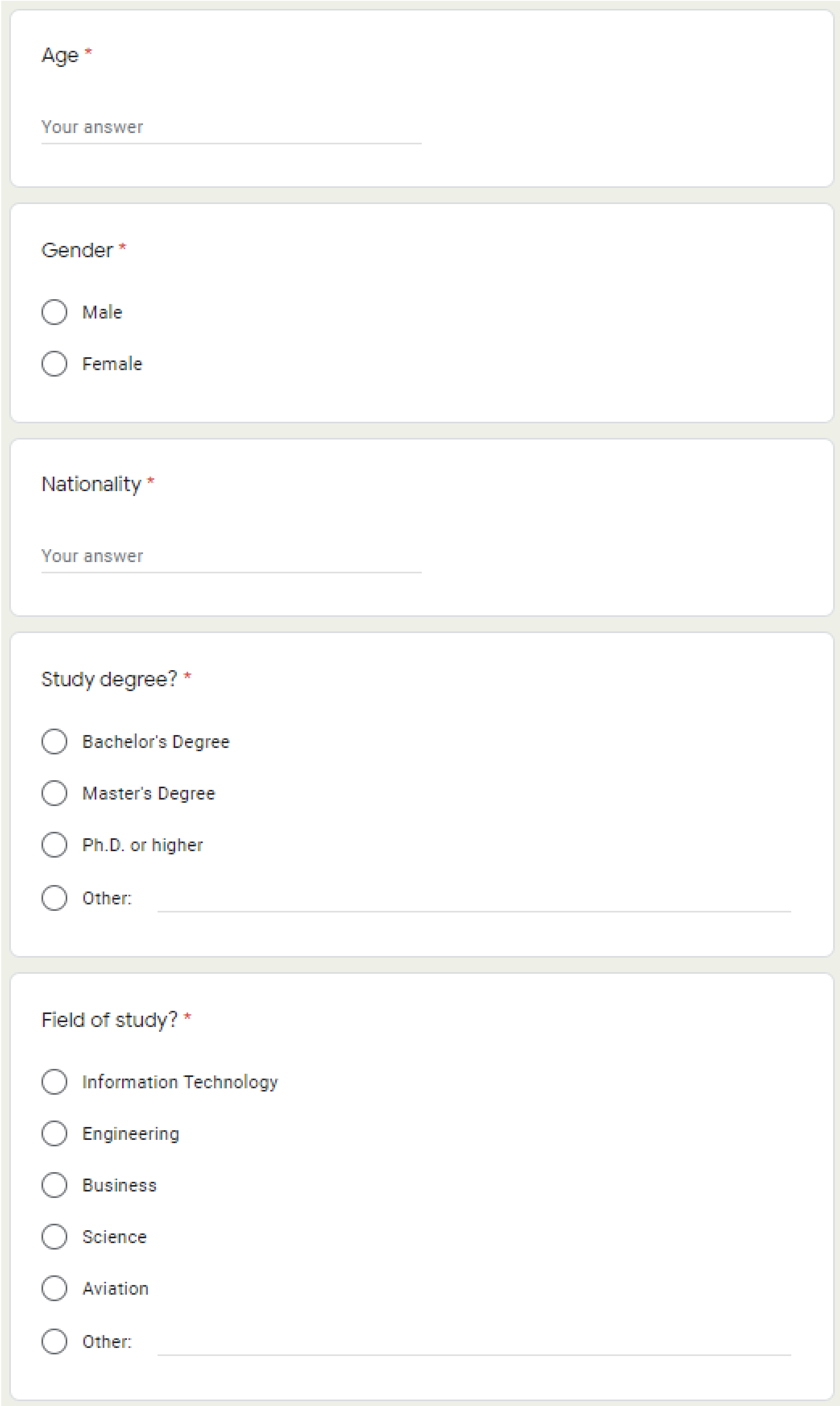
The PowerShell Script in Figure 11 simulates the attack. Comments in green are added to describe each command. We remapped the controller buttons on the Xbox One controller to initiate the script when the user started the mission and the timer.

```
# loading the assembly of "System Windows Forms" to show the
    warning message
[System.Reflection.Assembly]::LoadWithPartialName("System.
    Windows.Forms")
# Pause during execution for 3:30 minutes (180 seconds)
Start-Sleep -s 180
# First warning message after 3:30 minutes of starting the
    mission
[System.Windows.Forms.MessageBox]::Show("Danger, Aircraft
    detected, an aircraft is approaching, please descend and land
     immediately."
,"Warning",[System.Windows.Forms.MessageBoxButtons]::OK,[System.
    Windows.Forms.MessageBoxIcon]::Error)
# Pause during execution for 30 seconds
Start-Sleep -s 30
# Second warning message after 4:00 minutes of starting the
    mission
[System.Windows.Forms.MessageBox]::Show("Danger, Aircraft
    detected, an aircraft is approaching, please descend and land
     immediately."
,"Warning",[System.Windows.Forms.MessageBoxButtons]::OK,[System.
    Windows.Forms.MessageBoxIcon]::Error)
# Pause during execution for 30 seconds
Start-Sleep -s 30
# Third warning message after 4:30 minutes of starting the
    mission
[System.Windows.Forms.MessageBox]::Show("Danger, Aircraft
    detected, an aircraft is approaching, please descend and land
     immediately."
,"Warning",[System.Windows.Forms.MessageBoxButtons]::OK,[System.
    Windows.Forms.MessageBoxIcon]::Error)
```

Figure 11. *PowerShell Script to generate the simulated attack message*

4.4 Experiment

Participants had 15 minutes to familiarise themselves with the test setup before flying the mission. After the mission, they filled in a form (see Figure 12) that requested details of age, gender, nationality, study degree, and study field. One aim of the feedback was to understand why the participants either obeyed or ignored the warning messages indicating the immediate need of landing the drone. The interview aimed to verify whether the participants reacted as they would have in a real-life scenario or if their behaviour was different since the test setup was not authentic enough to portray a lifelike scenario.



