# Cognitive Performance of Spatially Disoriented Military Helicopter Pilots

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# Cognitive Performance of Spatially Disoriented Military Helicopter Pilots

Thesis report

by

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# Preface

*"That is one small step for man, one giant leap for myself."*

Before you lies my "master"-piece called *"Cognitive Performance of Spatially Disoriented Military Helicopter Pilots"*. Having a background in astronomy, this master has been a quite challenge, but challenges are what drives me in life. Despite the hard work, I enjoyed working on my thesis. I am proud of what I delivered and hope that you enjoy reading it. I am very grateful for all the opportunities I was offered the past months - from performing an experiment on the Desdemona motion simulator to working with military helicopter pilots.

On that note, I would like to thank the 14 pilots who participated in my experiment. Furthermore, thank you Annemarie for your guidance throughout the project. Discussions with you helped me a lot to get a good overview of and new insights on the topic. Max, Olaf and René, I want to thank you too for your support and wise words. The input of the four of you was of high value to me. Besides, I would like to express my gratitude towards Eric, Mark, and Annemarie for letting me embark on this thesis within their group at TNO. A special thanks to the men of multiSIM B.V. for all the help with the preparations and execution of my experiment!

Moreover, I would like to thank my friends and family for having a sympathetic ear. Also, shout-out to everyone in studyroom 2.56 for providing "a warm nest" at the TU! Lastly, I would like to thank my parents for their unconditional support and believe in me! Without you, I would not be at the point where I am today. Although this thesis marks the end of an era, I am looking forward to what the future brings!

*Fleur Evertsen*
*Delft, December 2023*

# Contents

# Nomenclature

**List of Abbreviations**

| | |
|---|---|
| AI | Attitude Indicator |
| ATC | Air Traffic Control |
| CFIT | Controlled Flight Into Terrain |
| CNS | Central Nervous System |
| CPG | Copilot/Gunner |
| CTL | Cognitive Task Load |
| DHC | Defensie Helikopter Commando |
| DVE | Degraded Visual Environment |
| IMC | Instrument Meteorological Conditions |
| LOC-I | Loss-of-control In flight |
| MRT | Multiple Resources Theory |
| NVGs | Night Vision Goggles |
| PAF | Polish Air Force |
| PF | Pilot Flying |
| PM | Pilot Monitoring |
| RAF | Royal Air Force |
| RNLAF | Royal Netherlands Air Force |
| SCC | Semicircular Canal |
| SD | Spatial Disorientation |
| SO | Spatial Orientation |
| USAF | United States Air Force |
| VMC | Visual Meteorological Conditions |

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# Part I

## Scientific Article

# Cognitive Performance of Spatially Disoriented Military Helicopter Pilots

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***Abstract*—Spatial disorientation (SD) is one of the main causes of incidents and accidents in aviation. While most studies have investigated the effect of SD on the control task, we tested the effect of SD on cognitive performance in an operationally representative environment.**

**Thirteen Dutch military helicopter pilots flew scenarios with six different SD events using an AH-64 Apache flight model in virtual reality in a 6-DoF motion simulator. The SD events used were: "False Horizon", "Featureless Terrain", "the Leans", "Brownout", "Somatogyral Illusion" and "Night Vision Goggles (NVGs)". Corresponding scenarios without the SD events were performed to obtain baseline measures of cognitive performance. When performing the scenarios, participants had either the role of pilot flying or pilot monitoring.**

**To test the cognitive performance, participants performed a mathematical processing task. The corrected reaction time and error rate were significantly higher during the SD events than during the baseline events.**

**These effects were most prominent in the "Featureless Terrain" and "the Leans" scenarios. The results indicate that SD has a negative impact on the cognitive performance of military helicopter pilots. These findings underline the importance of SD awareness training for pilots, as well as the use of workload management procedures when experiencing SD.**

## I. INTRODUCTION

Spatial disorientation (SD) in aviation refers to the incorrect perception of an aircraft's position or movement in relation to the Earth's surface [1]. This phenomenon can lead to hazardous situations, and in the most extreme cases, result in fatal accidents, either through loss of control in flight (LOC-I) or controlled flight into terrain (CFIT). CFIT-related spatial disorientation accidents are associated with SD Type-I [2]. SD Type-I can be seen as situations in which the pilot has lack of awareness regarding the incorrect perception of the aircraft's attitude and movement [3]. In contrast, SD Type-II refers to situations where the pilot is conscious of the disorientation. If the disorientation reaches a critical level where the pilot is unable to effectively overcome this, it can result in LOC-I [3–6]. Some studies introduce a third type of spatial disorientation, SD Type-III, where the pilot is aware of the disorientation, yet unable to effectively manage it, potentially resulting in confusion. Because SD Type-III does not rely on the pilot's perception, as is the case with Type-I and -II, it is not universally recognized [4].

SD is one of the major contributors to incidents and accidents within aviation. This issue spans across the entire aviation sector, encompassing general, civil, and military aviation. Belcastro et al. [7] reported that SD accounted for 11% of LOC-I accidents in commuter and transport aircraft from 1996 to 2010. Newman and Rupert [2] conducted an analysis of mishaps in transport planes spanning from 1981 to 2016 and observed a rising trend in mishaps attributed to SD. A study by Poisson and Miller [8] emphasized the significant role of spatial disorientation, stating that it contributed to 11% of serious accidents in the U.S. Air Force between 1993 and 2013. Additionally, a survey of UK military accidents revealed that 28.2% of fast jet accidents and 42.2% of rotary wing aircraft accidents in the period 1993-2002 could be linked to spatial disorientation [9]. Bushby et al. [10] determined this percentage to be 43% for rotary wing aircraft in the UK Military in the period 2000-2016.

Military helicopter pilots are especially susceptible to spatial disorientation due to the highly complex platforms and operations they fly compared to general and civil aviation. These military pilots have to be able to perform in high workload and stressful situations. They operate in challenging environments, such as low-level terrain, mountains and degraded visual environments [11], while not only controlling their vehicle, but also performing cognitive tasks related to tactical coordination and weapon systems.

Most studies focused on the effect of spatial disorientation on control task performance, since in certain situations SD causes this to be worse compared to normal situations [12, 13]. In SD Type-I, control errors occur due to misinterpretation of information, referred to as "orientation error" by Benson and Rollin Stott [4]. When control inputs are made based on this misinterpretation, it results in control errors. The authors also state that during SD Type-II, there is a conflict in perceptual orientation that can potentially impair the pilot's perceptual and motor abilities to an extent that jeopardizes control, which they refer to as "disorientation stress" [4]. However, there is an additional way in which SD may affect pilot performance, and that is by disrupting their cognitive performance. Disorientation stress can result not only in control errors, but also in mistakes related to navigation, communication, and tactics. Multiple incident reports, in amongst others the Aviation Safety Reporting System database (e.g., report number $615,534$; report number $1,376,835$), have given indications of SD impairing other cognitive tasks in flight besides the control task. Impairment of these other cognitive tasks could, for example, result in lower mission effectiveness in the military domain, which could lead to dangerous situations (e.g., in combat areas).

It is thought that SD draws attentional resources in order to regain and maintain orientation. The "orientation first" principle, as stated by Gresty et al. [14], suggests that pilots reallocate their mental resources to the control task whenever they experience SD, such that pilots are able to orient themselves, leaving fewer resources for other cognitive tasks. This principle is deduced from the "posture first" principle [5], which is, in turn, based on Wickens' Multiple Resources Theory [15].

Several studies focused on the effect of SD on the performance of concurrent cognitive tasks. It was shown that performance was impaired by SD (i.e., motion and visual) stimuli, which was in line with the orientation first principle [5, 14, 16–18]. Landman et al. [5] used a "Barany chair" to induce SD. Participants had to perform an orientation and a self-paced arithmetic task. It was shown that counting speed was on average reduced by 31%, which could be attributed to SD. However, Landman's study can be seen as an abstract research, as it was not executed in an operationally representative environment. Stróżak et al. [16] examined six distinct flight profiles that varied significantly from one another, yet only one showed a notable cognitive impact of spatial disorientation.

In a more recent study, Fudali-Czyż et al. [1] investigated the negative effect of SD on detecting visual changes in the cockpit visual scene. They use the term "attentive blank stare" to refer to situations in which a pilot looks at a change in visual area and fails to detect the change. The outcomes of the study indicate that more flight errors were made during SD conditions and pilots spent less time gazing at the area of change.

Webb et al. [18] showed that SD negatively affected cognitive performance in an operational setting. SD was manipulated by varying the intensity of formation flying. Since formation flying already induces a high workload for pilots, this could have confounded the measured effects of SD. Gresty et al. [14] were the first to investigate the cognitive impact of SD. In addition to demonstrating the impairment of cognitive performance caused by SD, this study also highlighted that SD has a greater impact on spatial tasks compared to verbal tasks within the scope of short-term memory.

Except for Landman et al. [5], none of the studies confirmed that participants were experiencing SD (Type-II), so it is unclear whether effects were related to SD or to other factors such as the visual or vestibular motion stimuli.

The current study builds upon the work of Landman et al. [5] and aimed to investigate the effect of SD on the cognitive performance of military helicopter pilots in an operationally representative experimental environment, while limiting confounding factors. Military helicopter pilots were exposed to several flight profiles which contained different SD events. Participants had to perform a cognitive task while also occasionally executing a control task. Outcomes could provide valuable insights into the cognitive impact of SD during flight operations. These insights could contribute to improving (military) spatial disorientation training by also taking into account this potential cognitive impact, resulting in more awareness on the potential risks and impact of SD, which ultimately leads to safer and more efficient (military) aviation.

## II. BACKGROUND

In the newest generation military aircraft, information processing is nearly as crucial as the control task itself. Military operations nowadays heavily rely on information-driven approaches. Most helicopters are manned by two cockpit crew members: a pilot in command (i.e., Captain) and a copilot. For some helicopter types, one of the pilots can be replaced by a tactical coordinator (according to an experienced Royal Netherlands Navy pilot, personal communication, March 4, 2023). This also depends on the military branch the helicopter type operates in. The division of cognitive tasks in the cockpit differs per helicopter type and mainly depends on the purpose of its missions. However, two main roles can be pointed out: pilot flying (PF) and pilot monitoring (PM).

In general, the pilot flying executes the control task, while the pilot monitoring performs all other flying related cognitive tasks, e.g., communications with air traffic control and navigation. Besides controlling the aircraft, the PF has to perform other tasks, such as being aware of crossing traffic and communicating with the PM. In attack helicopters (e.g., AH-64 Apache) for certain Air Forces (e.g., Royal Netherlands Air Force), the pilot monitoring mostly operates the weapon systems, and performs tactical-related tasks, whereas the pilot flying does all the flying and flying related cognitive tasks (e.g., communications with air combat command; according to a Royal Netherlands Air Force helicopter instructor, personal communication, May 16, 2023).

Pilots are thus constantly multitasking. In high workload situations, pilots operate according to the following principle: *"Aviate, Navigate, Communicate"* [19]. Keeping the aircraft in the air, or in other words, maintaining orientation and executing the control task, has the highest priority. Second in priority is understanding where one is and where to go to (i.e., navigation), while communication has the lowest priority. In stressful and high workload situations, the pilot first stops communicating, then navigating, all in order to have the flight path under control.

Due to the combination of flying complex platforms, challenging environments, high workload and stressful operations, military helicopter pilots are susceptible to spatial disorientation [11]. Numerous surveys have been held amongst military aviators from several air forces. Military rotary wing aviators from the Royal Netherlands Air Force [20], Polish Air Force [21], Taiwanese Air Force [22] and United States Air Force [23] indicated the most frequently experienced SD events. Most frequently reported events were: sloping horizon, undetected drift, lack of altitude cues due to featureless terrain, loss of horizon (due to sand/snow/atmospheric conditions), misleading altitude cues, the leans and SD while using night vision goggles (NVGs). The survey amongst Dutch military helicopter pilots also investigated the indicated impact of the SD events. The following events were rated as high impact and were frequently reported by the Dutch helicopter pilots: loss of horizon (due to sand/snow/atmospheric conditions), false horizon, undetected drift and misleading altitude cues [20].

Thus, due to the highly information-driven approaches in the military domain, it is all the more interesting to investigate the effect of spatial disorientation on the cognitive performance of military helicopter pilots, since it could impair mission effectiveness and in the worst cases lead to fatal accidents. In this study, we investigated the impact of several of the most frequently reported and impactful SD events. The primary aim was to test whether there was a general effect of SD on cognitive performance, whereas specific effects of SD events were investigated in an exploratory manner. To remain close to operational realism, several scenarios were flown in the pilot monitoring role instead of in the pilot flying role. Investigating specific effects for these roles was not an aim of this study, however these are also treated in an exploratory manner.

## III. METHOD

### A. Participants

This study involved a total of 14 participants, all licensed with a military pilot license. Nine subjects were helicopter pilots on the AS532-U2 Cougar and three subjects flew the CH-47 Chinook, both groups flew for the Royal Netherlands Air Force. The remaining two participants were Royal Netherlands Navy NH90 pilots. Because none of the pilots had experience flying the AH-64 Apache, a military attack helicopter, the flight model of this helicopter was used during this study. This means that all pilots were confronted with a new platform to fly.

All participants were male, with a mean age of $34.4$ years ($SD = 6.96$ years). The mean flight hours of the participant group was $M = 1,513$ hours, $SD = 1,068$ hours. Seven subjects had the function of Captain, while the remaining subjects were copilots. All but four subjects had experience with flying in virtual reality (VR). Six subjects had worked as flight instructor. All subjects participated voluntarily and gave informed consent. This study complied with the tenets of the Declaration of Helsinki and was approved by the Ethical Review Board of TNO Soesterberg, The Netherlands.

### B. Design

A within-subject design was used for this experiment. All subjects performed a cognitive task (see Subsection III-F1) during scenarios that were performed in an SD and a baseline (No-SD) condition (see Subsection III-D). SD was induced by applying different motion and/or visual stimuli. Each scenario consisted of an SD condition, which contained an SD event, and was matched with a similar scenario in the baseline condition without SD event (i.e., “No-SD condition”). There were six different SD (and No-SD) events. These events were chosen based on the most frequently reported and impactful SD events as determined in surveys amongst military helicopter pilots (see Section II) [20–23]. For the main research question, mean cognitive performance in the SD condition was compared with mean cognitive performance in the No-SD condition.

### C. Apparatus

The experiment was performed on the Desdemona motion simulator (Figure 1). Desdemona is a moving base simulator and has unique motion features due to its capabilities to combine the centrifuge design for sustained G-loading with five additional degrees-of-freedom [24]. All motion features were used in this study. Due to its unique motion features, Desdemona is considered well capable for replicating helicopter dynamics.

The cabin of Desdemona contained hardware to recreate an AH-64 Apache cockpit, this included the Apache collective and cyclic. Furthermore, the cabin held pedals. The AH-64 flight model used in this experiment was developed by multiSIM B.V. It presents a high-fidelity simulation of the Delta and Echo version of the AH-64. The flight model offers an accurate approximation of the helicopter behavior. Besides, large parts of the avionics have been modelled [25].

Visuals were presented in VR and were provided by the Varjo Aero VR headset, which has a $115°$ field of view [26]. VR was chosen due to its greater contribution to the operational representativeness of the experiment in Desdemona compared to using projection. The virtual cockpit of the AH-64 can be seen in Figure 2. The multi purpose displays (MPDs) and the “Target Acquisition and Designation Sights” Electronic Display and Control (TEDAC) are highlighted in this figure. The MPDs show tactical, technical and navigational information to the pilot, while the TEDAC is able to show sensor images, e.g., Forward Looking Infrared (FLIR).

The general configuration of the MPDs consisted of the Tactical Situation Display (TSD) visible on the left MPD and the flight page on the right MPD. No sensor images were shown on the TEDAC, however some flight information was displayed on it. During some scenarios, this configuration changed. This was mentioned before that specific scenario started. The helmet mounted display (HMD) was turned off during the entire experiment.

### D. Procedure

For each participant, the total duration of the experiment was three hours, which included briefing, familiarization, two simulator sessions, a break and a debriefing. A total of 24 experiments runs (six SD events and six No-SD events, all performed twice) were performed by each participant. These were divided in two simulator sessions consisting of 12 experiment runs with a total duration of 55 minutes per session with a break in between of 10 minutes. During each session, all 12 different scenarios were performed in a counter balanced order created using a Latin Square matrix on the six events. The corresponding event in the other condition was then put four runs after the event in the

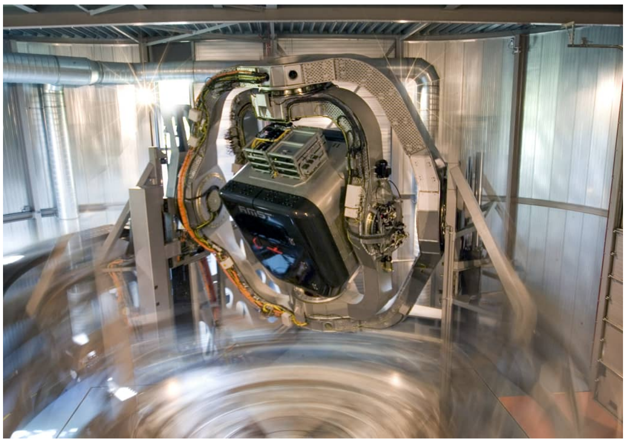


Fig. 1: The Desdemona motion simulator, located in Soesterberg, The Netherlands [24].

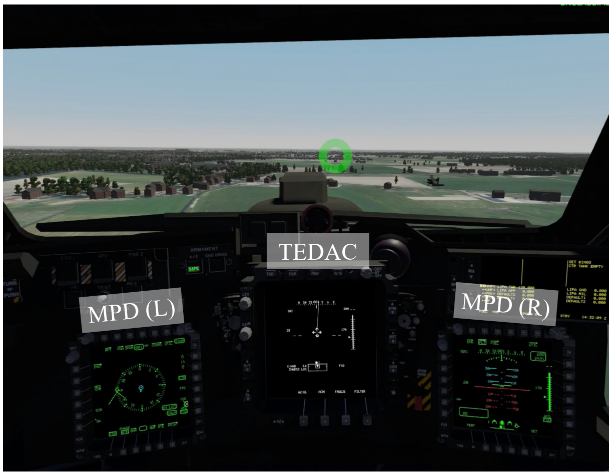


Fig. 2: VR-cockpit of the AH-64 as seen from the frontseater. The green circle indicates where the participant is looking at.

first condition. To avoid predictability of conditions due to conditions alternating, the third and fourth runs and the ninth and tenth runs were switched. Multiple repetitions of the Latin Square were used to cover the entire participant group. Between repetitions of the Latin Square, the order of SD and No-SD conditions was mirrored.

*1) Briefing:* The experiment began with a 20-minute briefing. During the briefing, participants were told that the goal of the experiment was to investigate the influence of different flight manoeuvres on the cognitive performance of military helicopter pilots. This concealed that the real goal was to study the effect of SD on cognitive performance. This decision was made based on the assumption that participants would be biased if they knew that SD events would be presented to them. The briefing further touched upon an explanation of the AH-64 flight controls and systems. Participants were told they would be flying on the copilot/gunner position (frontseater) of the AH-64, since that best resembles the outside view of the NH90, AS532-U2 and CH-47. The general configuration of the MPDs and the TEDAC was shown to the participants.

Furthermore, an explanation on the cognitive task was provided to the participants. Participants were told to act just as they would normally do in-flight while being the PM or the PF. Safety instructions with respect to Desdemona were given. Finally, participants were asked to fill in a questionnaire, which focuses on personal information and flight experience.

*2) Familiarization:* After the briefing, participants were guided to the simulator and supported with adjusting the seat and flight controls to their own preferences. Participants were then able to familiarize themselves with the AH-64, since they were not well-known with this helicopter type. The training session consisted of flying two circuits. At the start of the first circuit, participants had to takeoff from a hover. This circuit was flown in visual meteorological conditions (VMC). In between the two circuits, the cognitive task was presented to the participant three times, while having the helicopter located on the ground. The second circuit was flown in VMC with lower visibility (cloud deck at $3,000 ft$), in order to make clear to participants what different kind of weather circumstances look like in the virtual environment. During this circuit, the cognitive task was presented twice in-flight during the downwind stretch of the circuit.

*3) Experimental Set-Up:* Each of the 24 experiment runs had a duration of 180 seconds and contained three time intervals of approximately 30 seconds during which the cognitive task was presented. Figure 3 illustrates the general structure of an experiment run. The cognitive task will be explained in Subsection III-F1. The second interval of the cognitive task, at $t = 90s$, coincided with the SD or No-SD event, which also started at that moment in time.

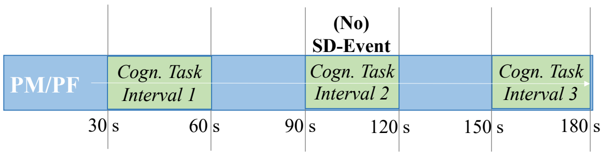


Fig. 3: General structure of an experiment run for both PF and PM scenarios, with a total duration of 180 seconds, including three intervals of the cognitive task.

After each experiment run, the participants were asked to answer three questions. First, whether they had noticed anything surprising. If yes, then an indication of that surprising element was asked to the participants, followed by rating it on a zero-to-ten scale. Zero would mean “no surprise at all”, whereas ten meant “extremely surprising”. If a participant indicated being surprised and pointed out noticing something with regard to the SD event (e.g., visual or vestibular sensations), it was determined that the participant had recognized the SD event and thus experienced SD Type-II.

After each simulator session, participants were asked to report motion sickness on a Dutch version of the Misery

Scale (MISC) ranging from 0 to 10 [27]. This, to ensure performance was not influenced by motion sickness. If participants scored higher than 7, the experiment would be stopped. Participants did not know this beforehand.

*4) Debriefing:* During a 20-minute debriefing, the actual goal of the experiment was made clear. Participants were then asked to fill in a post-experiment questionnaire. This questionnaire included questions on the experienced level of SD in each condition and how this subsequently affected their cognitive performance. This could be indicated using a 5-point Likert scale, where "1" indicated no disorientation, and "5" was "extremely disorienting". For the experienced cognitive impact of SD, "1" meant that SD had no effect and "5" indicated that the cognitive performance was extremely affected by SD. The questionnaire also contained a question about the participant's previous experience with SD. Participants could indicate if they had any remarks or if there would be any room for improvement.

### *E. SD and Corresponding No-SD Events*

*1) False Horizon:* The participant had to perform a control task and make sure that the helicopter was flying straight and level during the entire scenario. The participant had to fly above a cloud deck maintaining a heading of 310° with a speed of $95kts$ at an altitude of $4,800ft$ and was instructed to be aware of traffic. At $t = 60s$, traffic would become visible in the scenario. An AS532-U2 Cougar was flying at 12 o'clock, as seen from the ownship, at an altitude of $5,000ft$ with a speed of $100kts$. It was making a right turn away from the participant. In the SD version of this scenario, a false horizon would be presented at $t = 90s$, the moment the second interval of the cognitive task started. This false horizon was created using a sloped cloud deck with an attitude of 6° in roll and 3° in pitch, such that it blended properly with the surrounding cloud deck. In the baseline condition of this scenario, the attitude of the cloud deck at $t = 90s$ had an attitude which corresponded to a straight horizon, causing no SD.

*2) Featureless Terrain:* Participants had to execute a control task in this scenario. They had the exercise to perform changes in heading. The starting point of the scenario was at a heading of 200° with a speed of $95kts$ at an altitude of $500ft$. The outside view was such that the helicopter was located above the sea near the coastline, with the cockpit facing the coast. For the first 60 seconds, the participant was flying towards the coast. Right after the first interval of the cognitive task, the participant was instructed to make a right turn to a heading of 290° with 30° angle of bank.

The moment the second cognitive task interval started, the participant was out of sight of land. After the cognitive task, the participant was instructed to turn left with 30° angle of bank to a heading of 200°. At this heading, the participant had visuals on the coastline. In the SD condition, the water did not contain any flow or texture, which caused loss of reference during the second cognitive task interval. This made the perception of motion and speed very difficult, potentially causing SD. In the baseline condition, the water contained flow and texture, making it easier to perceive motion and speed.

*3) The Leans:* The participant had to fly the helicopter straight and level during the entire run at a heading of 080° with a speed of $115kts$ at an altitude of $4,000ft$. This run was flown in instrument meteorological conditions (IMC), so no outside visuals were presented. The outside view was white. The participant had to fly on instruments. In the SD condition, at $t = 90s$, the cabin of Desdemona was rolled to the right to $\phi = 15°$ with a roll rate of $1.5°/s$, while the instruments still showed straight and level. This caused a mismatch in vestibular and instrument information, which is similar to the leans illusion. In the baseline condition, this roll of the cabin was not present.

*4) Brownout:* The participant did not execute a control task, but performed monitoring tasks, just as if the participant was the pilot monitoring during normal military helicopter operations. During the run, the participant was following a leading helicopter at a distance of $150m$ three times into a hover at approximately $30ft$ altitude. Each time when the helicopter was in a hover, the participant had to perform the cognitive task. Besides that, before the start of the run, the participant was instructed to keep an eye on the time, which was visible on the Enhanced Upfront Display (EUFD), close to the cockpit window. The participant had then to verbally indicate when the time was at $14:34:30$. This was to make sure that the participant experienced the visual stimulus which was presented outside.

In the SD version of the scenario, a brownout occurred during the second hover. Brownout refers to the reduced in-flight visibility caused by the presence of sand or dust in the air. They occur in helicopter operations mostly during takeoff, landing or low-altitude hover. The stirred-up dust clouds can give pilots a sensation of self-motion, which is referred to as the vection illusion [3]. Furthermore, loss of horizon could occur during a brownout. In the No-SD condition, the opacity of the dust cloud was 11 times lower than the brownout in the SD condition, which meant that there was no vection nor loss of visual reference of the horizon.

*5) Somatogyral Illusion:* This SD event was based on the study of Landman et al. [5]. During this scenario, the participant had the role of pilot monitoring. The helicopter was located above a cloud deck at $t = 0s$ and followed a descending flight path through the clouds. The moment the helicopter left the clouds, it made a left turn. The first cognitive task interval was presented when still in the clouds. The second interval started the moment the helicopter left the clouds. The third interval was when flying straight and level after the helicopter rolled back to straight and level. During

TABLE I: Additional motion cueing for the somatogyral illusion, as based on the study of Landman et al. [5].

| **Condition** | **Sub-/Super-threshold motion** | **Duration ($s$)** | **Velocity function** |
|---|---|---|---|
| SD | Sub | 75 | $v = -25(\cos(\frac{\pi}{2} \cdot \frac{1}{75}t) - 1)$ |
| | Super | 2 | $v = -10(\cos(\frac{\pi}{2}t + \pi) - 1.5)$ |
| No-SD | Sub | 75 | $v = 2(\cos(\frac{\pi}{2} \cdot \frac{1}{75}t) - 1)$ |
| | Super | 2 | $v = 10(\cos(\frac{\pi}{2}t + \pi) + 0.8)$ |

this scenario, the MPDs did not show any flight information. The left MPD showed the performance page of the AH-64. The engine page was shown on the right MPD. The TEDAC was turned off.

In both the SD and the baseline conditions, extra motion cueing was added to the motion generated as connected with the AH-64 flight model. This extra motion cueing was used to simulate the somatogyral illusion. The motion profiles as used in the study of Landman et al. [5] were used for this motion cueing in both versions of this scenario. In both conditions, SD and No-SD, the motion profiles had a total duration of 77 seconds and consisted of two parts. The first part contained a sub-threshold acceleration, whereas the second part contained a super-threshold acceleration.

Table I shows the velocity profiles for both the SD and No-SD conditions. Both motion profiles started at $t = 13s$ in the experimental run, since the entire additional motion cueing took $77s$ and the second cognitive interval started at $t = 90s$. The additional motion was put on top of the motion cueing as generated by the flight model, resulting in the cabin being placed at the outer end of the linear track. The centrifuge function of Desdemona was used to simulate the somatogyral illusion in yaw.

In the SD condition, the sub- and super-threshold motion profiles were both counterclockwise movements. However, due to the super-threshold deceleration, the participant could sense this as a clockwise movement. Though, the direction of motion was still counterclockwise after the deceleration. This could have caused a mismatch in perceived angular motion and the motion of the helicopter, since the visuals provided a counterclockwise (left) turn, but a right turn could be sensed due to the somatogyral illusion.

In the No-SD condition, the sub-threshold movement was a clockwise movement and the counterclockwise movement was a super-threshold movement, causing the participant to sense a counterclockwise (left) turn, which matched with the provided outsided visuals of a left turn. At $t = 90s$ in both scenarios, the additional turning movement would continue at a speed of which the cabin was moving. After the second cognitive task interval was finished, this turning movement would be faded out within $10s$ to a turnrate of $0°/s$ with a low pass filter.

*6) Night Vision Goggles (NVGs):* The participant was flying over land near the coastline as pilot monitoring and then at one point would turn to sea. This was a night flight using night vision goggles. The helicopter followed a flight path over land near the coastline. The first cognitive task interval was when still flying above land. After that interval, the helicopter turned to the sea. When above water and no land was in sight, the second cognitive task interval started. After finishing this second interval, the helicopter turned 90°, causing land to be visible again. Here the third cognitive task interval started. In the SD condition, the stars had $0\%$ brightness and the moon had a brightness of $0\%$. This caused the participant to have no visual references when flying above water with land out of sight. The resulting loss of horizon reference was ranked as one of the most frequent forms of SD in SD surveys [20–23]. In the No-SD condition, the brightness of the stars was $8\%$, the brightness of the moon was $10\%$ and the overall lumination was higher. This caused the participant to have some visual references when flying above water. In this scenario, the TEDAC was turned off.

### *F. Dependent Measures*

*1) Cognitive Performance:* The Mathematical Processing Task was used to measure cognitive performance [28]. In this task, participants have to solve simple mathematical problems and decide if the answer is above or below a certain value. This task was chosen for its short duration, deterministic answers, and easy-to-measure reaction times. In order for the cognitive task to be minimally invasive in the cockpit environment, the exercises were presented auditorily. The participant could use the helicopter controls in the simulator to indicate the outcome. The "PNVS" switch on the collective was used to answer the mathematical exercises.

Moving the "PNVS" switch up, would mean that the answer was above "5". If the answer was below "5", the switch had to be moved down. Mathematical exercises were automatically generated with randomly drawn numbers between one and nine and with random use of plus and minus operators. The process of drawing random numbers was based on a uniform distribution. Furthermore, the exercises were generated such that it was impossible to decide the outcome of the exercise after hearing only the first two components of the exercise. Additions with the starting number being four or higher, and subtractions with the starting number being six or lower, were excluded. The possibility of hearing the same exercise two times in a row was ruled out. Furthermore, equations with an outcome of "5" were excluded.

Each cognitive task interval consisted of ten exercises which had to be solved. The total duration of presenting one equation was approximately $1.5s$ and participants had $3s$ to answer. The type of answer (correct/incorrect/missed) was automatically registered. The reaction time was defined as the time from which the audio of the last number of the exercise started until the participant used the switch. The dependent measures are thus error rate (included missed) and reaction time.

*2) Control Performance:* In the “False Horizon”, “Featureless Terrain” and “the Leans” runs, participants performed a control task which allowed the measuring of control performance. Since the “Featureless Terrain” and “the Leans” scenarios involved disturbances in the roll axis, the root means square (RMS) of the roll angle around 0° was obtained during the SD or No-SD event. The “Featureless Terrain” scenario aimed to induce uncertainty in altitude, so the RMS of altitude around the instructed altitude was obtained. A higher RMS means that pilots had higher deviations from the instructed flight path.

### *G. Hypotheses*

The main hypothesis was that cognitive performance will be higher in the No-SD condition than in the SD condition (mean of all SD events). It was expected that more incorrect and missed answers would be given and reaction time would be longer in the SD than in the No-SD conditions.

A second goal of this study was to test whether the effect of SD would be stronger for some events than for other events. This was done in an exploratory manner, so no specific hypothesis was made in this regard.

Furthermore, it was thought that the negative impact of SD on the cognitive performance (i.e., reaction time and error rate) would be less for more experienced pilots. Having more experience, measured in flight hours, increases the chance of having more experience with SD in-flight. Besides, more experienced pilots could need less mental resources for the control task than less experienced pilots, leaving automatically more mental resources available for other tasks. This way, it was thought that SD would have less impact on the cognitive performance of more experienced pilots.

### *H. Data Analysis*

Error rates and reaction times were corrected for performance in the same run by subtracting the mean performance of the two surrounding intervals from the stimulus interval, specifically to account for the participant’s performance within that particular run. Subsequently, the mean corrected error rate and reaction time were computed for each condition. For the calculation of the corrected reaction times, the “missed” answers were not taken into account.

To test whether SD impacted reaction time and error rate, a repeated-measures ANOVA with a 2x6 design was applied to the corrected reaction times and corrected error rates. This analysis considered two within-subject factors: SD condition (yes/no) and SD event (“False Horizon”, “Featureless Terrain”, “the Leans”, “Brownout”, “Somatogyral Illusion”, “NVGs”). The main effect of SD was used to test the primary hypothesis, namely that cognitive performance would be lower in the SD than No-SD condition. Second, the SD x event interaction effect was checked to explore whether the effect was more severe in some than in other SD events. *Post hoc* tests between SD and No-SD were used.

Sphericity had to be confirmed in order to perform the ANOVA and *post-hoc* paired-samples t-tests. If sphericity could not be confirmed, corrections had to be made on the p-values for the main and interaction effects.

If data followed a normal distribution, as verified by a Shapiro-Wilk test, paired samples t-tests were used to determine the potential effect of SD on the control performance of participants. In cases of non-normal distributions, Wilcoxon Signed-ranks tests were used. The tests were applied to the RMS values for both conditions of each pilot flying scenario.

Spearman’s rank correlation was used to investigate the potential relation between flying experience and cognitive impact of SD.

## IV. RESULTS

### *A. Exclusion of Runs*

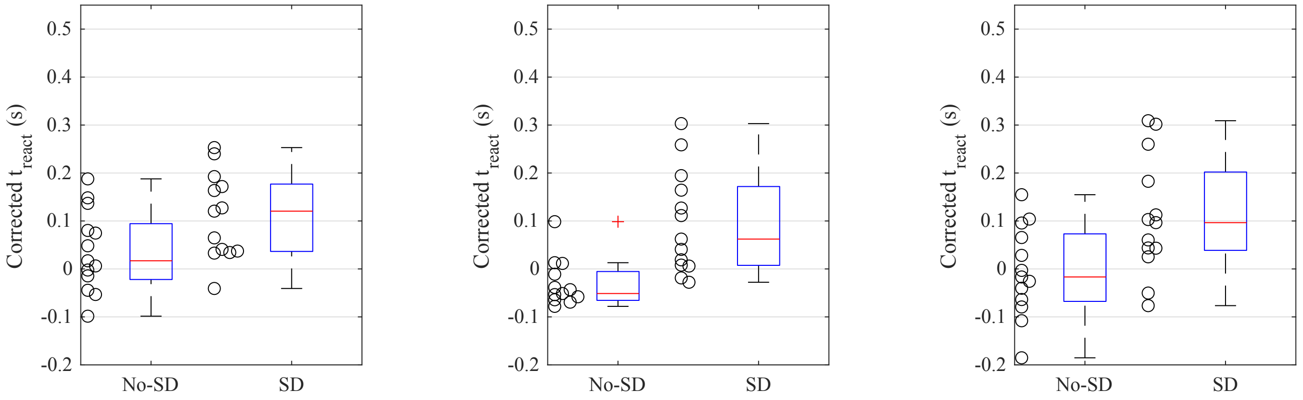
For one participant, only a small part of the experiment could be executed, due to technical malfunctions of Desdemona. This participant’s incomplete data set was excluded from subsequent analysis. Furthermore, the data set for another participant contained a corrupted file, resulting in missing data for one experiment run. The missing data were imputed using the average of all participants for this experiment run. The second SD run for the “Brownout” scenario was similarly imputed for another participant, due to simulator malfunctions. Lastly, the first data point for reaction time during the second cognitive task interval in the No-SD condition of the “Somatogyral Illusion” scenario was missing for another participant. This value was imputed using the average of the reaction times in that specific cognitive task interval for this participant.

### *B. Reaction Time*

From the repeated measures ANOVA followed that there was a significant main effect for SD on the corrected reaction time, $F(1, 13) = 14.48$, $p = 0.003$, $\eta^2 = 0.55$. It showed that corrected reaction times were higher in SD conditions, $M = 0.110s$, $SD = 0.111s$, compared to No-SD conditions, $M = 0.0555s$, $SD = 0.135s$. The impact of the SD stimuli on the corrected reaction time was on average $2.8$ times higher than the impact of the No-SD stimuli. Furthermore, there was a significant main effect for the factor “scenario” (i.e., SD event) on the corrected reaction time, $F(1, 13) = 3.57$, $p = 0.007$, $\eta^2 = 0.23$.

Moreover, there was a significant interaction effect between scenario and SD for the reaction time, $F(2, 13) = 3.21$, $p = 0.012$, $\eta^2 = 0.21$. The main effect for SD is overruled by the interaction effect. The *post hoc* pairwise comparison showed that there was a significant effect for the “Featureless Terrain” and “the Leans” scenarios, and no significant effect in the other scenarios.

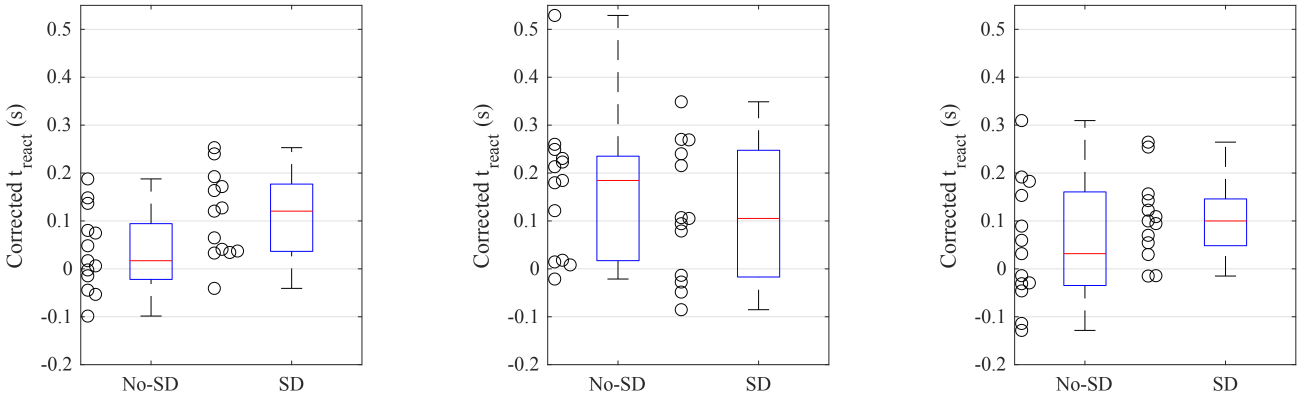
For “Featureless Terrain”, the corrected reaction time was higher in the SD condition than in the No-SD condition, with $M = 0.096s$, $SD = 0.11s$ in the SD condition and $M = -0.43s$, $SD = 0.072s$ in the No-SD condition, $p = 0.001$,



(a) False Horizon (PF)

(b) Featureless Terrain (PF)

(c) The Leans (PF)



(d) Brownout (PM)

(e) Somatogyral Illusion (PM)

(f) NVGs (PM)

Fig. 4: Boxplots for the corrected reaction times in the No-SD and SD conditions for each scenario. Corresponding data points for each scenario are visible left outside the boxes. Each data point represents a participant.

$d = 4.17$. This constitutes an impact of SD of $17.5\%$ with regard to the baseline performance measured before and after the SD or No-SD event.

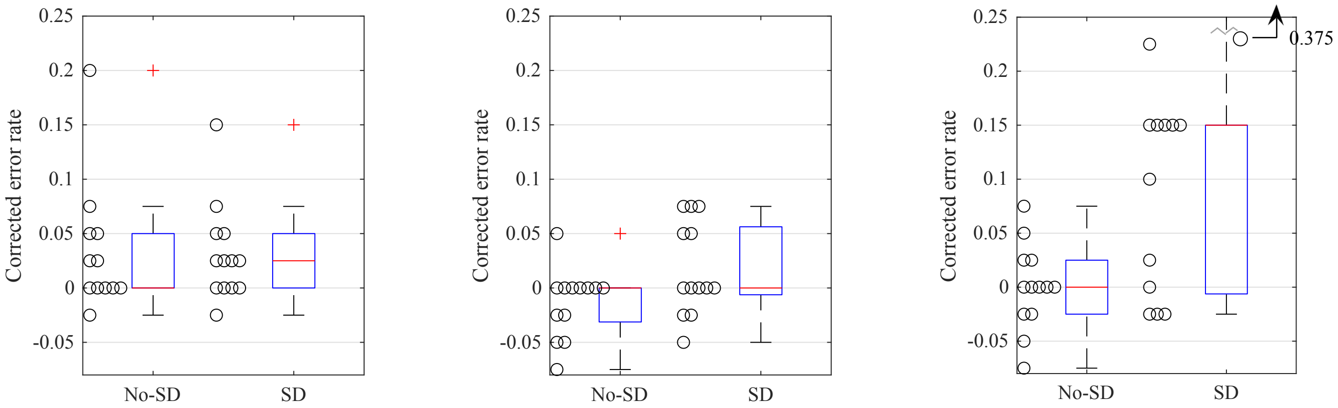
The corrected reaction time was also higher for the SD condition in "the Leans" scenario with $M = 0.109s$, $SD = 0.123s$, compared to the No-SD condition with $M = -0.006s$, $SD = 0.094s$, $p = 0.030$, $d = 0.71$. This constitutes an impact of SD of $17.9\%$ with regard to the baseline performance measured before and after the SD or No-SD event.

A marginally significant effect was found for the "Brownout" scenario. The corrected reaction time was higher for the SD condition with $M = 0.111s$, $SD = 0.0901s$ compared to the baseline condition where $M = 0.037s$, $SD = 0.0865s$, $p = 0.066$, $d = 0.56$. This constitutes an impact of SD of $11.6\%$ with regard to the baseline performance measured before and after the SD or No-SD event.

Figure 4 shows the boxplots of corrected reaction time for each scenario including both SD and No-SD conditions. Noteworthy is that the data are relatively widely spread for No-SD and SD conditions in the "Somatogyral Illusion" scenario compared to the other scenarios.