Age *

Your answer

Gender *

- ◯ Male
- ◯ Female

Nationality *

Your answer

Study degree? *

- ◯ Bachelor's Degree
- ◯ Master's Degree
- ◯ Ph.D. or higher
- ◯ Other:

Field of study? *

- ◯ Information Technology
- ◯ Engineering
- ◯ Business
- ◯ Science
- ◯ Aviation
- ◯ Other:

Figure 12. *Participants' form*

The interview questions were as follows:

- Landed after the warning/continued with the mission?
- Do you have any prior experience with flying a drone before? For how long?
- What field of drone are you working with?
- Are you a commercial/military/private pilot?
- Have you had any experience with flying remote-controlled (RC) aircraft/helicopters?
- What do you think about the experiment - was it realistic?
- What do you think about the scenario?
- Did you think of the mission as a game or a real-life situation?
- Would you do the same if you were in the same situation in real life?
- Why did you decide to land after the warning?
- How many warnings did you see before you started descending?
- Why did you decide to continue with the mission?

The flight simulator timer measured the total flight time. An observer judged whether the drone landed at the final destination, somewhere between the heliport and the hospital or returned to the heliport from where it started.

4.5 Consent of participation

All participants signed an agreement consisting of the purpose of the study, benefits to participants and society, potential risks or discomfort, and confidentiality. Appendix 3 shows a sample of the consent.

4.6 Selection of drone pilots

The drone pilots for the simulator were students from different educational facilities in Estonia, such as the Estonian Aviation Academy (EAVA), the Tallinn University of Technology (School of Engineering), and the Tallinn University (School of Natural Sciences and Health). We shared this information and the Doodle form for participation with Threod Systems and Dronee, two Estonian drone companies.

94 slots from the 05th of January 2021 till the 29th of January 2021 were available for participating in the experiment. 69 slots were filled and 25 were left free. The timetable in Figure 13 shows booked time of the experiments in January 2021. Due to Covid-19, 28% of participants were not able to participate and join the experiment.

Time	Monday	Tuesday	Wednesday	Thursday	Friday	Sunday
					1	3
Time	4	5	6	7	8	10
10:00 – 11:00		Booked	Free	Booked	Free	
11:00 – 12:00		Free	Booked	Booked	Free	
12:00 – 01:00		Booked	Booked	Booked	Booked	
01:00 – 02:00		Booked	Free	Booked	Booked	
02:00 – 03:00		Booked	Free	Booked	Booked	
03:00 – 04:00		Booked	Free	Booked	Booked	
	11	12	13	14	15	17
10:00 – 11:00	Free	Free	Free	Booked	Free	
11:00 – 12:00	Free	Free	Booked	Booked	Free	
12:00 – 01:00	Free	Booked	Booked	Booked	Free	
01:00 – 02:00	Booked	Booked	Booked	Booked	Booked	
02:00 – 03:00	Booked	Booked	Free	Booked	Booked	
03:00 – 04:00	Free	Free	Free	Booked	Booked	
04:00 – 05:00					Booked	
	18	19	20	21	22	24
10:00 – 11:00		Booked				
11:00 – 12:00		Booked				
12:00 – 01:00		Booked				Booked
01:00 – 02:00		Booked				Booked
02:00 – 03:00		Booked				Booked
03:00 – 04:00		Booked				Booked
04:00 – 05:00		Booked		Booked		Booked
05:00 – 06:00		Booked				
	25	26	27	28	29	31
10:00 – 11:00	Booked	Booked		Free	Booked	
11:00 – 12:00	Booked	Booked		Booked	Booked	
12:00 – 01:00	Booked	Booked		Booked	Booked	
01:00 – 02:00	Booked	Free		Booked	Booked	
02:00 – 03:00	Booked	Free		Booked	Booked	
03:00 – 04:00	Booked	Free		Free	Booked	
04:00 – 05:00					Booked	

Figure 13. *Free and booked time slots during January 2021*

In total, 50 people participated as shown in Table 2; 2 of them had previous experience as professional aircraft pilots, 4 had mid-level skills after having operating drones for several years, and 7 had accumulated lower level skills in drone flying. The participants came from a total of 21 different countries, as shown in Figure 14.

Table 2. *Participants' experience level*

Level of experience	**Number of participants**
Mid-level	4[a]
Lower level skills	7
Not experienced	39
Total	**50**