### C. *Error Rate*

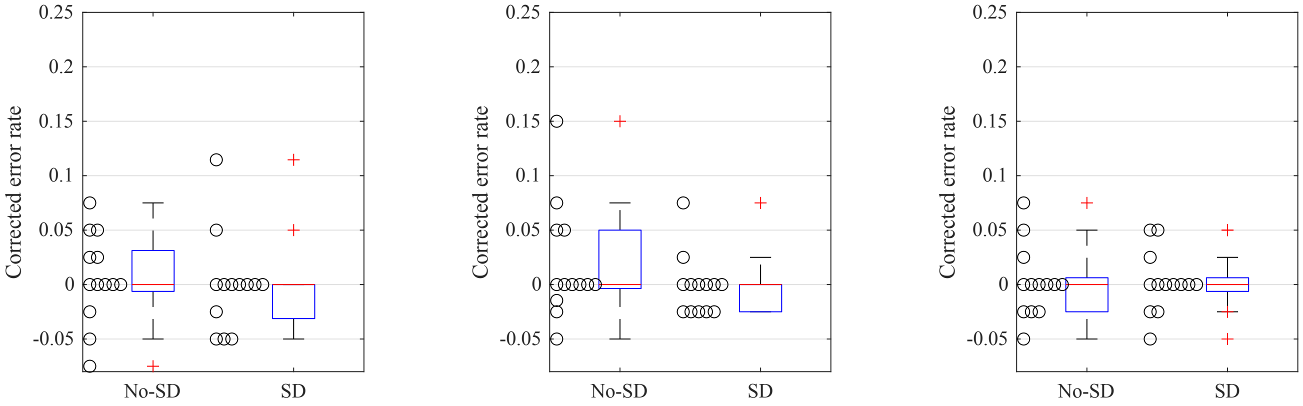
A repeated measures ANOVA showed that there was a significant main effect for the factor "scenario" on the error rate, $F(1, 13) = 3.99$, $p = 0.003$, $\eta^2 = 0.25$. There was a significant main effect for SD on the error rate, $F(1, 13) = 8.08$, $p = 0.015$, $\eta^2 = 0.40$. From this followed that error rates were higher in SD conditions, $M = 0.0258$, $SD = 0.0692$, compared to No-SD conditions, $M = 0.00590$, $SD = 0.0460$. Besides, there was a significant interaction effect between scenario and SD for the error rate, $F(2, 13) = 4.34$, $p = 0.002$, $\eta^2 = 0.27$. This interaction effect overrules the main effect of SD. The *post hoc* pairwise comparison revealed that there was only a significant effect of SD for "the Leans" scenario. In this scenario, the corrected error rate was higher in the SD condition, with $M = 0.108$, $SD = 0.119$, whereas this was $M = 0.000$, $SD = 0.0397$, $p = 0.010$, $d = 0.83$ in the No-SD condition. This constitutes an impact of SD of $11.1\%$ with



(a) False Horizon (PF)

(b) Featureless Terrain (PF)

(c) The Leans (PF)



(d) Brownout (PM)

(e) Somatogyral Illusion (PM)

(f) NVGs (PM)

Fig. 5: Boxplots for the corrected error rate in the No-SD and SD conditions for each scenario. Corresponding data points for each condition are visible left outside the boxes. Each data point represents a participant. For "the Leans" SD condition, there was an "outlier" at 0.375, which is plotted right outside the box.

regard to the baseline performance measured before and after the SD or No-SD event.

A marginally significant effect was found for the "Featureless Terrain" scenario, where $p = 0.083$. The error rate was higher in the SD condition with $M = 0.017$, $SD = 0.043$ compared to the No-SD condition where $M = -0.013$, $SD = 0.032$, $d = 0.53$. This constitutes an impact of SD of $3.1\%$ with regard to the baseline performance measured before and after the SD or No-SD event.

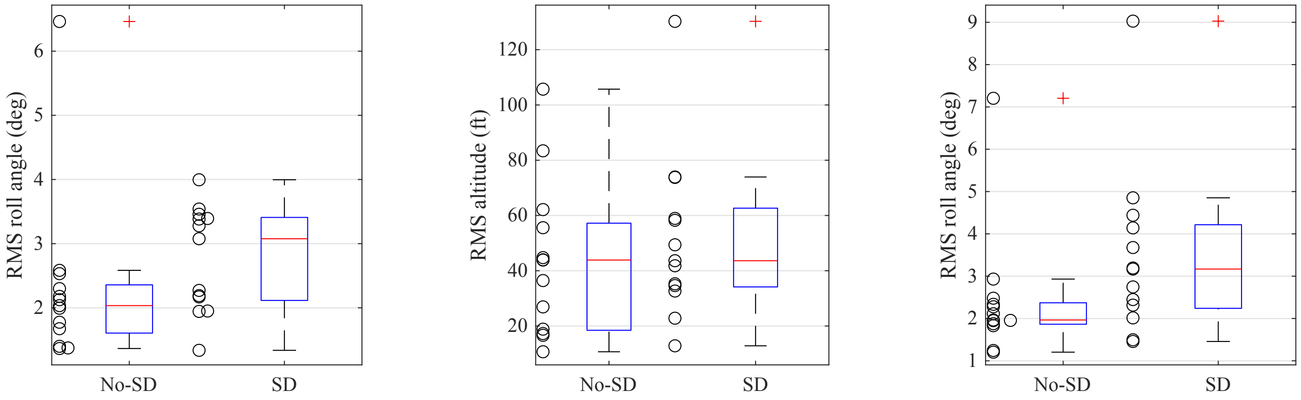
Figure 5 shows boxplots for the corrected error rates, for the SD and No-SD conditions for all events. When visually inspecting Figure 5, an increasing trend can be seen for the "Featureless Terrain" and "the Leans" scenarios, also indicating that more errors are made in the SD conditions than in the No-SD conditions. All scenarios, expect for "the Leans" scenario, show closely clustered data. Especially the SD condition in "the Leans" has widely spread data. The maximum corrected error rate for this condition is $0.375$ and is plotted right next to the box.

### D. *Control Performance*

The Wilcoxon Signed Ranks test was used for the "False Horizon" and "the Leans" scenarios. For the "False Horizon", the test led to an outcome of $Z(1, 13) = -1.57$, $p = 0.116$. This was $Z(1, 13) = -2.83$, $p = 0.005$, $d = 0.57$ for "the Leans" scenario, meaning that the control performance gets worse in the SD condition compared to the No-SD condition.

From the paired samples t-test followed for the "Featureless Terrain" scenario that $t = 0.805$, $p = 0.437$. Thus, only "the Leans" scenario demonstrated to be significant.

In the "False Horizon" scenario, the mean RMS in the No-SD condition was $M = 2.29°$, $SD = 1.32°$. In the SD condition, this was $M = 2.77°$, $SD = 0.818°$. The mean RMS for the "Featureless Terrain" No-SD condition was $M = 43.6ft$, $SD = 28.0ft$, whereas this was $M = 51.4ft$, $SD = 29.8ft$ in the SD condition. For "the Leans" scenario, the mean RMS was $M = 2.41°$, $SD = 1.51°$ in the No-SD condition, and $M = 3.46°$, $SD = 1.99°$ in the SD condition.



(a) False Horizon (PF)

(b) Featureless Terrain (PF)

(c) The Leans (PF)

Fig. 6: Boxplots for the RMS values in the SD and No-SD condition for each scenario. Corresponding data points for each scenario are visible left outside the boxes. Each data point represents a participant.

TABLE II: Percentages of participants that recognized SD and the corresponding average score as given by participants after each SD experiment run.

| **Scenario** | **Session I** | | **Session II** | |
|---|---|---|---|---|
| | **Recognized SD (%)** | **Average score** | **Recognized SD (%)** | **Average score** |
| False Horizon | 53.8 | 6.3 | 53.8 | 5.4 |
| Featureless Terrain | 23.1 | 4.5 | 15.4 | 3.0 |
| The Leans | 100 | 8.5 | 92.3 | 6.3 |
| Brownout | 100 | 7.5 | 30.8 | 4.9 |
| Somatogyral Illusion | 23.1 | 5.3 | 30.8 | 6.3 |
| NVGs | 15.4 | 4.3 | 7.7 | 2.0 |

Figure 6 shows the boxplots for each condition. When visually inspecting the figure, an increasing trend can be seen for the "False Horizon" and "the Leans" scenarios, visually indicating that the control performance gets worse in the SD conditions.

### *E. Recognition of the SD Events*

Table II summarizes per SD condition the percentage of participants that recognized the SD event and the corresponding average "surprise" score. A distinction has been made between simulator Session I and Session II.

It can be seen that for both "the Leans" and "Brownout" scenarios, all participants recognized the SD event during simulator Session I. These scenarios also scored the highest on the "surprise" scale. Furthermore, the table shows that all scenarios, except for the "Somatogyral Illusion", had a lower percentage of participants recognizing SD in simulator Session II compared to Session I. This trend was also seen in the "surprise" scores, which all decreased in Session II except for the "Somatogyral Illusion", for which the average score increased.

Moreover, some participants indicated a surprising element during the baseline conditions. This was mostly due to expectation management or to unfamiliarity with the AH-64 and its systems. For instance, in the No-SD condition of the "Brownout" scenario four participants indicated something surprising the first time they experienced it, whereas this was one participant during the second experience with this condition. According to them, this was due to the fact that a highly opaque brownout was expected, just as in the SD condition, but a lightly opaque brownout was presented to them.

### *F. Self-Reported SD and Cognitive Impact*

Differences between the SD and No-SD conditions indicated that the SD manipulation was effective in all scenarios. From the Wilcoxon signed-ranks test followed for the "False Horizon" scenario, that the outcome of the test was $Z(1, 13) = -2.32$, $p = 0.02$. For the "Featureless Terrain" scenario, the test led to $Z(1, 13) = -2.24$, $p = 0.025$. This was $Z(1, 13) = -3.12$, $p = 0.002$ for "the Leans" scenario. The outcome for the "Brownout" scenario was $Z(1, 13) = -2.91$, $p = 0.004$. For the "Somatogyral Illusion", this was $Z(1, 13) = -2.98$, $p = 0.003$. Lastly, the test lead to $Z(1, 13) = -2.45$, $p = 0.014$ for the "NVGs" scenario.

Table III shows the median, and the first and third quartile for the experienced level of disorientation and its cognitive impact for each condition. It can be seen that the SD conditions of "the Leans", "Brownout" and "Somatogyral Illusion" scenarios have the highest medians. These three scenarios, together with the SD condition of the "False Horizon", also score the highest when looking at cognitive impact of the SD

TABLE III: Median and corresponding interquartile ranges (IQRs) for the experienced level of SD and its cognitive impact per condition as determined by participants.

| Condition | SD/Baseline | Level of SD | | Cognitive Impact | |
|---|---|---|---|---|---|
| | | Median | IQR | Median | IQR |
| False Horizon | SD | 3 | (3, 4) | 3 | (2, 3) |
| | Baseline | 2 | (1, 2.25) | 2 | (1, 2) |
| Featureless Terrain | SD | 2 | (1.75, 2) | 2 | (1, 2.25) |
| | Baseline | 2 | (1, 2) | 2 | (1, 2) |
| The Leans | SD | 4 | (3.75, 5) | 4 | (2.75, 4) |
| | Baseline | 2 | (1, 2.25) | 2 | (1, 2) |
| Brownout | SD | 4 | (3.75, 5) | 3 | (2.75, 4) |
| | Baseline | 2 | (1, 2) | 2 | (1, 2.25) |
| Somatogyral Illusion | SD | 4 | (3, 4) | 3 | (2, 4) |
| | Baseline | 2 | (1.75, 2.25) | 2 | (2, 2.25) |
| NVGs | SD | 2 | (2, 3) | 2 | (1, 2.25) |
| | Baseline | 2 | (1, 2.25) | 2 | (1, 2) |

events. The SD conditions of these scenarios have the highest scores.

### *G. SD-Effects and Flying Experience*

Spearman's correlation test was applied to test whether there was a relation between the flying experience of participants and the impact of SD on cognitive performance. The test was executed twice, once for the impact of SD on the reaction time and once for the impact of SD on error rate. None of the tests indicated a significant correlation, so no relation was found between flying experience and the cognitive impact of SD for this set-up and sample size. From the test followed that $r(11) = -0.209$, $p = 0.493$ for the corrected reaction time, and $r(11) = 0.273$, $p = 0.367$ for the corrected error rate.

### *H. Motion Sickness*

After both simulator sessions, participants scored near the lowest end on the MISC, with $M = 1.4$, $SD = 1.9$ for the first session and $M = 1.7$, $SD = 1.9$ for the second session.

## V. DISCUSSION

This study found that SD impairs the cognitive performance of military helicopter pilots. A main effect of SD on both the reaction time ($\eta^2 = 0.55$) and error rate ($\eta^2 = 0.40$) was found. The observed effect sizes for both the reaction time and error rate are found to exceed the threshold for what is typically considered to be large ($\eta^2 > 0.14$).

From the responses to the surprise related questions followed that participants have given indications that they experienced SD Type-II. A substantial part of the participants, as evident from their responses, acknowledged recognizing the presented SD events. This, together with the significant main effect of SD on cognitive performance suggests that SD Type-II diverts attentional resources from a concurrent cognitive task (i.e., control task) to maintain orientation, which is as according to the orientation first principle [14].

These outcomes are in line with previous studies in this field of expertise. In the study of Stróżak et al. [16] participants had the role of pilot flying throughout the entire experiment. They only found a significant impairment of cognition due to SD in their leans scenario. No main effect of SD on cognitive performance was determined taking into account all six scenarios. Landman et al. [5] found that SD significantly decreased counting speed, and that error rate was not significantly affected by SD.

In contrast, this study showed in an operationally representative environment that SD impairs cognitive performance (i.e., higher reaction times and error rates), taking into account both the pilot flying and pilot monitoring roles, as well as relevant SD events for these roles. From the self-reported cognitive impact of SD followed that participants generally experienced a mediocre effect of SD on their cognitive performance. This emphasizes the need to raise awareness amongst pilots on how SD not only affects their control performance, but also their cognitive performance. The acquired knowledge can be incorporated into SD training. The findings also underline the importance of the use of workload management procedures when experiencing SD. In the long run, this could contribute to minimizing the influence of SD on mission effectiveness and fostering more efficient and safer military aviation.

Contrary to the hypothesis, there was no correlation between flying experience and the cognitive impact of SD with the current set-up and sample size. This finding emphasizes the significance of ensuring that pilots of all experience levels are made aware of the potential risks of spatial disorientation, rather than solely focusing on young, inexperienced pilots.

A secondary goal of this study was to examine whether the cognitive impact of SD would be larger for specific SD events. This was done in an exploratory manner. The results showed that the cognitive impact of SD varies depending on the scenario.

A significant effect of SD on the reaction time was found for the "Featureless Terrain" and "the Leans" scenarios. For both scenarios, the impact of SD on the reaction time was around $17.5\%$, which is large from an operational perspective. The "Featureless Terrain" scenario showed a marginally significant effect of SD on the proportion of errors. The impact of SD on the error rate was found to be $3.1\%$ with regard to the baseline performance.

The average impact of SD on the error rates in "the Leans" scenario was $11.1\%$. The corrected error rates are in this scenario widely spread amongst participants in the SD condition indicating that some participants set aside the cognitive task for a certain amount of time in order to maintain orientation, whilst others had more resources left for the mathematical exercises. The analysis of RMS in roll angle showed that SD also had a negative impact on control performance. From the responses to the surprise related questions, it can be concluded that participants experienced SD Type-II. In "the Leans" scenario, SD Type-II led thus not only to disorientation stress [4], i.e., a decrease in control performance, but also to disruption of cognitive performance.

The "Brownout" condition showed a marginally significant effect of SD on reaction time, with an SD impact of $11.6\%$ with regard to the baseline cognitive performance. This gives indications that SD not only impairs cognitive performance due to mental resources being reallocated in order to maintain orientation, but that it also directly impacts cognition.

In general, when looking at the six scenarios, it seems that pilot flying scenarios have been more effective than pilot monitoring scenarios, since especially the "Featureless Terrain" and "the Leans" scenarios have demonstrated this cognitive impact of SD effectively. It also appears that scenarios which contain clear (super-threshold) motion stimuli in order to induce SD, e.g., "the Leans", work better. Additionally, it seems more effective when participants are provided with a clear mismatch, as seen in "the Leans" and "Brownout" scenarios.

Nevertheless, the "Featureless Terrain" scenario has shown to be effective, while no clear mismatch was provided. SD was only recognized by a small part of the participant group. The analysis of control performance supports this by not showing a significant difference in RMS of the altitude between SD and No-SD conditions. Participants could have experienced no SD or participants (unconsciously) experienced SD (Type-I), but reallocated mental resources to the control task (i.e., orientation first principle) leaving fewer for the cognitive task. Thus, resulting in no difference in control performance between SD and No-SD conditions, and worse cognitive performance in the SD condition.

Scenarios that did not effectively show the impact of SD on cognition might suggest that participants either did not experience SD or encountered SD Type-I. This could also be seen in the outcomes from the questions related to surprise. Though, drawing conclusions from subjective data remains challenging. Pilots undergo specific training that might influence their responses to questionnaires, potentially leading them to answer in a way they believe aligns with the expected response instead of sharing their true experiences.

Training and habituation might have been factors here too. Military helicopter pilots are well-trained in performing in brownout conditions, which could also explain the marginal significant outcome in the "Brownout" scenario. It is also plausible that participants are accustomed to the false horizon illusion. A survey held amongst Dutch military pilots showed that military transport helicopter pilots pointed out the sloping horizon as the most frequently reported SD-event [20]. Analysis of control performance did also not show a significant difference in RMS between SD and No-SD condition. When visually inspecting the boxplot of the SD condition, two groups of participants can be distinguished. One group seems to be more affected by the false horizon than the other group.

This study has several limitations concerning the participant group and the flight model. Some participants found it challenging to identify the correct surprising element after the experiment due to their unfamiliarity with the AH-64 and its systems, particularly in the pilot monitoring scenarios. Participants were required to fly from the front seat of the AH-64 to better resemble the cockpit view of their own helicopters. The presence of the TEDAC caused participants to adapt to a new cross-check procedure.

Due to choices made for experimental purposes, certain scenarios are not entirely operationally accurate or representative. Flying IMC in an AH-64, for instance, is almost never done in practice. A follow-up study could take these factors into consideration. Additionally, the cognitive task could be made less abstract and placed more in an operational context by incorporating tasks related to tactics, navigation, or communication. Instead of expanding the simulation to an even more operationally representative environment, scenarios could also be made more delimited in future research, such that it is fully clear for participants what to expect and how to behave. Because participants were not informed about the real goal of the experiment, they did not exactly know what to expect and their performance could have been disrupted by unintended factors, due to, for example, an unannounced turn in the "Somatogyral Illusion" scenario or limitations of the simulation.

Participants found it somewhat unusual that they could not communicate with the pilot flying during these scenarios, which they normally do during operations. However, they were provided with information on the general flight path before each run. By using delimited and more abstracted scenarios, these kinds of issues can be prevented and SD Type-II can be more deliberately induced.

The additional motion profiles in the "Somatogyral Illusion" scenario (Table I) were based on the study of Landman et al. [5]. No significant effect of SD was found for this scenario, which might be due to the motion profiles not having been perfectly aligned. Having placed the cabin of Desdemona at the outer end of the linear track resulted in a sway component being added to the motion cueing. However, it is not unrealistic to have a sway component in actual helicopter maneuvers that contain yaw rotations. Given that this simulation of the somatogyral yaw illusion was used, it is important to consider that participants may have experienced some Coriolis effects if they pitched their heads up or down. Future research could focus on developing simulator motion profiles that more closely resemble the in-flight somatogyral yaw illusion.

More focus could be put on expectation management in a follow-up experiment. Due to each condition being performed twice, participants began to expect certain things to happen. This became particularly evident in the questions about "surprise" and this could have made the manipulation check for SD less watertight. For future experiments, it might be advantageous to ensure participants are less able to predict what will happen at the start of each experiment run.

In future research, it would be beneficial to use the flight model of the aircraft for which the participant holds a current type rating. This would eliminate any potential effects coming from unfamiliarity with a new aircraft. Furthermore, it could be interesting to focus on a more homogeneous group of participants, meaning pilots who all operate the same helicopter type. Pilots become accustomed to their specific conditions based on the helicopter type they operate, which also depends on the specific Air Force. Dutch CH-47 pilots are, for example, accustomed to flying in brownout conditions, whereas Dutch NH90 pilots are not as experienced in this regard.

## VI. CONCLUSION

This study has shown that SD causes both the reaction time and error rate to increase significantly when performing the mathematical processing task. Especially "the Leans", "Featureless Terrain" and "Brownout" conditions effectively demonstrated this effect. It can be concluded that SD has a detrimental effect on the cognitive performance of military helicopter pilots. Flying experience was found to have no influence on the extent of cognitive impact of SD with the current set-up and sample size. These findings can be relevant for re-evaluating and improving SD training, not only for young, inexperienced pilots, but also for highly experienced pilots. Pilots can be informed on and be made more aware of the potential risks and impact of SD. Recommendations can be made for crew resource management, contributing to more efficient and safer air operations.

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# Part II

## Preliminary Thesis

*This part has been assessed for the course *AE4020 Literature Study*.

# 1

# Introduction

*In aviation,* spatial disorientation (SD) is defined as the misperception of the attitude or motion of an aircraft with respect to the Earth. SD can cause dangerous situations which in the worst case scenario lead to fatal accidents due to loss-of-control in flight (LOC-I) or controlled flight into terrain (CFIT). Spatial disorientation accidents as a result of CFIT can be linked to SD Type-I. This is the type of SD in which the pilot is not aware of the wrong perception of the attitude and motion of the aircraft. SD Type-II causes situations in which the pilot is aware of the disorientation. When disorientation reaches a level of severity where the pilot cannot effectively counter it, it can result in LOC-I. Certain studies label this type of disorientation as SD Type-III, although this classification is not universally acknowledged due to the subtle distinction between SD Type-II and Type-III [1].