[a] Including 2 aircraft pilots

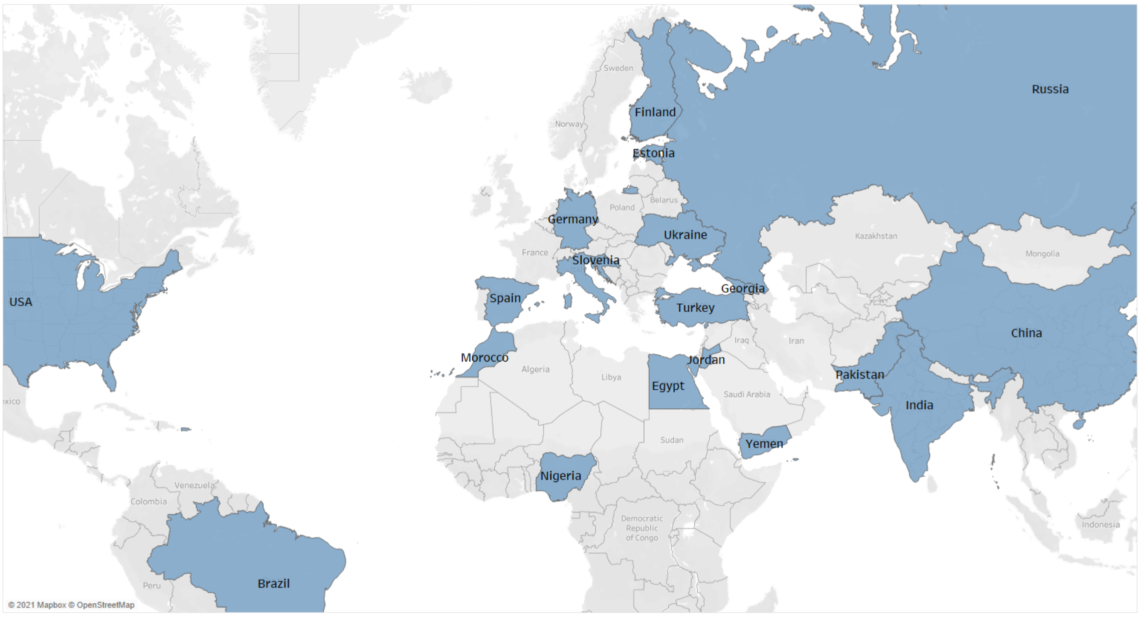


Figure 14. *Participants' nationalities*

4.7 Feedback

After completing the experiment, the participation form and the interview, the participants also filled in the form depicted in Figure 15 to rate the experience and leave feedback, comments, remarks, or suggestions. The form was compiled to gain an overview of opinions regarding the success of the experiment in the eyes of participants; and to collect any comments the participants might not have shared directly during the interviews with observer.

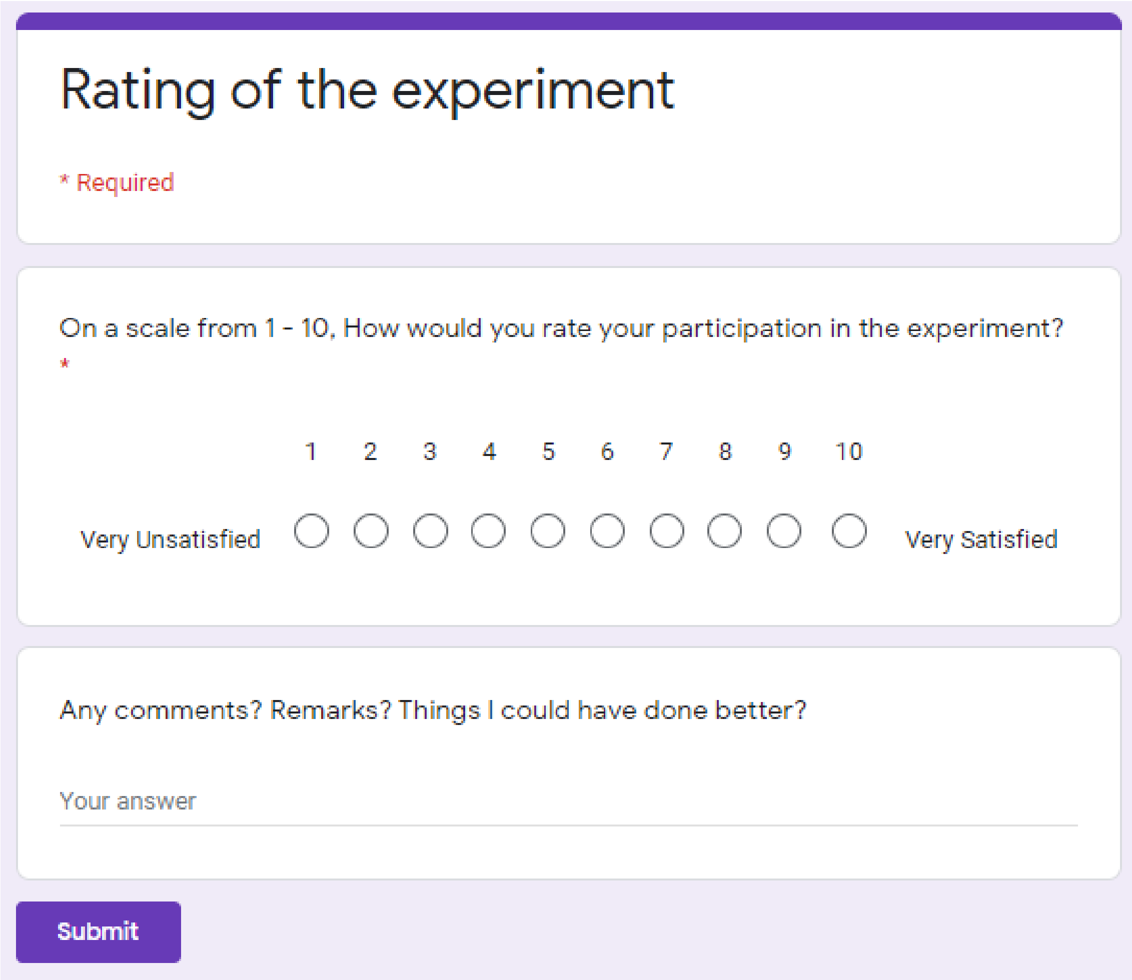


Figure 15. *Form for rating the experiment and feedback*

4.8 Demographic data

Figure 16 depicts the gender of participants and clarifies that 56% of them were male and 44% were female. Participants minimum age was 19, and the highest was 44. Most participants fell into the age group between 21 and 24 (see Figure 17 for more details). 23 participants are currently studying engineering or have previously completed a degree in engineering. Other participants were from several different fields of study such as business, IT, science, education and aviation (see Figure 18). In total, 49 students have already received a degree or are still pursuing tertiary education. Figure 19 shows the distribution between Bachelor's, Master's, PhD and others.