Spatial disorientation has a high contribution in the number of incidents and accidents happened in the past couple of years. According to Belcastro et al. (2017) spatial disorientation contributed for $11\%$ to LOC-I accidents in commuter and transport aircraft between 1996 and 2010 [2]. Newman and Rupert analysed mishaps in transport planes in the period 1981-2016 and discovered an increasing trend in the number of mishaps due to spatial disorientation (Figure 1.1) [3]. A survey of UK military accidents showed that $28.2\%$ of the accidents with fast jets in the period 1993-2002 can be related to spatial disorientation. For rotary wing aircraft this contribution was $42.2\%$ [4]. Bushby et al. (2018) found this percentage to be $43\%$ for rotary wing aircraft of the UK Military in the period 2000-2016 [5]. Another study by Poisson and Miller pointed out this major contribution of SD too. In $11\%$ of the serious accidents between 1993 and 2013 in the U.S. Air Force, SD had a contribution [6].

Multiple surveys have been held under (military) aircrew to investigate the occurrence of SD [7], [8]. Situations in which SD took place have been analysed in order to develop training programs such that pilots are made aware of the risks of spatial disorientation. Researches have looked into the influence of spatial disorientation on the performance of the control task. In certain situations, SD causes the control task performance to be worse compared to normal situations. Boril, et al (2020), looked into the effect of SD on the precise approach in a simulated flight. The results showed that the greatest deviations from the ideal trajectory were caused by a SD-illusion [9]. Landman, et al (2019) showed that SD induces roll reversal errors when pilots use the attitude indicator [10]. Though, there is a second pathway through which SD may impact pilot performance, and this is by interfering with pilot cognition. Based on a body of literature with regard to cognitive performance and posture disturbance, it could be the case that SD draws attention away from other cognitive tasks in SD Type-II. Numerous incident reports have given indications for this [1], [11], [12], [13]. The following incident illustrates how a pilot can struggle with other tasks after having experienced SD. In this example the pilot was departing in hurry due to worsening weather conditions and a scheduled meeting later that day. The pilot had no instrument rating. Unexpectedly, the aircraft was in the clouds shortly after take off, which caused spatial disorientation (Type-II) to occur.

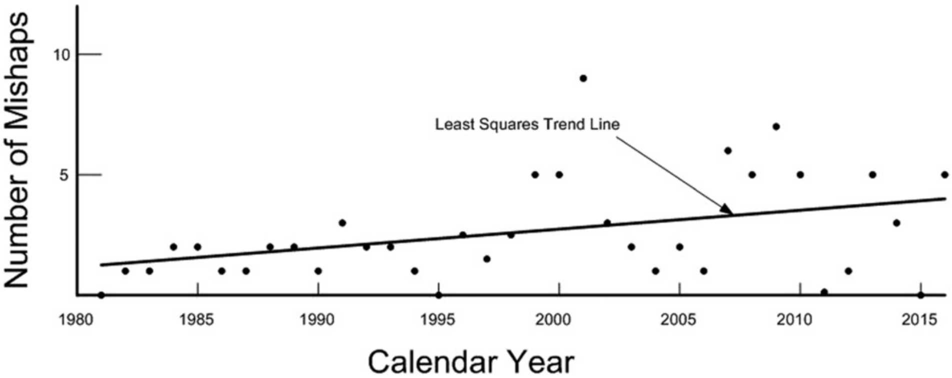


**Figure 1.1:** The number of mishaps per year in transport aircraft due to spatial disorientation in the period 1981-2016. A least squares trend line is also visualized in the graph. From “The Magnitude of the Spatial Disorientation Problem in Transport Airplanes”, by R.L. Newman and A.H. Rupert, 2020, *Aerospace medicine and human performance*, p. 65-70 [3]

“*Immediately after takeoff (0.5 mile and 300 ft), I was in the clouds. This was not what I had planned and immediately fear and panic set in. Next came spatial disorientation with much more fear and panic. Unknowingly I put the plane in a hard bank to the left and a very steep climb. Absolutely nothing was making sense to me and the next thing I remember was seeing the airspeed indicator at approximately 50 MPH. (…) The plane recovered and I remember doing this several times in the next few minutes of trying to stabilize the aircraft. The oscillations became less and less severe as I tried desperately to regain control of the aircraft. It was apparent that not only had fear, panic and spatial disorientation set in but also that I was probably in shock too. My mind was not able to digest the tremendous amount of data it was receiving and I was trying to hang on by a thread. I was grasping on to any single piece of data that I could possibly use, being in the state of shock I was in. (…) The passenger sitting next to me dialed in the code and pushed identification. I showed her how to do that during the morning flight and looking back I do not think I could have been able to dial that in during that time of the flight. ZAB then responded by telling me to head to 070 degree and climb to 13500 ft, which I said I could not do. As things progressed, I was able to climb to 10500 ft though my heading was all over the place.*” (ASRS Database, Accident 615534 [14])

In this example, the pilot very well describes that he is aware of the situation in which he has to cope with spatial disorientation. He puts all his effort in trying to control the plane. After having controlled the plane, he has contact with air traffic control, who tries to guide him to safe and stable flight path. In order to follow that path, the pilot has to dial a certain squawk code. His passenger does that for him. He describes that looking back on the event, he would not have been able to execute this (cognitive) task, due to the mental state he was in. This event gives an indication that spatial disorientation can affect the cognitive performance of a pilot. This example is from general aviation, however spatial disorientation occurs in civil and military aviation too. Having to deal with spatial disorientation is not uncommon for military pilots, since they fly in highly maneuverable and complex aircraft. In the newest generation military aircraft and helicopters information processing is almost as important as the control task. Military operations have become mainly information-driven. Especially military helicopter pilots are susceptible to spatial disorientation, due to the operations they are deployed in. Military helicopters operate in very challenging environments at low altitudes. As earlier mentioned, numerous surveys pointed out that SD is a serious problem for military rotary wing pilots. Due to the high prevalence of SD in rotary wing operations, and due to the high, cognitive workload present in military operations, this literature study focuses on the effect of spatial disorientation on the cognitive performance of helicopter pilots in the military domain.

This literature study is part of a master thesis Aerospace Engineering at Delft University of Technology and is in collaboration with TNO, the Dutch Organization for Applied Scientific Research. The master thesis is part of the Human Modelling work package of TNO’s NextGen research project, which aims to explore the modeling of human performance in the context of stressors present in next generation aircraft and helicopters. Driven by the recognition of the profound relevance of this research to the Dutch military, the project has been entrusted with the task of enhancing our understanding of how aircrew adapt and perform under challenging conditions.

This literature study forms the theoretical foundation for an experiment which aims to investigate the effect of spatial disorientation on the cognitive performance of helicopter pilots. This literature study investigates the literature related to the effect of spatial disorientation on the cognitive performance of these pilots. In order to give an answer to this question, multiple topics will be treated in this literature study. It can be split up in two main pillars: spatial disorientation, and cognitive performance. It will be discussed how humans orient themselves in space and how spatial disorientation occurs. It is important to investigate which SD event impacts the pilot performance the most and which ones are typical for military helicopter operations. Furthermore, the relevant cognitive tasks in flight will be indicated and investigated which ones are most affected by spatial disorientation. With multiple different cognitive processes it will be discussed how the dual task of controlling and a cognitive task relate in the cockpit. Finally, the state-of-the-art on the main research question will be looked into.

Chapter 2 focuses on the process of human spatial orientation. Spatial disorientation and the different kind of spatial disorientation illusions will be discussed in Chapter 3. This chapter also indicates the spatial disorientation illusions most common or unique for military helicopter pilots. Chapter 4 focuses on the relevant theories related to cognition and indicates the relevant cognitive tasks in the cockpit. The next chapter, Chapter 5, looks at the state-of-the-art in literature about the relation between spatial disorientation and cognition. It also indicates the gaps in literature. Chapter 6 points out the important factors to take into account for the experimental design and proposes an (example) design of the experiment. It covers the spatial disorientation scenario, the environment in which the pilot flies and the cognitive task he or she has to perform. Finally, conclusions of this literature study will be drawn in Chapter 7.

# 2

# Spatial Orientation in Flight

Human beings are able to to orient themselves with respect to their surrounding. They have learned to process signals from multiple sensory receptors to define their orientation in three-dimensional space. In this chapter, a description of these different sensory systems will be given in order to provide understanding of the process of spatial orientation (SO). The description will also be put in the context of aviation, since this it is more difficult to maintain orientation in the air due to the fact that man's natural habitat is Earth's surface.

## 2.1. General Process of Orientation

When humans are in their natural surrounding, statically or dynamically, they orient themselves with respect to their reference frame. When not in the air, this reference frame is provided by Earth's surface and the gravitational vertical. Humans need to know their orientation in order to accomplish their goal, for example picking up a coin from the street. The visual system contributes for a large part to spatial orientation. It provides the brain information on the position of the coin on the street. Furthermore, the non-visual receptors allow the sensing of one's position, attitude and motion relative the Earth's surface, too. The central nervous system (CNS), consisting of the brain and the spinal cord, plays a key role in orientation. It processes the signals as provided by the sensory systems in order obtain and maintain (bodily) orientation.

Figure 2.1 gives an overview of the closed-loop model of the pilot control of aircraft spatial orientation. The external scene, i.e. the outside view, visual displays, tactors, 3D audio and signal processing are part of the input signals for the process of orientation. There are the sensory modalities (focal vision, ambient vision, vestibular and G-receptors, tactile receptors, cochlea receptors), that sense the signals for spatial orientation and other processes. A spatial orientation percept is created by neural processing. The percept is compared to the expected orientation, after which a motor response is given. This response controls the aircraft dynamics, attitude and motion.

The visual and vestibular systems are the sensory systems that contribute the most to this stream of input signals. Furthermore, there the other non-vestibular and auditory systems that provide input signals, however, this contribution is significantly smaller. That is why only the visual and vestibular system will be discussed in detail [15].

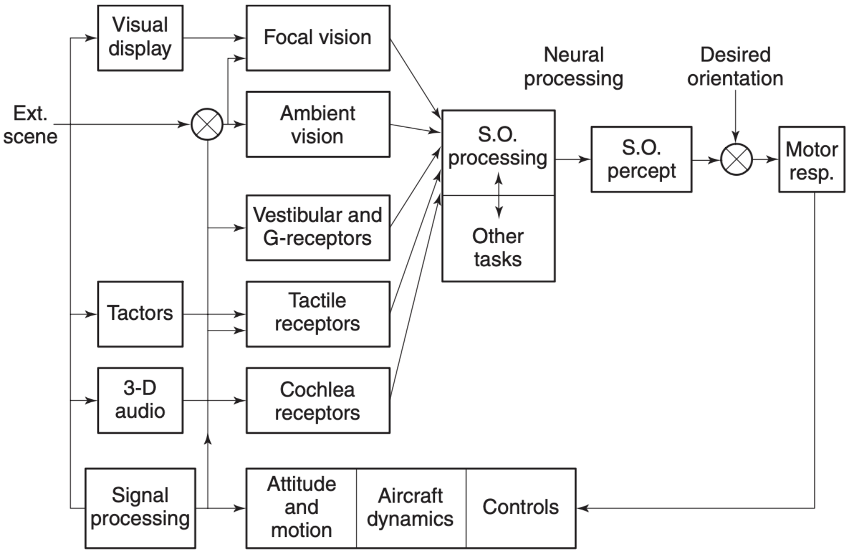


**Figure 2.1:** Closed-loop model of pilot control of aircraft spatial orientation (SO). From *Ernsting's Aviation Medicine* (4th ed., p.305), by D.J. Rainford and D.P. Gradwell, 2006, Hodder Arnold [15].

## 2.2. Visual System

The visual system acquires about $80\%$ of the information needed in flight [16]. Thus, this sensory system is of high importance when controlling an aircraft. The eyes sense light by using photoreceptor cells. The visual system uses rods and cones, two types of photoreceptor cells, to form an image of the environment. The rods provide information in dim conditions, whereas the cones provide information in bright conditions. The technique of sensing light is similar for both types of receptors. The optic nerve forms the connection between these receptors and the rest of the CNS.

Although the eye can be seen as one sensory organ, when looking at its functionalities, two different modes can be distinguished, the ambient mode and the focal mode. These can also be addressed to as the ambient visual system and the focal visual system [15], [17].

### 2.2.1. Ambient Visual System

The ambient visual system is concerned with the question “Where?”. It involves stimulation of the peripheral visual field and it is thus sometimes called “peripheral vision”. Ambient vision is primarily involved with orienting the individual in the environment, most importantly without conscious awareness of the visual cues. It can be thought of as two processes, where one is related to providing position cues and the other providing motion cues. In the context of aviation, the ambient visual system allows the pilot to sense the attitude and change of attitude of the aircraft in pitch and roll. Nevertheless, the ambient visual cues do not provide sufficient and adequate information on the perception of distance (i.e., the height above the ground), and derivatives of distances (i.e., rate of climb or descent) [15], [17].

### 2.2.2. Focal Visual System

The focal visual system generally answers the question of “What?”. It is concerned with object recognition and identification. This visual mode involves fine detail and stimulates mainly the central visual fields, causing the mode to sometimes being indicated as “central vision”. The focal visual mode contributes to the conscious percepts of orientation. It makes sure the individual is able to judge distance and depth. Two different types of cues can be distinguished, monocular cues and binocular cues. As the name already states, monocular cues are cues sensed with only one eye, whereas two eyes are needed for binocular cues.

Size constancy, shape constancy, motion parallax, gradient and illumination perspective are examples of monocular cues. The simultaneous movement of the pupils towards or away from each other during focusing, or in short vergence, can be assigned to the group of binocular cues. Vergence movements contribute to the maintenance of visual orientation in a dynamic environment, because the image is stabilized by the movements of the pupils of the eye [15], [17].

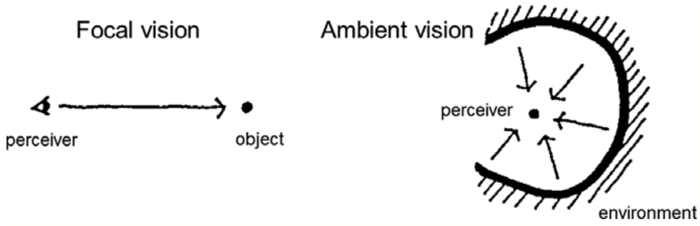


**Figure 2.2:** Schematic representation of the ambient and focal vision system. From "Studies on environmental perception during locomotion - a review of empirical studies by the Ohno Laboratory", by R. Ohno, 2018, *Japan Architectural Review* [18].

To conclude, the ambient visual system serves to orient the individual relative to the perceived environment, whereas the focal visual system serves to orient the perceived object relative to the individual. Figure 2.2 shows a schematic representation of these two visual systems.

To relate ambient and focal vision to spatial orientation in flight, an example on switching between Visual Instrument Conditions (VMC) and Instrument Meteorlogical Conditions (IMC) in flight, can be used. The pilot uses his/her ambient visual system for orientation during VMC, where there is a clear defined horizon. Little conscious processing is used for this, since it is pretty much similar to everyday life. However, when the pilot flies into a cloud, or any other degraded visual environment (DVE) like night conditions, the ambient visual cues degrade or disappear. The pilot must then switch from outside view to the inside cockpit view. The pilot will then determine its orientation by looking at its instruments. To be able to scan, read and interpret the displays and the associated symbols in the cockpit, the pilot uses its focal visual system. With experience, this task uses little to no working memory. Though, this visual system is not the natural orientation system and is thus thought to be more susceptible to impairment [15].

## 2.3. Vestibular System

Pilots often use the term "seat-of-the-pants" to indicate a special sensory modality that contributes to spatial orientation in flight. However, this modality does not exist as such. What they actually indicate are all sensory modalities that contribute to orientation, besides the visual and auditory. The vestibular system has the highest contribution to this process. The vestibular system is located in the inner-ear organ, together with the cochlear system, which plays a key role in the ability to hear. The vestibular system consists of the vestibule and the semicircular canals (SCC). Subsection 2.3.1 is devoted to the semicircular canals, while Section 2.3.2 focuses on the otoliths, which are located inside the vestibule.

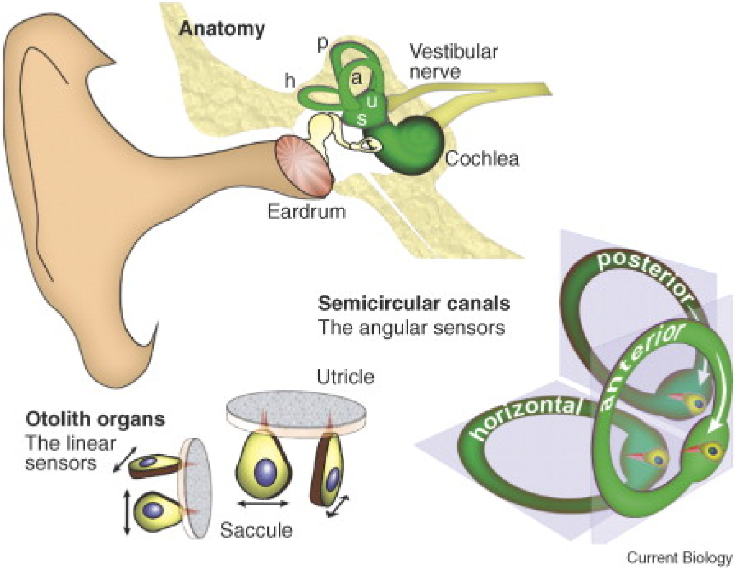


**Figure 2.3:** Schematic representation of the semicircular canals and the vestibule. The otolith organs are visualized down left, where the avocado-shaped objects represent the hair cells. The semicircular canals are illustrated down right, where the green dots represent the ampullae. From “The vestibular system”, by B. Day and R. Fitzpatrick, 2005, *Current biology: CB* [19].

### 2.3.1. Semicircular Canals

There are three semicircular canals, which are oriented in three mutually perpendicular planes. The three canals are being called the anterior vertical, the posterior vertical and the horizontal (or lateral) [17]. These can be seen in Figure 2.3. The semicircular canals (SCC) provide the individual information about angular movements of the head by converting inertial torques. Within these canals lie specialized sensory cells called hair cells, which are responsible for detecting and transducing mechanical movements into electrical signals that the brain can interpret. The hair cells are arranged in clusters within the ampulla, which is a widened portion at the base of each canal. The hair cells have hair-like projections, which are embedded in a gelatinous structure known as the cupula. The cupula acts as a barrier between the fluid-filled canal and the hair cells. When the head rotates or moves in a particular plane, the fluid inside the semicircular canals, known as the endolymph, also moves. This movement causes the cupula to bend, which in turn deflects the projections of the hair cells resulting in the production of electrical signals. Depending on the direction and speed of the head movement, the hair cells will be either activated or inhibited. This information is then transmitted via the nervous system to the brain, where it is processed and integrated with visual and proprioceptive information to generate a sense of balance and orientation. The brain is thus able to process angular accelerations in pitch, roll and yaw in an aircraft [15], [19]. Only angular accelerations with a value of above a certain threshold will be sensed by humans. This threshold depends on the frequency of the motion stimulus and differs per semicircular canal and per person. As seen in Figure 2.4, in the frequency range of $0.1 - 5Hz$, the thresholds exhibit minimal changes. However, as the frequency decreases to below $0.1Hz$, the thresholds increase rapidly [15].

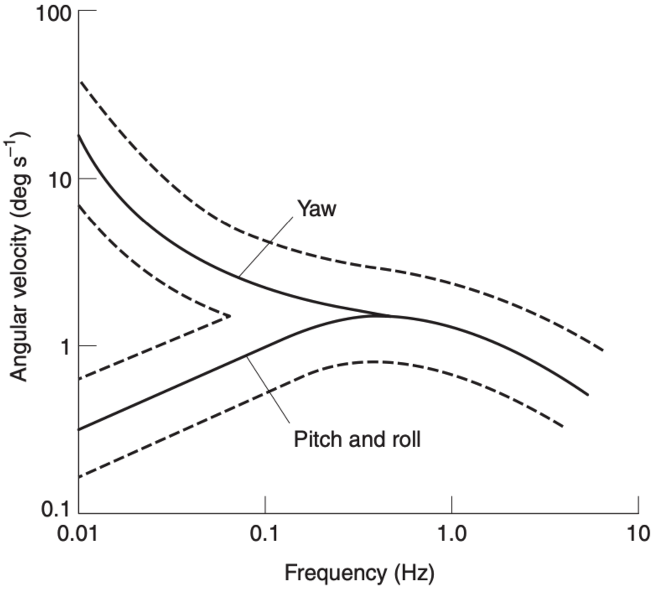


**Figure 2.4:** Perception threshold of angular motion as a function of motion stimulus. From *Ernsting's Aviation Medicine* (4th ed., p.303), by D.J. Rainford and D.P. Gradwell, 2006, Hodder Arnold [15].

### 2.3.2. Otoliths

Inside the vestibule lie the two otolith organs, the utricle and the saccule. These organs translate inertial and gravitational forces into spatial orientation information. The information is related to the linear motion of the head and tilt [17]. The utricle and saccule are located in the inner ear and contain the sensory hair cells, which are similar to those found in the semicircular canals. However, in the otoliths, the hair cells are not clustered in the ampulla, but are embedded within a gelatinous layer. The otoliths are also filled with endolymph. The density of the otolithic membrane, which is nearly three time greater than that of the endolymph, causes the bending of sensory hairs when there are changes in the head's orientation in relation to the force of gravity. The electrical signals created as a result of the deflecting hair cells, are processed in the brain. These signals are then integrated with information from other sensory systems too, to provide comprehensive understanding of body position and movement in space. The otoliths are located in the inner ear such that the utricle lies in a horizontal plane and the saccule lies in a verticle plane when the head is in the upright position (Figure 2.3). Only linear accelerations with a value which lies above the perception threshold, will be sensed by humans. As for the threshold of angular motion, the value differs per person and depends on factors like mental and physical state. It also varies with the frequency of the motion stimulus. In general, threshold is in the range of $1m/s^2$ at $0.01Hz$ to about $0.02m/s^2$ at $10Hz$, see Figure 2.5 [15], [19].