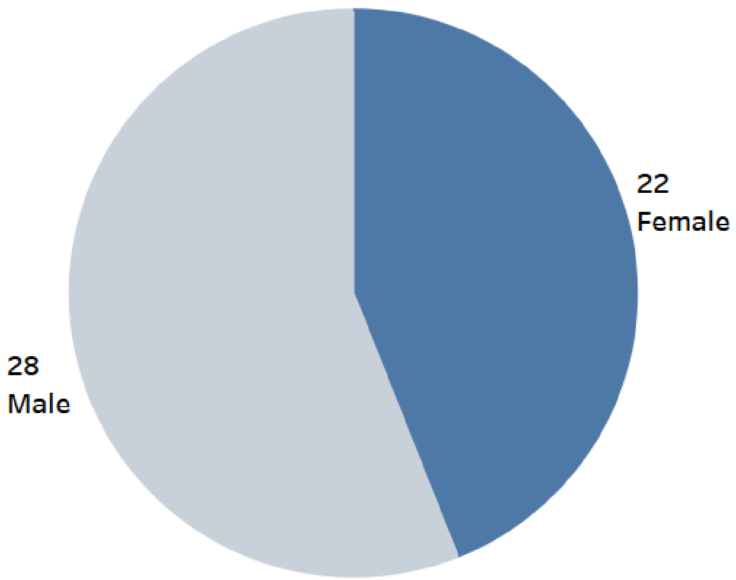


Figure 16. *Participants' gender*

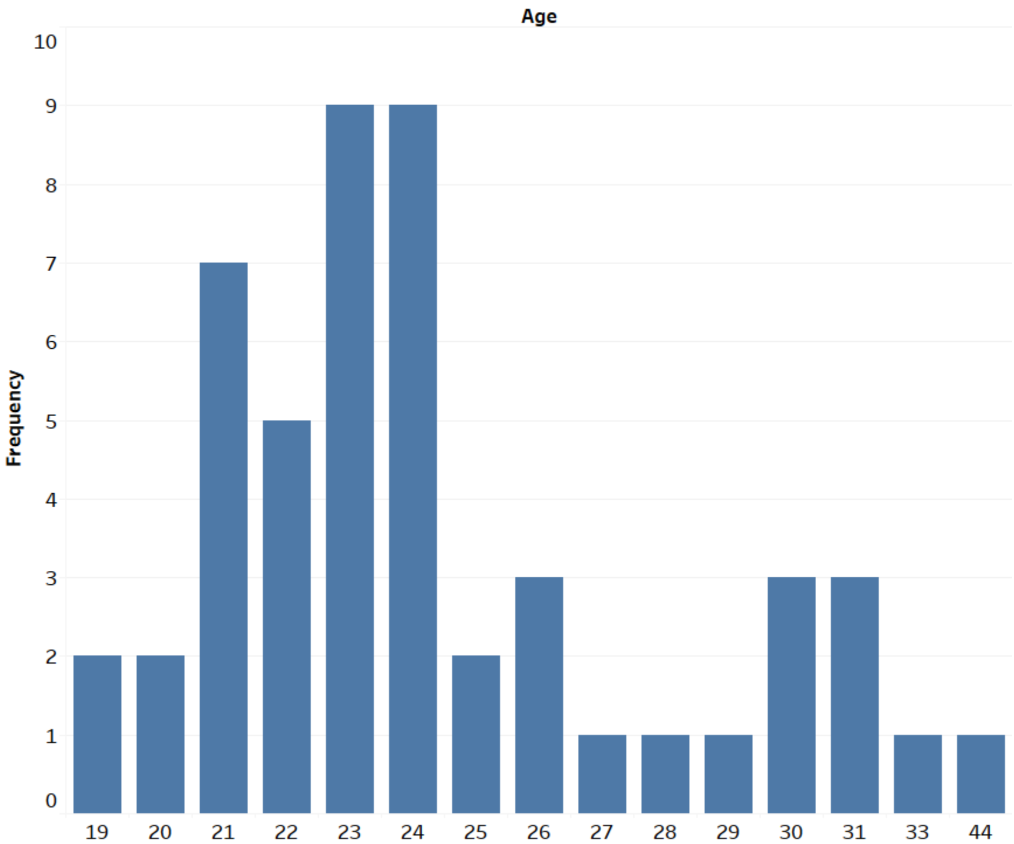


Figure 17. *Participants' age*

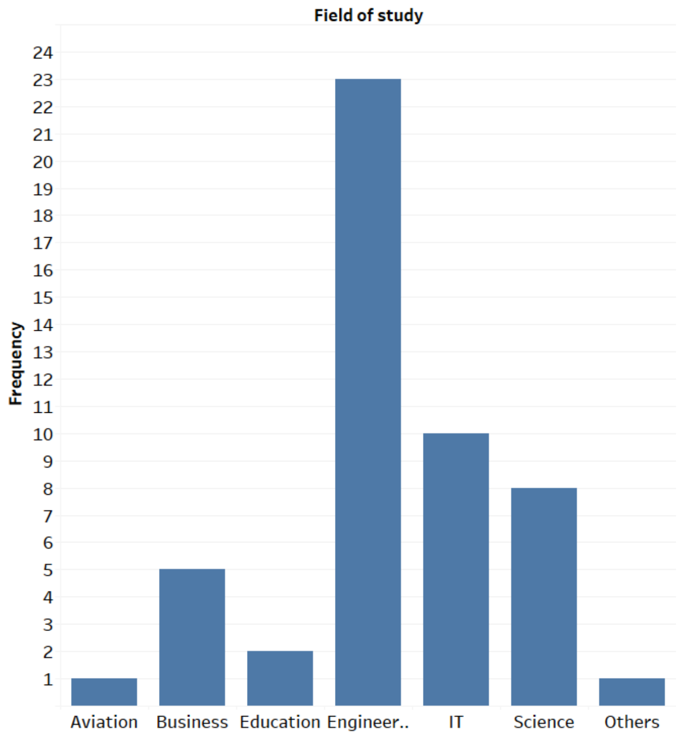


Figure 18. *Participants' field of study*

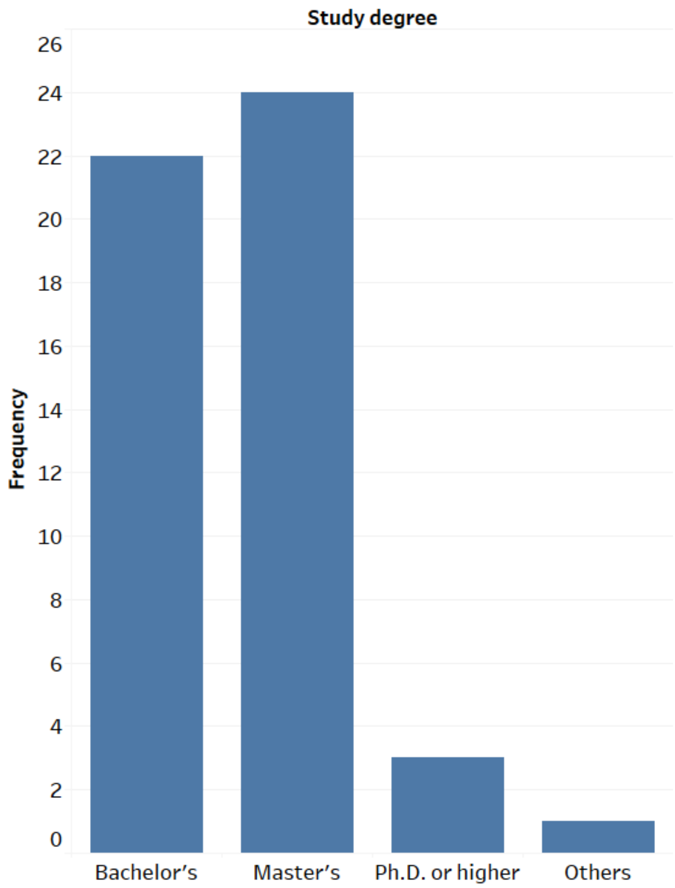


Figure 19. *Participants' study degree*

5. Results

5.1 Feedback

The experiment was enjoyable for most participants, as was stated in their answers. One of the participants wrote: "Fun experience, but I was aggressive with the controller by the end, and I wanted to get the organ to the hospital in time". Many others noted that the scenario was engaging.

The bar graph in the Figure 20 below shows how participants rated their participation in the experiment on a scale from 0 (Very unsatisfied) to 10 (Very satisfied). Twenty-five participants graded the experiment by the maximum score. None of the participants rated it with less than 7. The average result is over 9 out of 10.

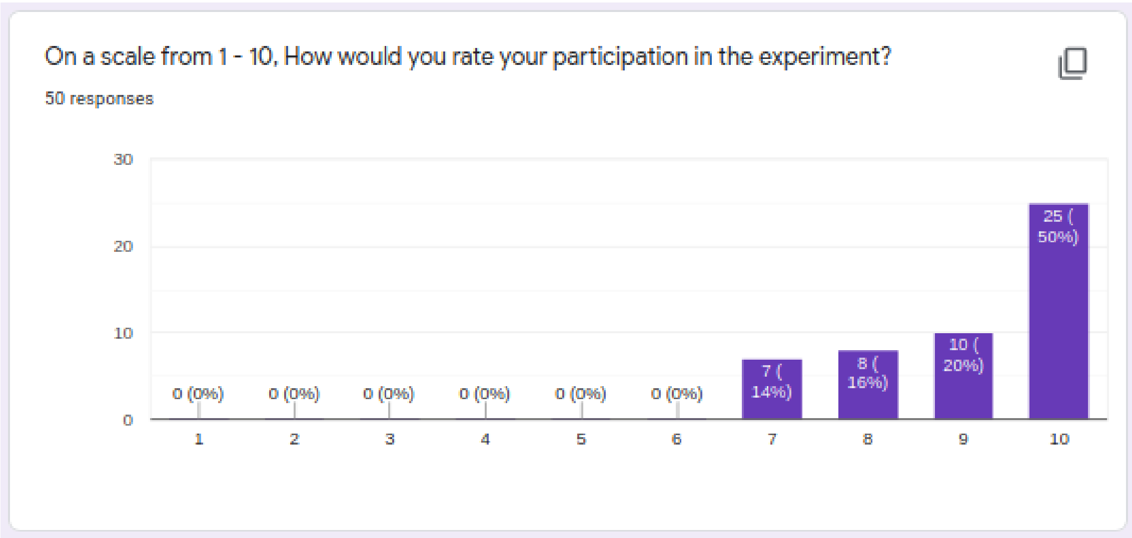


Figure 20. *Participants' experiment rating*

5.2 Recording EEG, PPG, accelerometer, and gyroscope

Figure 21 shows a collected sample data with the attack time at 3 minutes and 45 seconds after take-off, marked with the first vertical line. A peak in brain activity is easily distinguishable after this event. This participant landed after 4 minutes and 21 seconds of flying and the increased brain activity remains clearly distinguishable until the drone has been landed. It is noticeable that the participant's brain activity was less smooth after landing the drone than before the attack happened. The Muse 2 data stream starts 10 to 20 seconds before the mission begins to see if there is an impact on brain activity by starting the flight. However, this is not the case with this participant. The brain activity 'judgment' and 'impulse control' (AF7 and AF8) show the best correlation of the participant brain activity and the scenario.