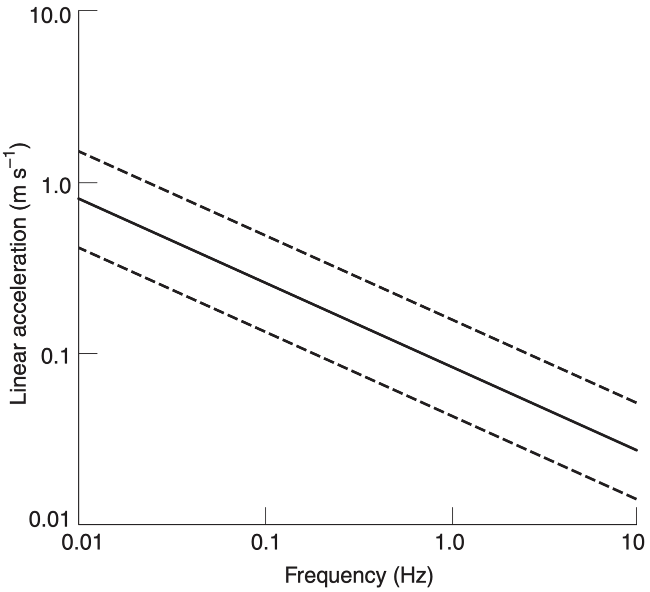


**Figure 2.5:** Perception threshold of linear motion as a function of motion stimulus. From *Ernsting's Aviation Medicine* (4th ed., p.302), by D.J. Rainford and D.P. Gradwell, 2006, Hodder Arnold [15].

## 2.4. Tacticle, Proprioceptive and Auditory Systems

The role of other sensory systems in the process of spatial orientation cannot be overlooked, although the visual and vestibular systems play dominant roles. In flight, the nonvestibular proprioceptors (i.e., muscle, tendon and joint receptors) are important, because the orientation derived from their functioning generally supports the one derived from vestibular orientation [17]. These proprioceptors are stimulated by the forces acting upon them, so to the linear accelerations the body is exposed to. Information about the magnitude and direction of the forces and orientation with respect to the gravitational vertical are provided by them. This is for example when pulling G's. The nonvestibular proprioceptors are much more sensitive than the vestibular organs, which are only stimulated when a supra-threshold change has taken place. Thus, they complement the otolithic signals [15].

Tacticle information involves the processing of stimuli by the different receptors in human skin, including mechanoreceptors, thermoreceptors (responses to temperature changes), and nociceptors (responses to (potential) damaging stimuli). This encompasses sensations like surface texture, friction, temperature and pain [20]. The information sensed by the tacticle and proprioceptive systems also contribute to what aviators call "seat-of-the-pants".

In daily life, one is able to locate a sound source, which contributes to the process of orientation. In this way one is able place itself in the reference frame of the sound. Differences in arrival time and congruent sounds allow the individual to localize the sound. In the early days of aviation, the auditory system was much more important to the pilot when orientating him-/herself than it is nowadays. Back in the days, the pilot used aircraft-generated sounds in the process of orientation. The sound of air rushing past the airframe depended on the airspeed and the angle of attack. The different sounds could be linked to values of the different parameters. As such, the pilot could use these sounds in the process of orientation, since a percept of velocity and pitch were created. Aircraft have now become more advanced and pilots have become more insulated from acoustic stimuli, which causes the dependency on auditory cues to diminish [17]. Present day, pilots relay on the auditory warning systems in aircraft, which give an indication of orientation too. These systems can give, for example, a low-altitude warning, indicating the height above the ground.

# 3

# Spatial Disorientation in Flight

Spatial disorientation (SD) can be referred to as the phenomenon in which an individual has a wrong sense of the aircraft's attitude, altitude and motion in relation to the reference frame of the Earth [21]. Different types of spatial disorientation can be identified. SD Type-I is related to situations in which the pilot is not aware of the disorientation. This type of SD is very dangerous and can cause fatal accidents. Because the pilot controls the aircraft with false percepts, it can lead to Controlled-Flight-Into-Terrain (CFIT) [1]. This type of disorientation might be due to the incapability of the conscious system to operate or supervise at the subconscious level [16]. When the pilot is aware of the SD and is still able to control the aircraft, it is referred to as SD Type-II. This type of SD gives the pilot an uncomfortable feeling. Although this type is referred to as the "recognized" type, it does not automatically have to mean that the pilot knows he/she is disoriented. They realizes there is a problem controlling the aircraft, and could think it is due to instrument failure, while the source of the problem is SD [1]. Unlike Type-I SD, the central nervous system is able to detect that disorientation is occurring [16].

Some studies also refer to a third type of spatial disorientation. This is when SD occurs, and the pilot is not able to manage it, although aware of it. It can lead to confusion. This situation is labelled as SD Type-III, the incapacitating type. Other consequences of it are "freeze", "startle" and "Loss-Of-Control In-Flight". The control task of the pilot is thus affected [1]. The central nervous system is able to determine the phenomenon of disorientation, however the information cues from the sensory systems are so discordant that the pilot is unable to get out of this situation [16]. Since the classification of SD Type-III is not based on the nature of the pilot's perception, which is the case for Type-I and -II, this third type is not universally acknowledged [15].

There are several types of spatial disorientation events, which can be categorized into two main groups. One group contains visual illusions, whereas the other group consists of vestibular illusions. The principles of these groups of illusions will be discussed in Section 3.1, respectively Section 3.2. Numerous factors contribute to the susceptibility of a spatial disorientation event. Section 3.3 examines the most important risk factors. The final section of this chapter, Section 3.4, points out the SD-events that are unique or common for rotary wing aircraft.

## 3.1. Visual Illusions

The visual system can be divided in the ambient visual system and the focal visual system (see Section 2.2). This section is divided into two subsections, where one subsection is dedicated to ambient visual illusions and and the other one to focal visual illusions.

### 3.1.1. Ambient Visual Illusions

The lack of ambient cues or false ambient cues could be the reason for numerous spatial disorientation events. This subsection discusses the most common ambient visual illusions.

**Absence of Ambient Cues**

An example of an ambient visual illusion is an illusion due to the absent of ambient cues. The so-called "black-hole approach" is an illustration of a such an illusion. When approaching the runway at night, the pilot normally receives some ambient cues from the surrounding. One can think of lights from a city close by. The pilot is able to orient him-/herself using both the ambient and the focal visual system. However, when the runway is located in a relatively dark environment, without reference points, the pilot is not able to use the ambient visual system due to the absence of ambient cues. Only the focal visual system can now be used. Since it is not suitable for achieving spatial orientation, the pilot can misjudge the distance and altitude with respect to the runway [17].

**Visual Autokinesis**
Visual autokinesis is a spatial disorientation illusion that is caused by a minimal available amount of ambient visual cues. It is the event in which a small light or group of lights, as seen in the dark, can appear to move, when in fact they are actually stationary. The brighter and larger the light source, the less the effect of this illusion is. This SD-event is hard to avoid during night flight, and is one of the reasons why pilots should always monitor their instruments [17].

**Vection Illusions**
The visually induced percept of self-motion in an environment can be indicated as vection. Vection gives the pilot the sensation of linear or angular self-motion. One of the most relatable examples of vection happens while being inside a train. Imagine you are sitting in the train, which is waiting at the station in order to continue its journey. You look outside and see another train at the track next to yours. The moment that neighbouring train starts to move, you have the feeling that your train is riding, while in fact it is the other train. The sensation of self-motion is thus called vection. Relating this to aviation, vection is the reason why formation flying is extremely difficult. The other aircraft in the formation provide a “new” reference frame for the pilot, while the most important reference frame should remain the reference frame provided by the Earth. Due to this, the sensation of self-motion can arise and lead to dangerous situations in which, for example, unnoticeable stalls can occur [17].

**False Horizon and Surface Planes**
Due to, for example, a sloping cloud deck, the pilot receives the horizon incorrectly with the ambient visual system. False horizons and surface planes can thus cause visual illusions. False horizons can give a wrong sensation of attitude, while sloping surface planes mainly cause the wrong sense of altitude above the terrain. Especially at night, pilots are susceptible to misinterpretation of the horizontal. Furthermore, pilots flying at high-altitude can have trouble with maintaining the attitude of the aircraft, because the horizon is lower at high altitude compared to lower altitudes [17], [22]. Figure 3.1 shows an example of the false horizon illusion at night.

**Figure 3.1:** Ambient visual illusion: False horizon, happening at night. From *Pilot’s Handbook of Aeronautical Knowledge*, by Federal Aviation Administration, 2016 [22].

### 3.1.2. Focal Visual Illusions

Focal visual illusions can be due to the lack of focal visual cues, but also due to the perception of objects that do not match with the expectation. The most common focal visual illusions will be discussed in this subsection.

**Absent Focal Cues**
Situations in which focal visual orientation cues are absent, can cause spatial disorientation events. Examples are snow-covered or smooth-water approaches in aviation, in which no focal visual orientation cues are present [17].

**Size Constancy**
When performing tasks, humans often refer to past experiences in order to determine a strategy to execute that specific task. In the context of aviation, pilots are used to the runway size they land on or take off from the most. They (unconsciously) expect that every other runway they use is of the same size. Unfortunately, runway sizes differ around the world. When doing an approach at an airport with a runway of a different size than the pilot is most used to, the pilot can misjudge its altitude and distance to the runway. This is a focal visual illusion, which mostly occurs at night time, when visual ambient cues are already largely missing [17].

**Shape Constancy**
As described for the size constancy illusion, humans use their past experiences when performing tasks. Different shapes of objects can also lead to focal visual illusions and thus to spatial disorientation. Consider the example of a runway constructed on uneven terrain to understand how false shape constancy cues can create orientation illusions during flight. As pilots approach the runway for landing, they rely on linear perspective and foreshortening cues to determine the approach slope.

Foreshortening cues are visual cues that provide the brain with information about the depth and distance of objects that are oriented at an angle relative to the observer. Foreshortening occurs when an object appears shorter in length in its perpendicular dimension due to the angle at which it is viewed. This effect is caused by the way the human eye perceives objects in 3D-space and can be used to infer depth and distance. In the context of aviation, foreshortening cues can help pilots judge the slope of the runway during landing approaches.

If the runway is sloped upward by $1$, the foreshortening of the runway appears reduced to the pilot approaching on a $3$ slope. This reduction in foreshortening creates an illusion that the pilot is too high on approach. As a result, the pilot's natural response is to adjust their approach slope, seeking a shallower angle. However, this response can be dangerous. In contrast, when the runway is sloped downward, the pilot must fly a steeper approach slope than usual to perceive the accustomed runway shape [17], [22]. An example scenario of shape constancy due to an upsloping and down-sloping runway is provided by Figure 3.2.

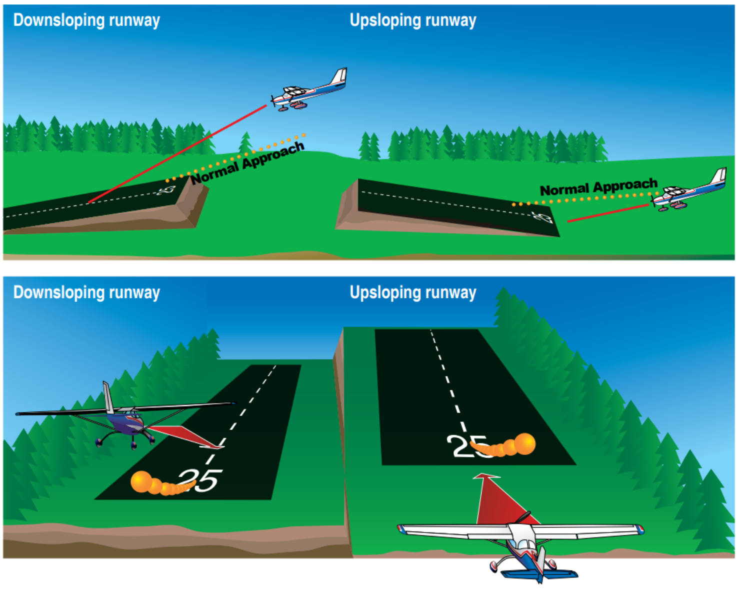


**Figure 3.2:** Focal visual illusion: Shape constancy. The yellow dotted line is the desired approach path, whereas the red line represents the approach due to disorientation. From *Pilot's Handbook of Aeronautical Knowledge*, by Federal Aviation Administration, 2016 [22].

**Aerial Perspective**
The environment can be interpreted wrongly by the pilot due to weather conditions, and day and night differences. Aerial perspective is the cause of this illusion. For example, in rainy or foggy weather, runway

lights are perceived as fainter than in clear weather conditions. This pilot could interpret this as the runway being further away than it in fact is [17].

## 3.2. Vestibular Illusions

As described in previous section, Section 3.1, spatial disorientation events can be of visual nature. Multiple SD-illusions exist which are of vestibular nature. Vestibular illusions can occur due to sub- or supra-perception threshold movements and accelerations of the aircraft. These illusions can be divided into two groups. One group is related to the working of the semicircular canals and the other to the otoliths. Furthermore, the phenomenon of the Giant Hand exist. There is still no single explanation for this illusion, so it will be discussed separately.

### 3.2.1. Illusions Related to the Semicircular Canals

This section describes the illusions which arise from the stimulation of the semicircular canals due to angular accelerations. These stimuli can be above or below the motion perception thresholds (Figure 2.4). Illusions discussed in this subsection are the somatogyral illusion, the Coriolis illusion and the oculogyral illusion. These three illusions have applications in different kinds of situations, of which some will be discussed in the upcoming subsections.

**Somatogyral Illusion**

This type of illusion occurs when the semicircular canals are unable to accurately detect sustained rotations at a constant angular velocity [17]. Once the angular movement is of a steady speed, it takes some time for the sensation of angular movement has died away. This depends on the axis of rotation, the nature of cues from other sensory receptors, the speed of the rotation and the level of habituation. The latter is the extent to which the pilot is familiar with the motion stimuli [15]. The sensation of angular acceleration can die out, due to the mechanism of sensing angular movement with the semicircular canals.

As already discussed in Section 2.3, the movement of the endolymph and thus the movement inside each semicircular canal is used to sense angular accelerations. However, a complication arises when inside an aircraft which is turning at a consistent rate for more than 20 seconds. In this type of prolonged turn, the fluid within the canal initially starts moving, but friction eventually causes it to match the rotation of the canal walls. As a result, the hairs inside the canal return to their upright position, incorrectly signaling to the brain that the turn has ceased, when it is actually ongoing. Subsequently, if you begin to roll out of the turn to return to level flight, the inertia of the fluid causes it to continue moving, and the hairs now bend in the opposite direction, falsely indicating to the brain that you are turning in the opposite direction, whereas you are actually decelerating from the original turn [17], [23], [24].

The somatogyral effect can also occur after a short roll maneuver in-flight. In a study by Ercoline et al. (2000), pilots were instructed to maintain a steady aircraft attitude following an automated coordinated roll while both the outside view and instruments were obscured. The results revealed that pilots showed a tendency to increase the aircraft's bank immediately after roll maneuvers, due to their misinterpretation of the roll deceleration. This phenomenon is referred to as the post-roll illusion [25], [26].

Other examples of the somatogyral illusion are the graveyard spin and the graveyard spiral. The graveyard spiral is the most common of the two. The graveyard spiral is associated with a return to level flight following an (un)intentional bank turn [15], [17]. This illusion can be illustrated with the following example. Imagine a pilot making a right turn. If the turn continues for a substantial amount of time, about 20 seconds, the sensation of turning will die out. As the pilot changes the aircraft's attitude to level flight, a sensation of turning to the left will be produced. If the pilot believes this illusion, he/she will correct for this turn by banking to the right, in order for him/her to fly with wings level. This action will result in re-entering the original turn to the right. While doing this, the aircraft continues to lose altitude, due to the turning movement. If the illusion is not recognized in time, these actions will lead to a spiral and finally to a ground collision. That is why this illusion is referred to as the "graveyard spiral" [23].

The graveyard spin is associated with the (un)intentionally entering of a spin. If a pilot enters a right spin, he/she will at first sense this movement of spinning. However, after some amount of time the sensation of spinning starts to die out, due to the constant spin rate. At that moment, if the pilot uses left rudder in order to compensate for the spin, he/she will experience a sensation of spinning to the left. In order to counteract this sensation, the pilot will use right rudder again, causing the aircraft to re-enter the original spin. The turn indicator will constantly provide the pilot with accurate information on the direction of the turn. However, this will give a conflict with the sensory information of the pilot. If the pilot chooses to trust his/her feeling and ignore the information provided by the instruments, the aircraft will continue spinning. If this happens at low altitude or this situation is not recognized at high enough altitudes, then there is little to no time to recover from this spin and the illusion will result into a ground collision. Hence the name "graveyard spin" [23], [17], [15].

The leans illusion is another example of a somatogyral illusion. The term "the leans" is being used for situations in which an instrument-rated pilot is flying in the clouds and experiences the feeling of flying one wing low, while the aircraft is actually flying level as indicated by the attitude indicator (AI). As a response to this sensation, the pilot leans towards the wrongly perceived vertical. Since the aircraft is flying straight in level, their is no additional force working on the aircraft, which affects the gravionertial force vector. The leans is thus a sensory conflict of rotations in roll, due to sub-threshold and supra-threshold roll movements (or a combination of both) [4].

The leans disappears almost immediately when the external view is clear. However, when perceiving the aircraft attitude by using the instruments, while still in a DVE, the leans will not disappear right away. Pilot training instructs pilots that they must trust their instruments at all time, so they will always remain aware of the orientation of the aircraft. The leans causes seldom any risk to flight safety. Though, the discrepancy between the pilot's sensed attitude and the attitude as indicated by the instruments, can be very distracting [4]. There are situations in which the leans are experienced even worse. This is when the circumstances are already very demanding, for example during air-to-air refuelling or formation flying when correct separation is extremely important [15].

**Coriolis Illusion**

The Coriolis illusion is due to an unusual stimulation of the semicircular canals, which can result in very unpleasant sensations. In aviation, the Coriolis illusion occurs when the aircraft is turning and the pilot or its passenger tilts his/her head up, down or sideways. A pilot might want to pitch up with his head to look at overhead instruments, or pitch down to look at the knee pad. Tilting sideways could be done to have over the shoulder visuals. By tilting the head, the pilot or passenger experiences the feeling of pitching, rolling and yawing at the same time. This causes the individual to become disoriented very easily and lose control of the aircraft, which is very dangerous and could lead to fatal casualties [23].

**Oculogyral Illusion**

In general, the oculogyral illusion describes the false sensation of motion of an object viewed by an individual, i.e. a pilot. It is due to inappropriate effect of the semicircular canals which affects visual perception. During the initial phase of rotation, such as a turn or a roll, the vestibulo-ocular reflex stabilizes the retinal image of a stationary visual scene, ensuring clear vision. However, these eye movements are unsuitable for perceiving objects within the aircraft, resulting in their apparent motion and displacement in the same direction and plane as the sensed rotation [15]. During a night flight or flight in degraded visual environment (i.e., fog), the oculogyral illusion generally confirms the somatogyral illusion. The somatogyral illusion causes the pilot to falsely perceive a turn in a certain direction. The oculogyral illusion causes the instrument panel to move in the same direction as the falsely perceived turned, which thus confirms the somatogyral illusion [17].

### 3.2.2. Illusions Related to the Otoliths

This section describes the spatial disorientation illusions related to the otoliths, which includes the somatogravic illusion, the G-Excess effect and the oculogravic illusion. As previously described, the otoliths contribute to the process of sensing linear accelerations. The upcoming descriptions of SD-illusions are thus related to the wrong sensation of linear acceleration.

**Somatogravic Illusion**

In normal circumstances, on the surface of the Earth, the otoliths sense the gravitoinertial force as the vertical. The acceleration due to gravity cannot be distinguished from other linear accelerations. However,

when the linear acceleration is of relatively short duration, humans are able to indicate this force as different compared to the gravity. The hair cells in the utricle experience a displacement towards the back due to the inertial forces caused by a forward linear acceleration. This displacement triggers a signal to the brain, conveying the sudden movement of the head and body in a forward direction [23]. The brain can utilize additional sensory information, such as visual cues and proprioception, to help distinguish between gravitational forces and other linear accelerations. By combining signals from the otoliths and the semicircular canals, the brain can distinguish between tilt and linear acceleration. When the head tilts, the otoliths sense the static head-tilt, which could also be interpreted by the brain as leftward linear acceleration. In addition to the signals from the otoliths, the brain receives signals from the semicircular canals reporting the transient head-rotation. In this way the brain knows the head is tilting [19].
When the acceleration sustained for a longer period of time, the vestibular system is unable to distinguish the linear acceleration from gravity. The result is that the two accelerations will be combined and the resulting acceleration will be the new vertical [15]. This will lead to a false sensation of body tilt, which is also referred to as somatogravic illusions [17].
"Somatogravic illusions" is actually an umbrella term for the group of illusions, which describes situations in which the sensed force vector differs in direction and/or magnitude from the gravity vector, resulting in a wrong perception of (aircraft) attitude. The somatogravic illusions are often paired with bad visual environments.

The inversion illusion is one of the illusions that belongs to the group of somatogravic illusions. In the inversion illusion, the resultant force vector is rotated such that it is pointing away from the Earth's surface, creating the illusion of being inverted [17]. This happens when a pilot levels the aircraft after a steep climb. The moment the pilot levels off, the aircraft's speed is relatively higher compared to the speed during ascent. This is a linear acceleration. The combined force vector of this acceleration and the gravioinertial force will then point away from this Earth. The pilot then has the sensation of being upside down. As a response, he/she will pitch down in order to lower the nose of the aircraft [23], [15].

Other somatogravic illusions are the head-up and head-down illusions. Both illusions can be explained by a sudden acceleration or deceleration during level flight. In the head-up illusion, the aircraft is flying level and suddenly experiences a linear, forward acceleration. The resultant vector, as found when combining the acceleration and gravity vectors, is then pointing diagonally backwards to the Earth. The pilot interprets this as the aircraft pitching up. In order to get the resultant vector back to the "normal" position, the pilot will pitch down. This can be seen in the second row of Figure 3.3 [15], [23]. An operational example of the head-up illusion is when an aircraft is taking off from an aircraft carrier at night. The aircraft is being catapulted from the deck. This linear acceleration makes the pilot think he is pitching up. To avoid the aircraft stalling, the pilot lowers the nose down. However, the sensation of pitching up was misleading and there is a possibility of crashing into the sea. During the night, there are no visual cues available, which makes the pilot more susceptible to this illusion. To avoid such situations to happen, measures where taken, which included the pilot to not touch the controls during the deck launch.

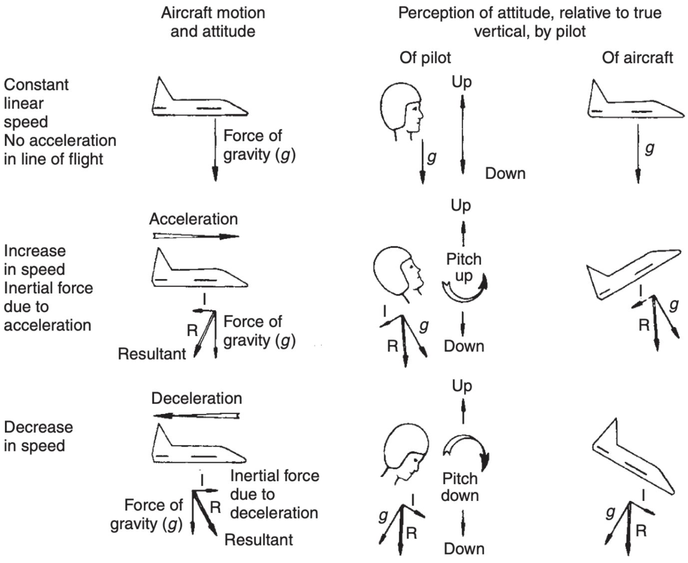


**Figure 3.3:** Schematic representation of the somatogravic illusions in flight leading to false perception of pitch attitude. From *Ernsting's Aviation Medicine* (4th ed., p.444), by D.J. Rainford and D.P. Gradwell, 2006, Hodder Arnold [15].

The head-down illusion is the opposite of the head-up illusion. This illusion happens when the aircraft is flying level and suddenly experiences a deceleration, which could be due to the lowering of the flaps or decreasing the engine power. The resultant force vector will now be pointing diagonally forwards to the Earth (third row in Figure 3.3). The pilots experiences this as the aircraft pitching down. To compensate for this, he/she will pitch up. If this happens during a low speed final approach, there is a possibility of the aircraft stalling [23], [15].

**The G-Excess Effect**

Movements of the head in pitch, roll or yaw during the exposure of G-forces could also lead to false sensations of aircraft attitude. This sensation was perceived in high-performance aircraft when pilots were flying a large-radius coordinated turn with a low rate of turn [27]. It is now suggested that a transient and atypical stimulation of the otoliths are the cause of this sensation. This, because the head movement of the pilot changes the orientation of the otoliths with respect to the combined force vector. It results in a false or exaggerated sensation of body tilt. This illusion is also referred to as the G-Excess effect. Some pilots even experience this as the sensation of tumbling forward in pitch when they move their head forward in pitch during a pull-up from a dive [15].

**Oculogravic Illusion**

The oculogravic illusion can be seen as the visual component of the somatogravic illusion. During an acceleration, the resultant force rotates backwards, causing a sensation of nose-up attitude of the aircraft (the somatogravic illusion). This can be accompanied by an apparent upward movement and displacement of objects in the visual field. It is thought that the displacement of the visual scene is primarily due to the integration in the brain of the retinal information with signals from the otoliths and other receptors stimulated by linear accelerations. The pilot can interpret the apparent movement and transient displacement of objects in the external and internal view as a change in attitude. This leads to disorientation [15].

The oculogravic illusion often occurs when external visual cues are not well defined. Helicopter pilots performing night landings at remote locations often encounter an oculogravic effect, where the illuminated T-shaped guide on the ground appears to move as the helicopter manoeuvres during the approach. This phenomenon occurs when there are no other visual cues nearby, causing the pilot to perceive the T as a mobile visual target within a stable gravitational environment, rather than the opposite [4].

### 3.2.3. The Giant Hand Phenomenon

The Giant Hand phenomenon is a spatial disorientation illusion that is not very well understood. Though, many pilots can confirm its existence. In the Giant Hand phenomenon, the pilot is suffering from the effects of SD by falsely experiencing that the aircraft is not responding properly to control inputs. For example, when the pilot suddenly becomes aware of the aircraft being in a roll (SD), he or she tries to correct for it and tries to get the aircraft back to level flight. However, the pilot experiences that the control inputs are not responding and the aircraft is not being put in a wings level attitude. It is as if there is a giant hand pushing down one of the wings. The Giant Hand phenomenon can be indicated as SD Type-II, since the pilot is aware of the SD, is not able to control the feeling, but is not fully incapacitated. Some studies suggest that this phenomenon is due to a reflex which is in response to the physiological and psychological conditions which have an effect on the pilot before and during the incident. Others state that this phenomenon is caused by a conflict between conscious and subconscious control of the aircraft [28].

According to Malcolm and Money (1972), analysed events of the Giant Hand phenomenon have four preconditions in common. First, a few minutes before disorientation takes place, the pilot is in a state of anxiety or mental arousal. Second, one or both hands are used to control the aircraft. The moment before the SD-event takes place, the pilot is distracted from the control task and maintaining the attitude of the aircraft. In the last precondition the resultant gravity experienced has been shifted forward (as during deceleration), or the pilot experienced a sensation of being tilted forward, similar to what occurs during diving or certain types of head movements that cause cross-coupling [29].

## 3.3. Factors Contributing to SD (”Risk Factors”)

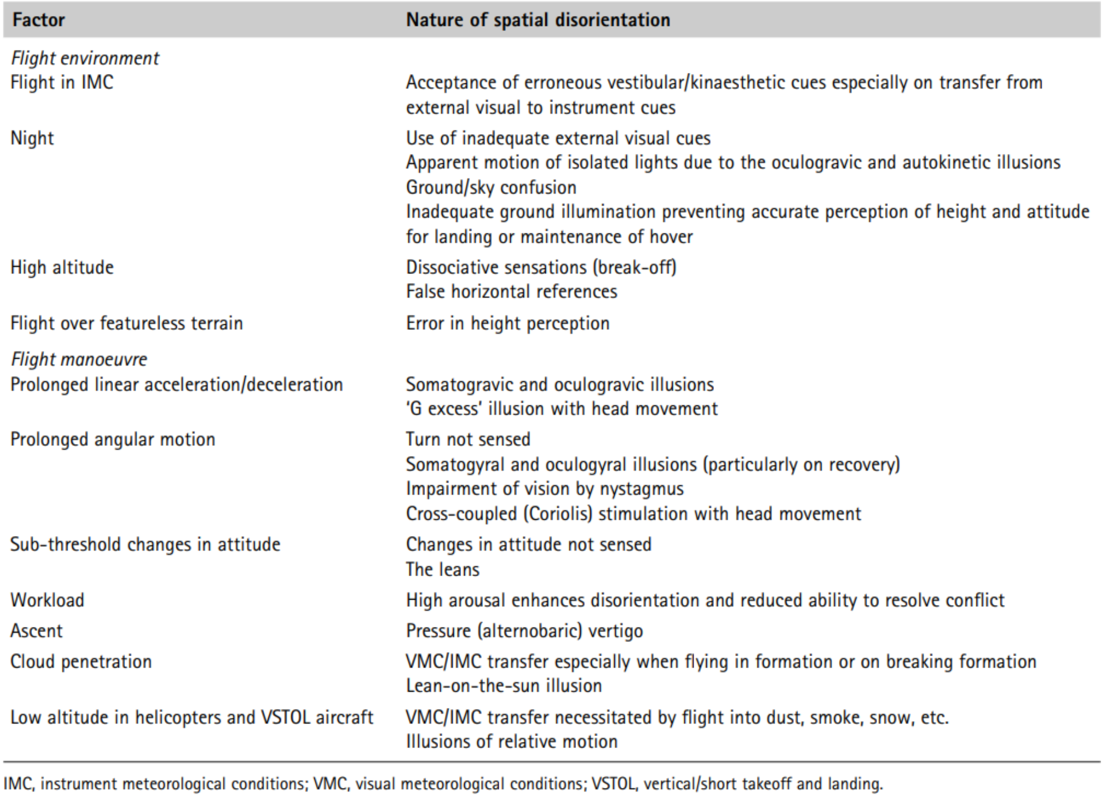
There are multiple factors that contribute to the increase in susceptibility of a pilot to spatial disorientation. One group of factors is related to the environment in which the pilot is controlling its aircraft. Certain environmental factors increase the chance of spatial disorientation to occur. Night flying is one of them. As described previously, during the night, a large amount of ambient visual orientation cues are absent. This makes it more likely to become spatially disoriented by night, than by day. Other Degraded Visual Environments (DVEs) are fog and blizzards, so Instrument Meteorological Conditions (IMC). The switching between VMC (Visual Meteorological Conditions) and IMC is a critical moment too, in which the pilot can get disoriented more easily. Formation flying is also a high risk environment, as discussed in Section 3.1. Formation flying in adverse weather conditions is indicated as the situation in which SD is most likely to occur [17]. DVEs are most frequently mentioned as the main factor that caused or contributed to the occurrence of spatial disorientation [30].

Besides environmental factors, psychological and physiological factors can be related to the susceptibility to spatial disorientation. These include conditions that affect the physical or mental health of the pilot, overconfidence and fatigue. Drugs and alcohol, for example, cause the pilot to become more easily disoriented [30].

Furthermore, cognitive factors contribute to the rate of susceptibility to spatial disorientation. These are for example spatial ability and workload. Also task saturation could cause the pilot to become more easily disoriented. Acute or chronic stress decreases the ability of pilots to concentrate on the instrument crosscheck Little instrument flying skills could also increase the susceptibility to SD [30]. With a lot of instrument flying experience, the task of flying in IMC is achieved without undue obtrusion in consciousness. However, when necessary, it does involve the focal visual system, since one needs to read and interpret the instruments in the cockpit. Since this is not part of the “natural” orientation mechanism, this is more susceptible to impairment. Thus, SD is more likely to occur in IMC than when in good VMC, since ambient cues are then well processed by the ambient visual system. So a pilot with little instrument flying experience becomes more easily disoriented, because the task of instrument flying involves the consciousness [15].

Other external factors can cause the susceptibility to SD to increase. An example is the usage of night vision goggles (NVGs). NVGs offer a significant advantage to enhance the operational effectiveness of flying by enabling nighttime operations. Nonetheless, when compared to daytime flight, the availability of various depth perception and orientation cues is significantly reduced. This diminished availability of cues increases the likelihood of SD for pilots [31]. Benson and Stott (2006) described in their chapter *Spatial*

*Disorientation in Flight* for *Aviation Medicine* the principal environmental factors and flight manoeuvres that are likely to produce disorientation. These can be found in Figure 3.4.



| Factor | Nature of spatial disorientation |
|---|---|
| *Flight environment* | |
| Flight in IMC | Acceptance of erroneous vestibular/kinaesthetic cues especially on transfer from external visual to instrument cues |
| Night | Use of inadequate external visual cues<br>Apparent motion of isolated lights due to the oculogravic and autokinetic illusions<br>Ground/sky confusion<br>Inadequate ground illumination preventing accurate perception of height and attitude for landing or maintenance of hover |
| High altitude | Dissociative sensations (break-off)<br>False horizontal references |
| Flight over featureless terrain | Error in height perception |
| *Flight manoeuvre* | |
| Prolonged linear acceleration/deceleration | Somatogravic and oculogravic illusions<br>'G excess' illusion with head movement |
| Prolonged angular motion | Turn not sensed<br>Somatogyral and oculogyral illusions (particularly on recovery)<br>Impairment of vision by nystagmus<br>Cross-coupled (Coriolis) stimulation with head movement |
| Sub-threshold changes in attitude | Changes in attitude not sensed<br>The leans |
| Workload | High arousal enhances disorientation and reduced ability to resolve conflict |
| Ascent | Pressure (alternobaric) vertigo |
| Cloud penetration | VMC/IMC transfer especially when flying in formation or on breaking formation<br>Lean-on-the-sun illusion |
| Low altitude in helicopters and VSTOL aircraft | VMC/IMC transfer necessitated by flight into dust, smoke, snow, etc.<br>Illusions of relative motion |

IMC, instrument meteorological conditions; VMC, visual meteorological conditions; VSTOL, vertical/short takeoff and landing.

**Figure 3.4:** Factors and situations in which SD is likely to occur as described by Benson and Stott (2006). From *Ernsting's Aviation Medicine* (4th ed., p.455), by D.J. Rainford and D.P. Gradwell, 2006, Hodder Arnold [15].

## 3.4. Helicopter Specific SD-events

The subject of this literature study is the effect of spatial disorientation on the cognitive performance of helicopter pilots. Past sections discussed spatial disorientation illusions and factors that increase pilot's susceptibility to spatial disorientation for all aircraft in general, so for both fixed and rotary wing aircraft. Since this study is related to rotary wing aircraft, this section will be dedicated to SD-events that are most common or even unique for helicopters.

Spatial disorientation is a serious concern in helicopter operations, with a higher incident rate per flying hour for rotary wing aircraft than for other aircraft types, according to a recent survey in the UK military [32]. The dynamical principle of helicopters differs from that of fixed wing aircraft. In the longitudinal axis of the fuselage, a helicopter does not have motor power, unlike fixed wing aircraft. When transitioning from hover to forward flight, the helicopter's nose is pitched down to allow a component of the lift provided by the main rotor to accelerate the aircraft forward. However, the forward acceleration of a helicopter creates a sensation of being pitched up, despite its actual attitude being different. During the initial stages of forward flight, before significant aerodynamic drag is created, the sensation of being pitched up precisely balances the actual pitch-down of the aircraft, creating the impression that the helicopter is level, just as it was during the hover. This is similar for the transition from forward flight into hover.
As a result, a helicopter will give the impression of being level regardless of its actual attitude, which contributes to the occurrence of SD during helicopter operations [15].

Though, it is mainly the type of operations helicopters fly that they have to deal with spatial disorientation

more frequent than other aircraft types. Helicopters have become very complex platforms over the years. As they are required to fly within challenging environments, such as low-level terrain, degraded visual environments, complex mission sets, and non-permissive tactical airspace, SD remains one of the most significant physiological threats to rotary wing crew [32].
Due to its operations, certain SD-events are almost unique for helicopters. One can, for example, think of the brownout and whiteout (Figure 3.5a). A brownout is the in-flight visibility reduction due to sand or dust in the air. In helicopter operations, brownouts occur mostly during take-off or landing, when the rotor downwash causes dust clouds to be stirred up. This causes an extreme reduced visibility environment, in which the pilot is not able to see the nearby objects which provide the outside visual references to control the aircraft near the ground. There could also be a loss of horizon. During the critical moments in flight, i.e. take-off and landing operations, brownouts cause flight safety risks. These can be collision with ground obstacles or other aircraft, and rollover of the helicopter due to an uneven and sloped terrain. The stirred up dust clouds can give the pilot a sensation of self-motion, i.e. the vection illusion. The sand and dust is moving around the cockpit, which can make the pilot think that the helicopter is turning, while it is actually in a level hover. The stirred up dust clouds could also give the feeling of descending, while being in a hover or on the ground. Furthermore, the brownout could cause a sensation of false horizon. During night operations, the brownout can be experienced even more intense when visual illusions are enhanced due to the aircraft light illuminating the dust/sand cloud. Whiteouts are similar to brownouts, however during a whiteout snow clouds are stirred up instead of sand and dust.

Helicopters perform a lot of search and rescue (SAR) missions. Naval helicopters execute these missions mostly at sea. The vection illusion can be a problem here too. When hovering above the water in order to pick someone up from the water, the rotor downwash causes waves to appear. These waves can give the pilot the sensation of self-motion due to vection. The waves are moving away from the helicopter, so the pilot has the feeling of moving backwards, while in fact the helicopter is hovering in level. Figure 3.5b illustrates the conditions for this vection illusion for a maritime operation.

**(a)** A CH-47 “Chinook” of the RNLAF performing a brownout landing. From *Militaire helikopters trainen zandlandingen*, Ministerie van Defensie, 2020 (`https://www.defensie.nl/actueel/nieuws/2020/08/17/militaire-helikopters-trainen-zandlandingen`) [33].

**(b)** Conditions for the vection illusion during a sonar operation of the NH90 of the Royal Netherlands Navy. From *NH90, beschermer van de vloot*, by RITM B. Brasser, 2017 (`https://magazines.defensie.nl/allehens/2017/12/02_fost`) [34].

**Figure 3.5:** Two of the most common spatial disorientation illusions for rotary wing aircraft.

A unique spatial disorientation illusion for rotary wing aircraft is the so-called undetected drift. During this illusion, the pilot is not aware of the helicopter drifting since the movements are below the perception threshold. A helicopter can have the tendency to move laterally in the direction of the tail rotor thrust. This translating tendency is also referred to as translating drift. When undetected, this is called undetected drift. The undetected drift is one of the most common spatial disorientation illusions among military rotary wing aviators [15]. Several surveys were held among military pilots of multiple air forces from around the world. Tables 3.1, 3.2 and 3.3 show the five most reported SD-events for the Dutch, United States, Polish and Taiwanese Air Forces.

**Table 3.1:** Most reported spatial disorientation events for rotary wing aviators of the RNLAF [8].

| | **Transport** | **Attack** |
|---|---|---|
| **1** | Sloping horizon (91.3%) | Loss of horizon due to sand/snow (92.6%) |
| **2** | Undetected drift (90.2%) | Sloping horizon (88.9%) |
| **3** | Lack of altitude due to featureless terrain (90.2%) | Lack of altitude cues due to featureless terrain (88.9%) |
| **4** | Loss of horizon due to sand/snow (87.0%) | Undetected drift (85.2%) |
| **5** | Misleading altitude cues (85.9%) | Loss of horizon due to atmospheric conditions (83.3%) |

**Table 3.2:** Most reported SD-events for rotary wing pilots in the US Air Force (USAF) [35] and the Polish Air Force (PAF) [7]. *If one does not account SD due to NVGs, then the fifth most reported event is "Loss of horizon due to atmospheric conditions".

| | **PAF** | **USAF** |
|---|---|---|
| **1** | Loss of horizon due to atmospheric conditions (77%) | Undetected drift (90.2%) |
| **2** | Loss of horizon due to sand/snow (65%) | Misleading altitude cues (80.2%) |
| **3** | Poor crew coordination (65%) | Loss of horizon due to sand/snow (76.2%) |
| **4** | Misleading altitude cues (55%) | The leans (75.2%) |
| **5** | Giant hand (45%) | SD while using NVGs (72.3%)* |

**Table 3.3:** Most reported SD-events for rotary wing pilots in the Taiwanese Air Force [36].

| | **Taiwanese Air Force** |
|---|---|
| **1** | The leans (37.7%) |
| **2** | False sense in clouds (34.0%) |
| **3** | Loss of horizon in bad weather (31.5%) |
| **4** | Undetected drift (26.5%) |
| **5** | False horizon (25.3%) |

Table 3.1 is based on the survey as done at the Royal Netherlands Air Force. The survey was given to 368 pilots, flying different types of aircraft. The indicated table (Table 3.1) shows the top five most reported SD-events, for transport helicopters (e.g., CH-47 "Chinook") and for attack helicopters (e.g., AH-64 "Apache"). $91.3$% of the transport helicopter pilots reported that they had experience with the sloping horizon illusion, whereas this was only $88.9$% for the attack helicopter pilots. The most mentioned SD-event among attack helicopter pilots was "Loss of horizon due to sand/snow" with $92.6$%.
This survey not only looked at frequency of reported SD-events, but also at the impact of these events. Pilots could indicate if the SD-incident they experienced was either "of minor risk to flight safety" or "the safety risk was significant or severe". From this followed that the"Loss of horizon (brownout/whiteout/spray out)" was reported most as incident causing the highest safety risk. Other SD-events reported with a high impact (high safety risk) were "False horizon (sloping clouds or terrain)", "Loss of horizon (atmospheric conditions)" and "Undetected drift or descent in hover (rotary wing only)", "Black hole approach" and "Misleading altitude cues" [8].

The surveys among Polish, American and Taiwanese military pilots did not distinguish transport and attack helicopter pilots. For the Polish Air Force (PAF), "Loss of horizon due to atmospheric conditions" was most mentioned by its aviators ($77$%) [7]. For the United States Air Force (USAF), the most reported illusion was undetected drift ($90.2$%) [35]. This can be seen in Table 3.2. When comparing the three surveys (RNLAF, PAF and USAF), it can be said that "Loss of horizon due to sand/snow", "Undetected drift" and "Loss of horizon due to atmospheric conditions" are of frequent occurrence among these air forces. It can be seen that most illusions are of visual nature and not vestibular.

Table 3.3 shows the results of a similar survey but then among Taiwanese military pilots. However, the illusions indicated on the survey were different when comparing to the other three surveys. The most reported SD-event among rotary wing pilots was the leans ($37.7$%). It is remarkable that the percentages of the top five illusions are relatively low. It could be the case that the Taiwanese aviators have less experience with spatial disorientation and thus are not as capable to recognize SD-events as USAF, PAF and RNLAF pilots. Just as the other three surveys, the illusions in which the horizon is lost or there is a false horizon, are in the top five. Besides, undetected drift is a common illusion [36]. According to Benson and Stott (2006), vection illusions are mostly experienced by helicopter pilots trying to maintain an accurate hover at low altitude[15]. As previously described, brownouts, whiteouts and hovering above water can also cause the vection illusion.