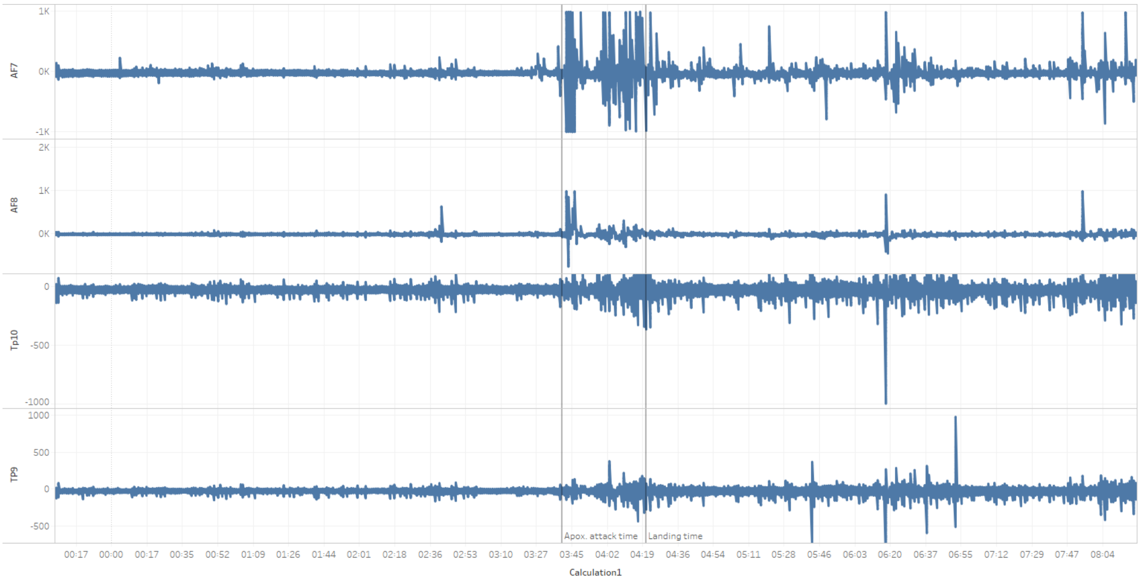


Figure 21. *Muse 2 EEG data sample of a participant*

Significant challenges regarding data collection involved the maintenance of the live stream of the Muse 2 data. Some of the Muse 2 data was unreliable, therefore, we do not have enough data to make justified conclusions on brain activity after a cyber attack. On the other hand, the results of the participants that were correctly recorded do not show any incoherence. Ultimately, we excluded the brain wave results from the analysis of the experiment.

5.3 Correlations between parameters

We looked for correlations among parameters (see Table 3) and landing the drone before it had reached its destination or not. Some of the observed correlations, such as age and course of study, landing before arriving at destination point and flight time, were not relevant for this research.

There is no indication that experience in flying drones or crewed aircraft influences the decision to land immediately or to continue the mission. Still, a clear correlation exists between being Estonian or non-Estonian.

Table 3. *Correlation matrix of variables values that where collected during the experiment*

	Age	Gender	Nationality	Est - Non Est	Study degree	Field of study	Landed or Continued	Time flown	Descend after warning	Realistic experiment	Real/Fake
Age	1										
Gender	0.343	1									
Nationality	-0.019	0.212	1								
Est - Non Est	0.271	0.345	0.550[a]	1							
Study degree	0.640[a]	0.314	0.206	0.438[a]	1						
Field of study	-0.325	-0.298	0.050	-0.125	-0.135	1					
Landed or Continued	-0.024	-0.225	-0.376[a]	-0.711[a]	-0.205	0.197	1				
Time flown	0.034	0.165	0.362[a]	0.655[a]	0.157	-0.113	-0.916[a]	1			
Descend after warning	-0.038	-0.274	-0.399[a]	-0.645[a]	-0.206	0.272	0.911[a]	-0.806[a]	1		
realistic experiment	-0.043	-0.160	-0.324	-0.256	-0.104	-0.122	0.208	-0.077	0.240	1	
Real/Fake	0.197	0.053	-0.305	-0.022	-0.095	0.039	0.371[a]	-0.238	0.338	0.146	1

[a]significant $p - value < 0.01$.

5.4 Recorded landing times

Of the 50 participants, 8 stated that the scenario was not realistic enough to measure what they would have done in a real-life scenario. All these 8 participants continued the mission. We ignored those answers since the research looks at how people react in a real-life scenario.

One participant landed before the first attack took place. She declared afterwards, "I did not know what to do, and I was still near the start point." We discarded the data from this participant because the flight simulator showed no warning message.

Figure 22 shows the timeline of the remaining 41 participants, of whom 15 participants landed after one alarm and 5 participants after the second alarm. None of the 21 participants who continued the mission after receiving the second warning message changed their mind after receiving the third message and continued their flight until reaching the destination point.

In Figure 22 the reference vertical red lines indicate when the warning messages appeared, and the green lines show when participants decided to land before reaching the destination. Blue lines visualise the times when participants landed on the destination spot.

Since the experiment took place in Estonia, this nationality had a larger representation (17 out of 41) than other nationalities (between 1 and 3 participants per country). Of the Estonian participants, 13 landed after the first warning message, and 4 participants landed after the second alarm. None of the Estonians continued the mission after the third alarm.

Among the non-Estonian participants, 2 out of 24 participants landed after the first alarm, and only 1 participant landed after the second alarm. The remaining 21 participants continued their mission.

We take as null hypothesis that there is no difference in landing before reaching the destination or continuing the mission between Estonians and non-Estonians. Table 4 shows the distribution of the participants.

Table 4. *Distribution table of participants that landed or continued the mission by nationality*

	Estonian	**Non-Estonian**	**Total**
Landed after the warning	17	3	20
Continued the mission	0	21	21
Total	17	24	41

By using a χ^2 test we obtain 30,49. With one degree of freedom, this means that the chance that there is no correlation is low (less than one chance in 15 million).

We also explored from the answers from the interview the reasons why participants landed earlier or not. There was no significant difference in the participants' reasoning regarding nationality (being Estonian vs non-Estonian). Participants who landed earlier stated that they decided to land because the system advised them to do so or because they were afraid of an in-air collision. Participants who continued their mission said that the mission was more important or that the drone's onboard camera showed no other aircraft or other threat.