So to conclude, SD is a problem for rotary wing pilots, due to the complex platforms they fly in challenging environments. Most common reported SD-events are due to visual illusions.

# 4

# Cognition and Relevant Cognitive, Pilot Tasks

The realm of the aviation industry encompasses not only the design and construction of aircraft, but also the critical examination of human factors that influence their operation. As technology has advanced, the focus on the cognitive aspects of pilot performance has gained prominence.
This chapter aims to delve into the field of cognition in general and cognition in the cockpit, with a particular emphasis on understanding the relevant cognitive tasks faced by pilots during flight operations, since that contributes primarily to the process of answering the main research question of this literature study. In the first section, Section 4.1, a description of the basic principles of cognition will be given, including the Multiple Resources Theory. Section 4.2 focuses on the relevant cognitive task a pilot has to execute in flight. This will be discussed in order to, in Chapter 6, come to a well designed experiment.

## 4.1. Multiple Resources Theory and Mental Workload

Cognition encompasses a wide range of processes within the brain, involving information handling and manipulation of mental representations, aiming to generate appropriate responses. These processes include attention, memory, language and executive function [37]. Cognitive tasks are related to these processes or functions and can be described as follows:

1. Sustained attention: These tasks require focusing on a particular stimulus while ignoring distractions.
2. Divided attention: Tasks involve double tasking.
3. (Working) Memory: These tasks involve encoding, storing, and retrieving information.
4. Executive function: Higher-order cognitive processes such as planning, decision-making, and problem solving are involved in these tasks.
5. Psychomotor abilities: Tasks involve coordinating movement and controlling motor responses.
6. Spatial orientation or visuospatial ability: Orientation is involved in these tasks [38].

Most cognitive tasks are a combination of multiple cognitive functions. For example, remembering the location of a square in a grid involves both working memory and visuospatial ability. Another example would be related to the control task of pilots in an aircraft or helicopter. The control task can be seen as a cognitive task which uses, among others, psycho-motor abilities, spatial orientation and executive functions. The aforementioned grouping of cognitive functions is one method of doing this. Another way of dividing cognitive tasks would be to assign them to being a verbal process or a spatial process. The theory of Wickens (1980) focuses more on this grouping.

Wickens (1980) described a theory regarding the aforementioned mental processes, the Multiple Resources Theory (MRT). This theory states that an individual has a limited set of resources available for mental processes. Mental resources or capacities refer to the complex system of information processing within the human mind. When stimuli reach the sensory receptors, they undergo the process of perception and translation, ultimately leading to a response [39]. MRT proposes that several different cognitive resources can be used simultaneously. So, when different tasks require different resources, for example tactile and vestibular perception, these tasks can be processed simultaneously. If different tasks require the same cognitive resources, these tasks must be processed sequential [40].

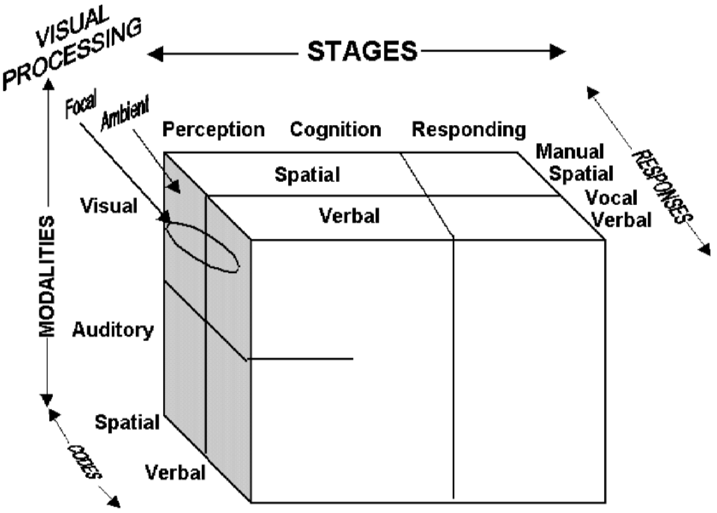


**Figure 4.1:** A schematic display of the Multiple Resources Theory as described by Wickens (2002). From "Multiple resources and performance prediction", by C.D. Wickens, 2002, *Theoretical Issues in Ergonomic Science*, 3, p. 159-177 [41].

The Multiple Resources Theory consists of a four dimensional model (Figure 4.1). This original model could be seen as a three dimensional model with a "Stages of Processing" dimension, "Codes of Processing" dimension and a "Modalities" dimension. The Stages of Processing consist of three stages: perception, cognition and responding. The perception stage is the stage in which the input is being perceived. Cognition is the stage which describes the process in which a response to the input is being selected. Unsurprisingly, this stage is sometimes also referred to as "response selection". The last stage is response, in which an action as a response on the input signals is executed.

The "Codes of Processing" dimension refers to the theory that spatial and verbal processes use different resources. These resources are separate across the three perception stages. It explains why programming the GPS, while flying an aircraft manually is very hard. Both process demand on spatial working memory. Both tasks disrupt each other.

The "Modalities" dimension refers to the different ways an individual perceives input signals. This dimension consists of visual, auditory, vestibular and tactile perception [21]. Figure 4.1 shows only two modalities, the auditory and visual perception. For the sake of completeness, tactile and vestibular perception should be added to this figure. This, because these two modalities contribute to the process of orientation and above all, play an important role in cognition. Two new rows should be added to Figure 4.1. Later, a fourth dimension was added to the MRT-model, which distinguishes the different visual processing systems, the focal and the ambient visual processing system. It is suggested that both processing systems are located in different parts of the brain and that their way of processing differs. Dual tasks involving focal and ambient processing will have little interference. An example is reading text messages on a phone (focal vision), while walking down the street (ambient vision). However, dual-task involving only ambient or focal processing have to deal with great interference. In this model, the response can be divided into manual, spatial, vocal and verbal responses.

Some studies have raised concerns regarding the third dimension of the MRT, "Modalities" dimension. In a study conducted by Wickens and Liu (1988), it was observed that the performance on a continuous visual task was significantly impaired when combined with a discrete auditory task, in comparison to when the concurrent task was presented visually [42]. In a simulated flight deck, Latorella (1999) demonstrated that auditory interruptions had a greater disruptive effect than visual interruptions when pilots were engaged in visual tasks [43]. Additionally, in the study by Morris and Leung (2006), it has been observed that pilots frequently interrupt their actions to respond to air traffic controllers [44]. Gladstones et al. (1989) identified another issue pertaining to the modality dimension. One of their findings was that when individuals were simultaneously engaged in two discrete tasks at their maximum speed, the capacity to process information remained unchanged regardless of whether the perceptual modality used for the tasks was the same or different [45].

Despite the criticism, the Multiple Resources Theory has received support in the domain of dual-task and mental workload. Wickens' model can be relevant to the concept of mental workload. The notion of workload encompasses the extent to which tasks consume the limited resources of individuals, whether they are considered individually or collectively. This consumption can be classified into two distinct zones of task demand. In the first zone, the demand falls below the available resource capacity, resulting in unused performance potential. This represents an optimal state as it ensures that the worker retains some resources to handle unforeseen circumstances. However when this task is executed for a prolonged time, it can lead to underload situations, due to the lack of stimulation to maintain alertness. This is an explanation to why it is very hard for a person to watch radar displays for hours. In such a situation, there is a lack of (new) stimuli to maintain alert [46].

The second zone involves demands that exceed the capacity. The Multiple Resources Theory model is especially applicable to situations in the second zone. In these situations, the MRT-model contributes to the prediction of how much performance will have failed once overload has been reached. The model can then provide guidance in how to redesign tasks such that the performance level can be restored [47].

The Cognitive Task Load (CTL) can be analysed with a three dimensional model, according to Neerincx (2003). Three load factors form the cognitive load space. These three factors are related to the level of information processing, the time occupied and the amount of task set switches. The factor of information processing consists of the three levels of the Skill-Rule-Knowledge framework of Rasmussen (1986). At skill-based level, information processing occurs effortlessly, leading to actions that are not highly cognitively demanding. At the rule-based level, input information prompts automated solutions, enabling efficient problem-solving with minimal cognitive effort. At the knowledge-based level, the problem is analysed and solution(s) are planned based on the provided information, particularly when encountering unfamiliar situations. This type of information processing can place a substantial burden on the limited capacity of for example the working memory [39], [48], [49].

The second load factor, the time occupied dimension, has been used to assess workload for time-line assessments. Complex task situations consist of several different tasks, which is why the CTL-model distinguishes the task set switches as a third cognitive load factor. Multiple task performance can be analysed in a framework consisting of three levels of abstraction, “Activity”, “Task”, “Action”. “Activity” is the overall activity the operator is doing, e.g. managing emergencies. This activity can be split up in different tasks, e.g. restore propulsion engine and fire fighting. Each of these tasks requires its own actions, which is the third level of abstraction. In the case of managing emergencies with tasks “restore propulsion engine” and “fire fighting”, actions could be determining the cause and announce the fire alarm [48]. The more an individual needs to switch between tasks, the higher the cognitive task load.

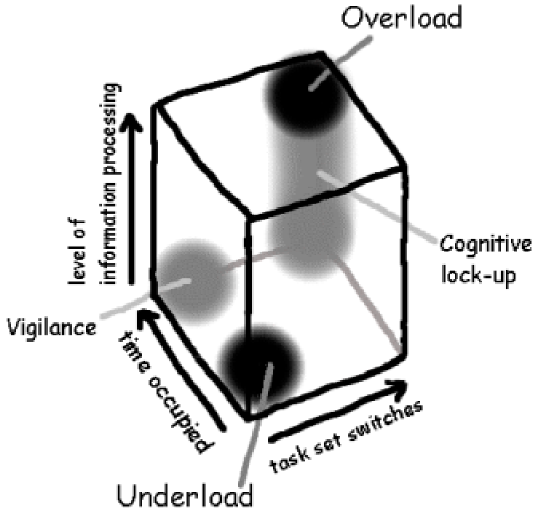


**Figure 4.2:** Cognitive Task Load model with four interesting regions as described by Neerincx (2003). From "Cognitive task load analysis: allocating tasks and designing support", by M. Neerincx, 2003, *Handbook of Cognitive Task Design*, p.283 [48].

Figure 4.2 shows the CTL-model with three "problem" regions as described by Neerincx. These regions are overload, under-load and cognitive lock-up and are due to a imbalance of the three load factors. Cognitive lock-up is the phenomenon in which the operator is not able to switch to another task, even if the other task has a higher priority. Under-load can only appear after a certain work period. Overload on the other hand can occur any moment.
Another region can be seen in this figure and is referred to as "vigilance". Vigilance, also known as sustained attention, is the capability of observers to consistently maintain their focus and stay alert to stimuli for prolonged periods. This can be seen as a desired mental state [46]. In practice, the operational tasks performed by operators do not encompass all conceivable regions within the cube, depicted in Figure 4.2. An increased level of information processing can lead to an increased load in the time required for task completion. Furthermore, a larger amount of task-set switches can also result in increased time consumption due to the significant costs associated with these transitions, thereby necessitating additional execution time for the operator [48]. When applying a spatial disorientation event to the CTL-model, it can be said that an individual does not automatically increases the amount of tasks switches. However, the level of information processing increases, since the SD-event could be an unfamiliar situation. So the task of, for example, orienting oneself could become rule-based instead of skill-based, making it more effortful. The time occupied with obtaining self-orientation and confirming it, may also increase. This model thus suggests that spatial disorientation could lead to a higher cognitive task load.

## 4.2. Pilot Related Cognitive Tasks

Cognitive tasks in the cockpit are generally the same for all aircraft types. The pilot needs to be able to orient him-/herself in space, communicate with air traffic control (ATC), navigate through the air, etc. The priority of cognitive tasks can be summarized as following: *"Aviate, Navigate, Communicate"* [50]. Keeping the aircraft in the air, thus the control task, has the highest priority. After that comes navigation. Finding out where one is and where to go to. The lowest priority of the basic cognitive tasks has the communication task. When a pilot is in the overload state, the first thing he or she will do, is stop communicating. After that, navigation will be thrown overboard [50]. However, most of the times, the pilot is not in an overload state, and he/she performs dual-tasks consisting of the control task and another cognitive task such as communicating with the other pilot about the route.

Military aviation differs from civil aviation due to its overall purpose. Civil aircraft are used to transport its passengers and/or cargo. Military aircraft, on the other hand, are operated in the name of safety, security and peace. They can be seen as very complex platforms operating in highly challenging environments. Military pilots have to perform in high workload and stressful situations. In addition, they have to execute cognitive tasks related to tactical coordination and weapon systems. This literature study focuses on military helicopter pilots. Military helicopter pilots operate more frequently in highly challenging environments, compared to civil helicopter pilots. This is one of the reason why can it be said that military helicopter pilots are more susceptible to spatial disorientation. That is why the focus will be on military pilots specifically.

The division of cognitive tasks in the cockpit can differ when comparing different kind of military helicopters. This is mainly due to the purpose of their missions. To illustrate this, the helicopter types of the Royal Netherlands Air Force will be shortly discussed. In the “Defensie Helikopter Commando” (DHC) or the defense helicopter command operate the CH-47 “Chinook”, the AH-64 “Apache”, the AS532 “Cougar” and the NH90, see Figure 4.3 [51]. The Cougar and Chinook are both transport helicopters and are operated with two pilots, a captain and a copilot. From a personal interview with an instructor pilot of the Cougar, the Chinook and the Cougar operate very much alike. In the cockpit, the several tasks are divided between the two pilots. The captain starts as pilot monitoring (PM) and is responsible at all times. He/she executes all cognitive tasks, such as communication with ATC and navigation. The copilot starts as the pilot flying (PF) and has no active, cognitive tasks, besides the control task. Though, he/she still has to understand the instructions and commands the captain gives and he/she needs to execute a flight plan. Besides, as PF he/she needs to be constantly aware of the external situation. If for example another aircraft is visible, the PF will check the observation with the PM. The captain and copilot can switches roles of PF/PM in flight.

**(a)** The Chinook, Cougar and Apache of the RNLAF during an international training in the United Kingdom.

**(b)** The NH90 of the RNLAF during an international maritime training in France.

**Figure 4.3:** The different helicopter types of the Royal Netherlands Air Force. From *LinkedIn post*, by A. Steur, 2023, (`https://www.linkedin.com/feed/update/urn:li:activity:7064938820063879168/`) [52].

The AH-64 “Apache” is an attack helicopter, for which the aircrew consists of a pilot and a copilot/gunner (CPG). The pilots are in a tandem seat, meaning they are positioned behind each other. The front seat is used by the CPG and the backseat by the pilot. The division of tasks is for this helicopter very different compared to the Chinook and Cougar. The CPG mostly operates the weapon systems, and performs tactical-related tasks, whereas the pilot does all the flying and flying-related cognitive tasks (e.g., communications with ATC, navigation). Though, the CPG is also capable to fly the helicopter.

The NH90 is an attack helicopter mainly used for maritime operations. It supports among others the fleet by tracking down submarines with sonar, performing search and rescue operations, and being the eyes of the ship at very large distances. This helicopter can be flown by two pilots, in which there is one pilot flying and one pilot monitoring, just as for the Cougar and Chinook. However, it is very common that the copilot is replaced by a tactical coordinator, a tacco. As the name suggests, a tacco has the function of performing all tactical tasks. Besides, he/she is able to do all non-flying tasks, such as communications with ATC. When in not highly complex, tactical situations, the tacco will do these tasks. The moment the situation requires high tactical input, the tasks of communication with ATC, navigation, etc. will be given back to the pilot.

Pilots are constantly multitasking. Situations in which a pilot has to talk while also steering and monitoring the instruments occur frequently. According to Martins (2016) unexpected events that require two or more tasks that need to be executed simultaneously might result in high workload levels and a loss of situational awareness [39]. In these situations, as previously indicated, pilots use the following order: *Aviate, Navigate, Communicate*. Keeping the aircraft in the air has the highest priority, and communicating to for example ATC or ACC (Air Combat Command) the lowest. In high workload situations, the first task a pilot will stop doing, is communicating. This is an indication of a pilot getting into the state of overload. People will become less communicative. In order to prevent these situations, cockpit crew are constantly managing their workload levels. The Multiple Resources Theory is highly applicable to cockpit processes, since pilots perform lots of (cognitive) tasks sequentially and simultaneously. It helps to understand how the limited resources of pilots are divided over the different tasks and what happens in times of high workload levels.

# 5

# Spatial Disorientation and Cognition

Multiple studies have put their focus on the occurrence of spatial disorientation in flight. How does it occur? What types of spatial disorientation illusions are there? How often does aircrew cope with these illusions and which illusions appear most frequent? Though, there has been little research into the effect of spatial disorientation on cognitive performance. This chapter addresses the state-of-the-art concerning the relation between spatial disorientation and cognition. Section 5.1 is devoted to the currently existing theories which are applicable to the relation between SD and cognition. Section 5.2, focuses on the studies that have been done on the effect of spatial disorientation on the cognitive performance of pilots. These studies were aviation related and the pilots had to perform a flying task. Finally, Section 5.3 indicates the gaps in the literature with respect to the relation between SD and cognition.

## 5.1. State-of-the-art

From the Multiple Resources Theory, as described in Section 4.1, different principles can be derived, amongst others the “posture first” and “orientation first” principles. Spatial orientation is important in our everyday life. Figure 5.1 shows the closed-loop of aircraft spatial orientation. The four dimensions of the Multiple Resources Theory can be recognized in the figure. When orientation and balance are endangered, there is an inherent instinct to reallocate resources from other tasks to regain stability and orientation. As a result, secondary tasks may be halted or experience a decline in performance [53], due to the limited resources one has, as described in the Multiple Resources theory [41]. When referring to balance while walking or standing, this principle is being called the “posture first” principle. When extended to self-orientation in general, for instance when operating in vehicles in the sky, this principle is then being called the “orientation first” principle [1], [54]. The “orientation first” principle thus suggests that when a pilot experiences spatial disorientation, he/she allocates resources to the control task in order to orient him-/herself leaving little resources for other cognitive tasks. In other words, the “orientation first” principle supports the hypothesis that spatial disorientation impairs the cognitive performance of (helicopter) pilots. Attentional control theories (Kahneman, 1973 and Lavie, 2005) also support this relation. These theories state that the human attentional system has a limited capacity, and as the primary task becomes more demanding, there are fewer resources available to carry out a secondary task [55], [56].

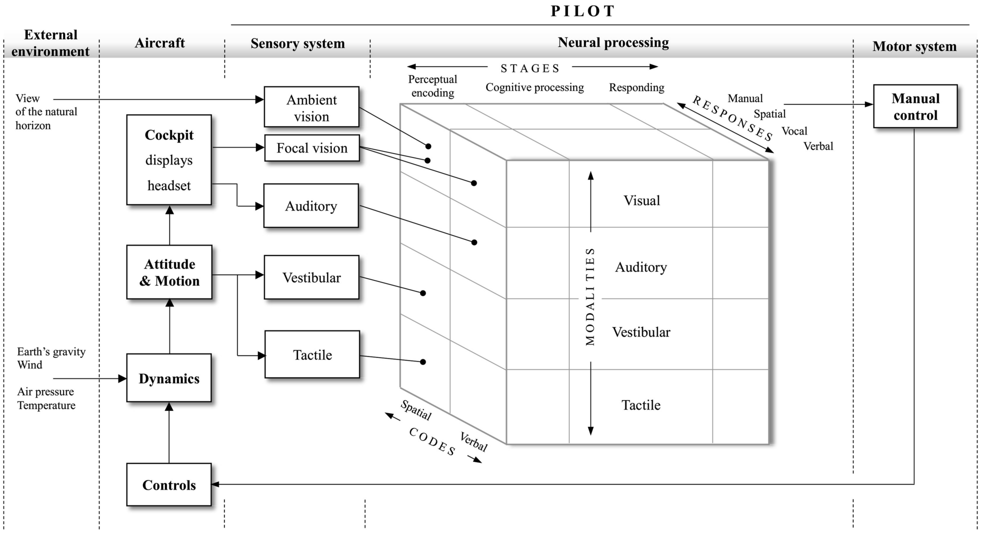


**Figure 5.1:** An overview of the closed-loop control of aircraft spatial orientation. From "An Attentive Blank Stare Under Simulator-induced Spatial Disorientation Events", by Fudali-Czyz et al., 2022, *Human Factors*, p. 2 [21].

According to Benson and Stott (2006), during SD Type-II, perceptual conflict of orientation arises, potentially impairing the pilot's perceptual and motor abilities to a degrees that jeopardizes control. They refer to this phenomenon as "disorientation stress". This could not only result in control errors, but also in errors related to, for example, navigation, communication and tactics. Disorientation stress can result in general in three things. First, the incorporation of misleading cues into aircraft control. Second, the disruption of motor function leading to insufficient or inappropriate control responses. Third, a decline in higher mental functions, leading to errors in judgement. In contrast, in SD Type-I, control errors stem from misinformation, referred to "orientation error" by Benson and Stott. These errors arise from an incorrect perception of orientation, leading to control mishaps [15].