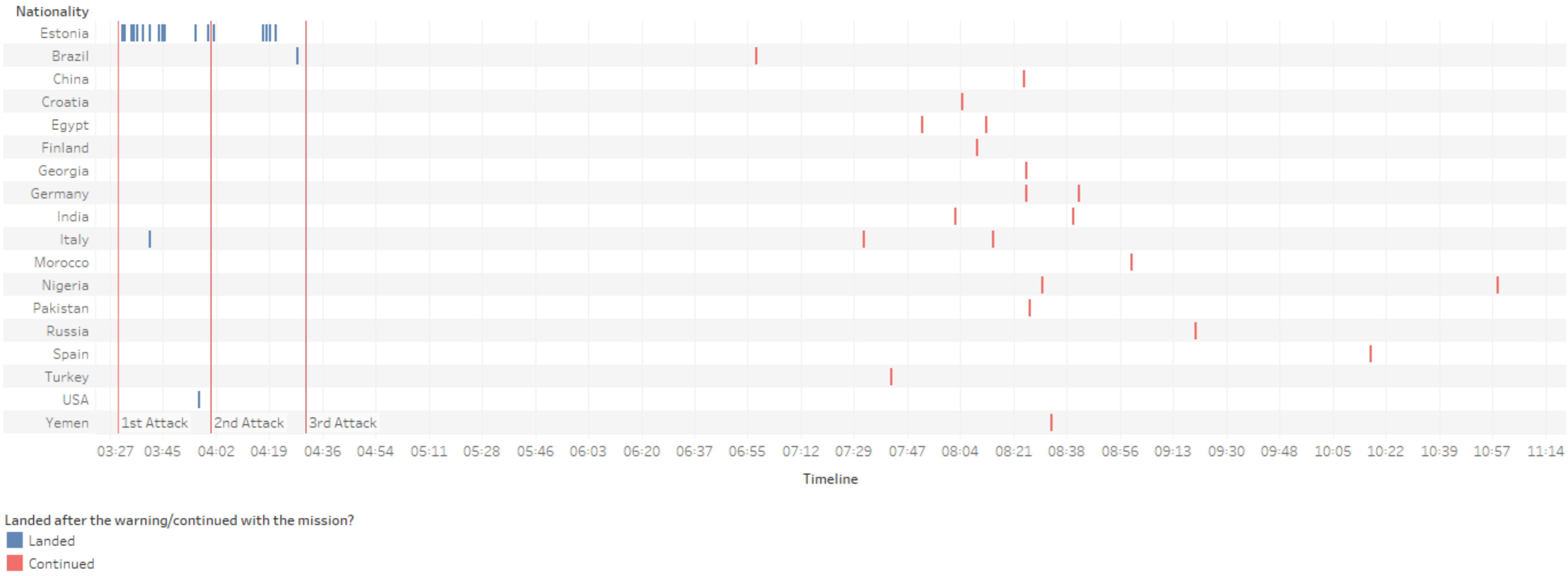


Figure 22. *Participants timeline and attacks between take-off and landing*

6. Conclusion

The process of comparing the group of participants who landed before reaching the destination alongside those who did not was not identifiable by socio-demographics (age, education level and field, gender). Since both groups received similar instructions for the task and the only correlation that appeared was whether the flight participants were Estonian or coming from abroad. This indicates that nationality could play a role in prioritising a mission or a task versus obeying rules and regulations when facing a ghost injection attack on ADS-B equipped drones. There were no correlations found between experience in flying, neither remote controlled nor manned. We acknowledge that there may exist psychological phenomenons that led to this result and were not measured. Those can be but are not limited to emotions, stress tolerance, resilience, internal locus of control, or other personality traits.

7. Future work

Additional research on the underlying parameters as to why people from Estonia reacted differently when compared to those from abroad should be performed. Examining the underlying reasons why people would react in this way is key.

Retaking this experiment with a bigger population size would increase the accuracy of the results. Conducting the experiment in other countries could give interesting results from a perspective of the behaviour of different nationalities versus foreigners.

It would be useful to integrate brain activity measurements, heart rate, muscle activity and flight accuracy data into the experiment to assist in determining the root cause of the results seen in this research.

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Appendices

Appendix 1 - Selecting the simulator

The Wikipedia page "RC flight simulator"[1] provide 37 remote-controlled flight simulators. With additional research on gaming platforms such as Steam[2] and VivePort[3] few more options were added to the list. Microsoft Flight Simulator[4] was also considered, but the release date was 22nd of December 2020[5]. The plan was to have the tests in January 2021.

The Augmented reality lab had 4 different simulators to try:

- RC Flight Simulator 2020 VR on VivePort[6].
- X-Plane on Steam[7].
- FPV Speed Drone on Steam[8].
- DCS World Steam Edition[9].

The reason to pick RealFlight 9.5[10] was because of its capabilities and most importantly the following features[11][12]:

[1] RC flight simulator Wikipedia page: https://en.wikipedia.org/wiki/RC_flight_simulator

[2] Steam offical website: https://store.steampowered.com/

[3] VivePort official website: https://www.viveport.com/

[4] Microsoft Flight Simulator on Steam https://store.steampowered.com/app/1250410/Microsoft_Flight_Simulator/

[5] Microsoft Flight Simulator release date for PC: https://news.xbox.com/en-us/2020/12/22/microsoft-flight-simulator-virtual-reality-update-available-now/

[6] RC Flight Simulator 2020 VR on VivePort: https://www.viveport.com/33799801-145c-42eb-85db-bc7a4d182916

[7] X-Plane on Steam: https://store.steampowered.com/app/269950/XPlane_11/

[8] FPV Speed Drone on Steam: https://store.steampowered.com/app/1466010/FPV_Speed_Drone/

[9] DCS World Steam Edition: https://store.steampowered.com/app/223750/DCS_World_Steam_Edition/

[10] RealFlight 9.5 website: https://www.realflight.com/

[11] See footnote 10

[12] Real Flight 9.5 System requirements: https://www.realflight.com/?moreinfo=system-requirements

- OS compatibility (Windows).
- Variety of drones.
- Airports and fields.
- "Industry-leading True-To-Life physics that make every flight more lifelike than any other sim"[13].
- VR compatibility.
- Release date.
- Real Flight community (Knife Edge[14]).
- custom-made content (aircraft, drones, fields, airports, ...)

In the beginning, The plan was to have the experiment in VR to make it more realistic. However, when the testing started with Muse 2, it was uncomfortable to wear the VR headset while wearing the Muse 2 for an extended period. Therefore a decision was made not to use the VR headset and keep the Muse 2.

[13] See footnote 10

[14] Knife Edge:https://www.knifeedge.com/forums/index.php

Appendix 2 - Muse LSL collected data sample

Muse LSL collected data sample The tables bellow

a. Table A1 is a sample of the output of running the command "muselsl record –duration 600" to record EEG data.
b. Table A2 is a sample of the output of running the command "muselsl record –type ACC –duration 600" to record accelerometer data.
c. Table A3 is a sample of the output of running the command "muselsl record –type PPG –duration 600" to record PPG data.
d. Table A4 is a sample of the output of running the command "muselsl record –type GYRO –duration 600" to record gyroscope data.

timestamps	TP9	AF7	AF8	TP10
1610014973	-19.531	-24.414	-26.855	-19.531
1610014973	-33.691	-20.996	-33.691	-33.203
1610014973	-28.809	-26.855	-16.113	-21.973
1610014973	-26.855	-31.738	-12.695	-15.625
1610014973	-30.273	-49.805	-19.531	-26.367
1610014973	-22.949	-44.434	-17.578	-25.879
1610014973	-29.785	-35.645	-17.09	-35.156
1610014973	-37.598	-24.902	-22.949	-41.016
1610014973	-24.414	-20.02	-27.344	-19.043
1610014973	-20.996	-72.266	-14.648	-20.508
1610014973	-35.645	-65.918	-12.207	-30.762
1610014973	-36.133	17.578	-19.043	-26.367
1610014973	-33.691	13.672	-17.09	-27.832
1610014973	-31.25	-31.25	-12.695	-37.598

Table A1. *Sample of the output of running the command "muselsl record –duration 600" to record EEG data.*

timestamps	X	Y	Z
1610014974	-0.146	-0.013	0.987
1610014974	-0.152	-0.009	0.988
1610014974	-0.149	-0.014	0.98
1610014974	-0.15	-0.015	0.986
1610014974	-0.149	-0.013	0.984
1610014974	-0.153	-0.01	0.987
1610014974	-0.156	-0.01	0.988
1610014974	-0.16	-0.007	0.993
1610014974	-0.157	-0.01	0.989
1610014974	-0.155	-0.008	0.988
1610014974	-0.154	-0.007	0.985
1610014974	-0.155	-0.007	0.985
1610014974	-0.155	-0.007	0.989
1610014974	-0.154	-0.009	0.987

Table A2. *Sample of the output of running the command "muselsl record –type ACC –duration 600" to record accelerometer data.*

timestamps	PPG1	PPG2	PPG3
1610014976	499	101739	69880
1610014976	500	101663	69876
1610014976	496	101724	69793
1610014976	500	101700	69919
1610014976	499	101697	69861
1610014976	500	101759	69929
1610014976	498	101760	69952
1610014976	498	101791	69995
1610014976	498	101790	69912
1610014976	500	101817	69929
1610014976	496	101810	69953
1610014976	498	101834	69960
1610014976	498	101856	69958
1610014976	499	101852	69880

Table A3. *Sample of the output of running the command "muselsl record –type PPG –duration 600" to record PPG data.*

timestamps	X	Y	Z
1610014975	-2.258	4.688	-0.643
1610014975	-2.026	4.366	-1.002
1610014975	-1.757	3.993	-1.166
1610014975	-1.839	3.484	-1.136
1610014975	-2.041	3.35	-1.136
1610014975	-1.787	3.088	-1.032
1610014975	-1.809	3.125	-0.561
1610014975	-1.735	3.439	-0.344
1610014975	-1.368	3.753	-0.426
1610014975	-1.219	3.895	-0.576
1610014975	-0.935	3.783	-0.299
1610014975	-1.032	3.843	-0.336
1610014975	-0.763	3.858	-0.493
1610014975	-0.822	3.611	-0.202

Table A4. *Sample of the output of running the command "muselsl record –type GYRO –duration 600" to record gyroscope data.*

Appendix 2 - Consent to participate in research

CONSENT TO PARTICIPATE IN RESEARCH

Ghost Injection Attack on Automatic Dependent Surveillance-Broadcast Equipped Drones Impact on Human Behaviour

You are invited to participate in a research study conducted by Yazeed Basim Aeadah Alhaddad, who is a Master student from the School of Information Technologies at Tallinn University of Technology. Yazeed Basim Aeadah Alhaddad is conducting this study for his Master thesis. Your participation in this study is entirely voluntary.

PURPOSE OF THE STUDY

The purpose of this study is to see "Ghost Injection Attack on Automatic Dependent Surveillance-Broadcast Equipped Drones Impact on Human Behaviour".

POTENTIAL RISKS AND DISCOMFORTS

We expect that any risks, discomforts, or inconveniences will be minor and we believe that they are not likely to happen. If discomforts become a problem, you may discontinue your participation.

POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

It is not likely that you will benefit directly from participation in this study, but the research should help us learn and answer our question. Non-direct benefits that you will get to know your overall productivity and cognitive performance indicators, test your flying skills and see your brain activity.

COMPENSATION FOR PARTICIPATION

You will not receive any payment or other compensation for participation in this study. There is also no cost to you for participation.

CONFIDENTIALITY

Any information or data that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of a code number. We will not use your name in any of the information we get from this study or in any of the research reports. When the study is finished, we will destroy the list that shows which code number goes with your name.

Information that can identify you individually will not be released to anyone outside the study. We will also use any information that we get from this study in any way we think is best for publication or education. Any information we use for publication will not identify you individually.

The Interviews records that we will get will not be viewed by anyone outside the study. Unless we have you sign a separate permission form allowing us to use them. The records will be destroyed after the end of the study.

PARTICIPATION AND WITHDRAWAL

You can choose whether or not to be in this study. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you do not want to answer. There is no penalty if you withdraw from the study and you will not lose any benefits to which you are otherwise entitled.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study.

____

Name of Participant

______________________________ ____________________

Signature of Participant Date