Figure 2.1 showed the closed-loop model of pilot control of spatial orientation as proposed by Benson and Stott (2006) [15]. For this literature study, an extension to this model can be made. This extension covers SD Type-II, where two versions of this type could possibly be distinguished. These two forms differ from each other in terms of where they originate in the closed-loop orientation model. One of the visions on the closed-loop control model is that after all the signals are sensed by the different modalities and processed and then one stumbles upon a mismatch in these different signals, it can also be said that one is disoriented. The mismatch arises for example when the visual system and tactile receptors provide contradictory signals. To resolve this mismatch, the input signals may be reconsidered. This is the first form of SD Type-II. The other form arises when the SO percept is compared with the desired, or expected, orientation and a mismatch between these two occurs. If one is aware of this mismatch, it can reconsider the input signals, i.e. the surrounding, in order to try to resolve the SD. If one is not aware of the mismatch, motor responses can be given. This situation could then be indicated as SD Type-I. A motor response can also be given when this form of SD Type-II occurs. This could be a result of disorientation stress.

This literature study and thus master thesis also puts the focus on attempting to demonstrate an indirect causal relation between spatial disorientation and control performance of a pilot, namely through the reduced availability of cognitive resources, according the orientation first principle. This is referred to as "disorientation stress".

## 5.2. Previous Studies

Multiple studies contribute to the state-of-the-art concerning the topic of this literature study. One of the most recent studies is done by Landman et al. (2022). In *Orientation Comes First: Becoming Aware of Spatial Disorientation Interferes with Cognitive Performance* a rotating chair was used to create spatial disorientation in a darkened room. In the test condition participants were exposed to a sub-threshold acceleration, followed by a supra-threshold deceleration to a non-zero velocity. This creates the sensation of rotation in the opposite way than the actual rotation direction. The actual rotation direction was revealed by turning the lights on. In the control condition, the turning started from a zero-velocity and accelerated to the same velocity as in the test condition. This created a correct sensation of rotation direction for the participants. During the runs, the participants had to perform a self-paced arithmetic task. Their cognitive performance was measured at the moment the lights were turned on. This study also looked into the magnitude of the motion stimuli with higher or lower peak deceleration. It was shown that the proportion of counting errors as well as the reaction time increased significantly when the participants were surprised by the rotation direction in the test condition with a high motion magnitude [1]. This study focuses on the concept of disorientation stress.

Landman's study can be seen as an abstract research. It did not take place in an operationally representative environment. However, there are four studies, which did take an operationally representative environment into account. Webb et al. (2012) investigated the effect of SD on cognitive performance by disorienting (36 UH-60 Blackhawk helicopter) pilots in a flight simulator (6 degree of freedom motion base). Pilots had to perform aurally presented cognitive tasks while they were flying oriented and disoriented flight paths. They applied formation flying to their flight conditions, which had three levels: oriented, oriented-in-formation and disoriented-in-formation. The participants had to perform a control task and a cognitive task. The cognitive tasks used were the addition and digit span task, two common tests of working memory. To induce disorientation in the formation flight, participants experienced multi-directional motion stimuli in a DVE without instrument panels. It was concluded that accuracy for both cognitive tests were negatively affected by SD. Also SD impaired participants' reaction time on the addition test [30]. Webb et al. (2012) stated that this is in line with the "posture first" principle. A remark can be made on this study. Formation flying induces a very high workload for pilots. The highest workload was during the "disorientation-in-flight" condition. This could possibly have confounded the effects of SD.

Stróżak et al. (2018) performed two experiments in the GYRO-IPT flight simulator in order to test working memory and selective attention under spatial disorientation. Participants had to manually fly six different flight profiles in disorientation and control conditions. The disorientation conditions contained three vestibular illusions (somatogyral, Coriolis and the leans) and three visual illusions (false horizon, shape constancy, size constancy). During the flight profiles, the participants had to perform a duration discrimination task, which is an auditory selective attention task, or a N-back test, which is an auditory working memory task. It was found that the accuracy for both cognitive test decreased for flight profiles with the leans [11]. This suggested that SD affects the cognitive performance of pilots. However, many flight profiles were analysed separately and it is quite remarkable that only in one flight profile, the impairment was found. Besides, the stimuli presented in orienting and disorienting flight profiles differed in many regards, for which the experiment did not control.
Furthermore, the cognitive tasks were performed 20-30 seconds after the SD stimuli were applied. It is possible that the effect of SD was already in the first 20-30 seconds after SD had taken place. Since the cognitive tasks were not performed in that time interval, one is not able to exclude that SD could have had an effect on the cognitive performance in that interval.

Gresty et al. (2003) were the first to publish on the influence of spatial disorientation on the cognitive performance of pilots. Their experiment took place in a flight simulator which was either stationary (control condition) or oscillated about upright in pitch ($20$ amplitude with a frequency of $0.2Hz$). The experimental conditions consisted of veridical, inverse or orthogonal movement. A flight profile was visually shown that was pitch-inverted or orthogonal to the platform motion. 20 participants took place in the experiment. Each participant only had to perform a spatial or verbal cognitive task while experiencing the motion. Thus, they had no active control tasks like participants in the other experiments listed in this section. Brooks spatial (number matrices) and Brooks verbal tasks (repeat non-matching word) were used as cognitive tasks and were concurrent with the SD stimuli. The experiment showed great inter-subject variability indicating individual differences in susceptibility to the cognitive impairment of spatial disorientation. Though, no difference in mean performance were found. However, pitch-inverted motion induced higher variance, because of the decreased performance of six participants. This could give evidence that spatial cognitive tasks are more effected by spatial disorientation than verbal cognitive tasks [12]. In another similar study by Gresty et al. (2008), it was indicated that there was a moderate preferential impact of SD on spatial tasks [54]. Yet, there are several studies that found no significant effect when comparing spatial and verbal tasks.

Şen et al. (2003) investigated the effect of SD on the cognitive performance of military pilots by combining their experiment with SD-training of the Turkish Air Force. 82 pilots participated in the experiment. They were flying in the SD training device, the “Gyrolab” and experiencing SD. The pilots had to perform the Letter Cancellation Test and the Wechler Adults Intelligent Scale Digit Symbol Substitution Test right after they completed the SD simulator training. Two days before or two days after the training, each participant performed these tests as well as control/baseline condition. It was seen that the cognitive performance was worse after SD-training [13]. Though, it is unclear what kind of flight profiles were flown. Besides, it is remarkable that the cognitive tests were not performed right after the SD-event had taken place.

## 5.3. Gaps in the Literature

Since Landman et al. (2022) focus on disorientation error, this study forms the foundation of this literature study and thus of this master thesis. The other aforementioned studies all have their remarks why they do not fully cover the research question of this literature study. Both Webb et al. (2012) and Stróżak et al. (2018) investigate disorientation stress too. However, in the Webb’s study, the intensity of the control task can be seen as a confounding factor. Formation flying is associated with high workload. Stróżak (2018) had six flight profiles that differed a lot from each other, but they only found one significant effect of spatial disorientation. In addition to the occurrence of an SD-event, there were several other distinguishing factors between the version of this specific flight profile with and without SD. These additional variables could also be considered as potential confounding factors.

Landman et al. (2022) demonstrate a consistently significant impact of spatial disorientation on cognitive performance, as their various conditions show minimal variation from one another. It is thus important to isolate the factors one wants to investigate and make sure that the different conditions resemble each other the best possible. Furthermore, not every study had (experienced) pilots as participants. Having the correct target audience could end up in different results. Only Webb et al. (2012) and Şen et al. (2003) used military pilots as participants, where Webb et al. specifically used military helicopter pilots. Moreover, almost none of these researches confirmed that the participants had experienced spatial disorientation.

The gap in the literature can thus described as following: No research has done which focuses on the influence of spatial disorientation on the cognitive performance of helicopter pilots (indicated as disorientation stress), where all factors are well isolated and no confounds could have occurred. This, while performing the experiment in an operationally representative environment on a highly advanced flight simulator. The experiment for this master thesis is going to be executed on the Desdemona simulator, which is a 6 Degree of Freedom simulator with the option to simulate G-forces by having a centrifuge mode. Desdemona is one of the most advanced (flight) simulators in the world with its unique motion characteristics [57]. It is furthermore important that it will be confirmed that the participants experienced spatial disorientation. The experimental environment should not be too demanding, unlike Webb et al. (2012) with formation flying. Even without SD, enough mental resources should be available for the cognitive tasks. The group of participants should be large enough and should consist of the correct target group, in this case military helicopter pilots.

In conclusion, the integration of the aforementioned factors ensures that the experiment as proposed in this literature stands out as unique, ultimately filling the gap in literature.

# 6

# Experimental Set-Up

Understanding the cognitive effects of spatial disorientation on military helicopter pilots is essential for developing effective training programs and safety measures. To address this critical gap, this chapter presents a comprehensive experimental set-up designed to investigate the impact of spatial disorientation on the cognitive performance of helicopter pilots. The experimental design incorporates a multi-faceted approach, considering various aspects that need to be taken into account when designing the experiment. The chapter explores for example the different types of spatial disorientation illusions that are commonly experienced by military helicopter pilots. By understanding the specific illusions that pose significant risks in helicopter operations, researchers can tailor the experimental set-up to replicate these scenarios. The chapter also examines the type of cognitive task that will be employed to assess pilot performance under SD-conditions. A range of cognitive tasks will be considered to comprehensively evaluate the impact of SD on the pilots' cognitive abilities.

## 6.1. Important Factors to Take into Account

Several factors need to be taken into account when designing an experiment that fills the gap in literature as describes in Section 5.3. These will be described in this section.

### 6.1.1. Spatial Disorientation Event

As described in Chapter 3, spatial disorientation events can be divided into two groups, the vestibular illusions and the visual illusions. As seen from the surveys amongst military helicopter pilots (Section 3.4), visual illusions have been reported more frequently than vestibular illusions. SD-events in which there is a loss of horizon due to atmospheric conditions or sand/snow would thus be suitable for this experiment. It would however be a shame to not make use of the unique motion features of the Desdemona simulator. That is why it would be relevant to implement vestibular illusions as well. Most commonly reported vestibular illusions amongst military helicopter pilots are undetected drift and the leans. Vestibular illusions mostly have an impact when their occurrence is in situations of degraded visual environment [7], [8], [35], [36].

The vestibular illusions could be related to the pitch, roll and yaw axis of the simulator. It is known that humans have a higher threshold for motion around the roll axis than for yaw and pitch, with pitch the lowest threshold [13]. In a study by Foucher et al. (2016) it was found that motion was more difficult to detect for certain axes, from least to most for the pitch, roll, forward-backward, left-right, up-down and yaw axes. These perceptual motion differences are likely caused by posture and self-motion. Furthermore, Foucher et al. (2016) found that spatial disorientation occurred less for faster motion speeds than for slower speeds, which were sub perception threshold [58]. So preferably, the vestibular illusion is around the roll or yaw axis or a combination of these axes. Having a vestibular illusion around the yaw axis would be interesting, since that will resemble the experiment of Landman et al. (2022) [1].

For the design process of the experiment, it is essential that besides frequency of reported SD-events, also the impact of the SD-event is taken into account. The survey held among Dutch military aviators reports both the frequency and impact of SD-events [8]. According to this, "Loss of horizon (brown out/

white out/ spray out)", "False horizon (sloping clouds or terrain)", "Loss of horizon (atmospheric conditions)", "Undetected drift or descent in hover (rotary wing only)", "Black hole approach" and "Misleading altitude cues" are the events with the most impact, which are also frequently reported.

It is important that during this experiment, there are enough variations in scenarios and SD-events, in order to prevent training effects. When participants are constantly experiencing the same spatial disorientation illusion, they will get used to it and the effects of SD on the cognitive performance will probably not be significant at some point in time. However, when illusions differ too much, some less effective illusions may reduce the overall effect size. Pilot testing will therefore be performed to select illusions that appear most impactful on performance.

### 6.1.2. Cognitive Task

The cognitive task the participant has to perform, has to be linked to tasks pilots have to perform in the cockpit. A pilot task must be simplified to a cognitive test for the experiment. It is best if an already validated cognitive test is used for this experiment, since that makes the results more scientifically substantiated. Furthermore, the task must not interfere with the visuals of the experiment, since that reduces the operational representativeness of the experiment. Therefore, the cognitive task must be auditory. Besides, in order to get results that are not multi-interpretable, the task must be deterministic and the reaction time must be measurable. In this way, cognitive performance can be measured. It is also important that the task does not last too long, because it is possible that the effect of SD is only visible within a short time span after the SD-event.

Taking all these requirements in consideration, the Mathematical Processing Task seems to be best suitable for this experiment. In the Mental Processing Task the participant has to perform simple mathematical exercises and has to decide whether the answer is below or above a certain value [59]. The task is of relatively short duration, has a deterministic answer and the reaction time is simple to measure. In this experiment, the test can be implemented as following. One could think of the participant being the copilot and he/she is being asked by the captain if the values of certain mathematical exercises are below or above a certain threshold. The sums will thus be presented auditory. The participant can use the helicopter controls in the simulator to indicate the outcome. Buttons or switches with (more than) two options can be used for this. An example would be a slide switch, which can slide up or down and has a neutral position. If the outcome of the exercise is below a certain value, the participant should slide the switch down. If the outcome is above the value, the participant should slide up. The position of the button or the switch on the controls should be such that the participant has to make a minimal movement in order to operate. Otherwise, mental resources are needed for this hand movement.

### 6.1.3. Flight Model

In order to get the best results, the group of participants should be the most representative as possible for real life situations. This means that the target audience should consist of military helicopter pilots. For this experiment, the group will be a combination of AS532 "Cougar", CH-47 "Chinook", and NH90 helicopter pilots from the Royal Dutch Air Force and Royal Dutch Navy. There is no NH90 flight model available in the software of the Desdemona simulator, only the Cougar, Chinook and Apache. It is not desired that one of the groups of pilots has advantage over the others. It is thus chosen that all pilots fly an helicopter type which is unknown for them. That is why it is decided to use the AH-64 "Apache" flight model.

### 6.1.4. Operationally Relevant Scenario

NH90 pilots are used to fly above water with minimal visual cues. Flying above aerial terrain is out of their comfort zone. For Cougar and Chinook pilots this is just the other way around. They highly value the visual aerial cues below them. However, there was a time that the Cougar was used frequently for maritime operations, so there is still a group of Cougar pilots which is used to flying above sea. This knowledge should be taken into consideration when designing the scenario in order to avoid performance differences between these groups of pilots. Furthermore, the scenarios must be designed such that they are not too simple, otherwise there is a chance that fatigue will occur. However, it must be simple enough. Mountain flying would be too difficult, since pilots will constantly think about emergency routes and deciding the direction of the wind. This will, unintentionally, take mental resources.

### 6.1.5. Dependent and Independent Variables

Since this experiment aims to investigate the effect of spatial disorientation on the cognitive performance of helicopter pilots, multiple main variables can be identified. The independent variables are the presence of spatial disorientation and the presence of the control task. Both are factors with two levels (yes/no). The dependent variables are related to the cognitive and the control tasks. For the cognitive task, these variables are reaction time and accuracy. The dependent variables related to the control task are the control inputs of the pilot. These could show the potential deviation of the aircraft attitude from the desired aircraft attitude (straight and level flight), which could give an indication of the participant experiencing spatial disorientation. If the participant is disoriented he/she steers opposite from the desired flight path. The first control input to correct for the provided situation could give an indication for this. When for example using the leans as SD-event in the experiment, roll reversal error would be an interesting variable which could indicate experienced SD. However, if no deviation is measured, it does not exclude that the participant did not experience SD. It could be the case that he/she experienced SD, but is still able to keep the aircraft straight and level. This variable only holds for experimental runs in which the participant is asked to perform the control task.

The presence of the control task will determine if the application of the scenario is for the pilot flying (PF) or the pilot monitoring (PM). When the participant has both the control and the cognitive task, the influence of spatial disorientation on the cognitive performance of the PF is investigated. When not having to execute the control task, this potential relation is analysed for the pilot monitoring. It would be interesting to see the differences in results between scenarios with and without the control task.

### 6.1.6. Virtual Reality

The Desdemona simulator has to option to provide the visuals in virtual reality (VR) or via screens inside the cabin. Virtual reality adds value to the experiment by making the visual environment more representative. It is thought that the visual illusions would be experienced more intense, since the participant is not able to look away from the screens.

### 6.1.7. Duration of the Experiment

The duration of the experiment is contingent on the number of runs and ethical considerations for participant well-being. It would not be considered humane to have participants in the simulator for a continuous four-hour period, especially while wearing VR-glasses. According to pilots, spending approximately two hours in the simulator, including a break, is reasonable.
Additionally, the total duration of the experiment should account for briefing, training, and debriefing sessions. A briefing of 20 minutes, a 10 minute training session, and a debrief of 20 minutes should be sufficient. The training session comprises approximately 5 minutes of simulated flight, such that the participant is able to familiarize him-/herself with the Apache flight model. Subsequently, an additional 5-minute segment is allocated for practicing mathematical exercises, both on the ground and in flight.

When using a set up of three pairs of SD/non-SD scenarios for pilot flying and three pairs of scenarios for pilot monitoring, it comes to a total of 12 scenarios. Each scenario pair should be executed twice. Taking into account the maximum total amount of time a participant can spend in the simulator, comes to a duration of 3 minutes per scenario.

## 6.2. Example Design Experiment Desdemona

An example design of the experiment in Desdemona will be described in this section. The participant will fly a desired flight path in virtual reality in Desdemona. He/she will be flying passively (pilot monitoring) or actively (pilot flying), dependent on the scenario. This, because this study aims to investigate the phenomenon of disorientation stress, or in other words how SD affects cognitive resources during concurrent tasks. The control task could be a confounding factor. By having conditions without control task, it is aimed to rule out that the effects of SD observed are caused by orientation error. That is why also no control task conditions are implemented in the experiment design. Besides, since the pilot monitoring and the pilot flying have their distinct set of tasks in flight, it is interesting to investigate the effect of SD on cognitive performance for each of these roles.

For the proposed experiment design, there are four possible conditions, in which the cognitive task is to be executed by the participant in every condition:

1. Pilot Monitoring: No control task, no spatial disorientation event
2. Pilot Monitoring: No control task, spatial disorientation event
3. Pilot Flying: Control task, no spatial disorientation event
4. Pilot Flying: Control task, spatial disorientation event

Each scenario is designed using the same format, which can be seen in Figure 6.1. The total duration of each scenario is 3 minutes (= 180 seconds). During the scenario, three series of mathematical exercises will be presented auditorily to the participant, in which each series consists of 10 exercises with a total duration of 30 seconds. The first series of exercises has the function of baseline measurement for cognitive performance. The second series can coincide with a spatial disorientation event, depending on the condition of the scenario. The last series of exercises functions a post SD-event measurement.

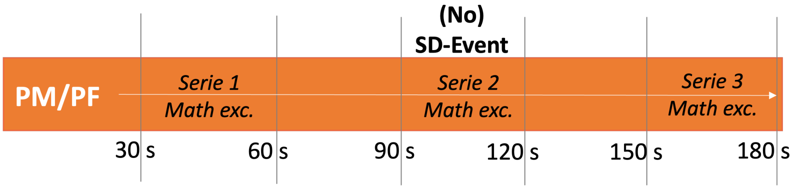


**Figure 6.1:** Visualization of the general format of every scenario.

Taking into account that there should be enough variation in the scenarios, six different SD-events are chosen to be used in the scenarios. Three events are dedicated to pilot monitoring scenarios and three to pilot flying scenarios. These events should be relevant, depending on the role (PM/PF) the participant has in that specific scenario. Relevant and high impact SD-events are discussed in Section 6.1.1. The following six SD-events are used in this proposed experiment design (see 6.1):

**Table 6.1:** The SD-events used for the example design of the experiment. Three scenarios are used in the PM scenarios and the other three are used in PF scenarios.

| Pilot Monitoring | Pilot Flying |
|---|---|
| Brownout | False horizon |
| Somatogyral yaw illusion | Featured versus featureless terrain |
| Night Vision Goggles (NVGs) | The leans |

During the brownout, there is a loss of horizon and vection illusion. The somatogyral yaw illusion results in the participant experiencing a movement in the opposite direction of the actual movement. The somatogyral yaw illusion will be in line with the study of Landman et al. (2022) [1]. In the scenario in which NVGs are used, the participant loses sight of the horizon and all other references points. Surveys among USAF rotary wing aviators have pointed out that “SD while using NVGs” is in the top five most reported SD-events [35]. These events will be used in the scenarios corresponding to the second condition. Scenarios with the first condition will be similar to the scenarios with the second condition, the only difference is that the SD-event will not be present.

During the false horizon scenarios, the participant will be presented a false horizon by usage of a sloped cloud deck. For the featured versus featureless terrain scenario, the participant will fly over water without any texture such that there is a lack of altitude cues. The leans are simulated by rolling the cabin of Desdemona a few degrees, while showing the participant on its instruments that the helicopter is flying straight and level. These SD-events are thus used in scenarios corresponding to the fourth condition. Scenarios obeying the third condition will be similar to the scenarios for the fourth condition, but now the SD-event will not be present. Scenarios obeying the first and third condition function as baseline scenarios for scenarios corresponding to the second and fourth condition. Further refinement of the described scenarios will be provided during the future stage of the design process of this experiment.

There are thus three scenarios per condition, which makes a total of 12 scenarios. Each scenario will be performed twice, so the participant performs 24 scenarios during the entire experiment, in which each scenario lasts three minutes. The experiment will be divided into two simulator session in which the participant performs all scenarios per simulator session. The two sessions are separated by a break of approximately 10 minutes. Each simulator session has a duration of approximately 45 minutes (12 scenarios of three minutes). A Latin square will be used to decide the order of the scenarios for each participant. This is used such that any order effects are avoided.

## 6.3. Hypotheses and Statistics

The main goal of the previously described experiment is to investigate the effect of spatial disorientation on the cognitive performance of military helicopter pilots. The following hypotheses are thought of, keeping this goal in mind:

1. When comparing the pilot monitoring scenarios (conditions 1 and 2), it is expected that the cognitive performance (both accuracy and reaction time) will be worse for scenarios obeying condition 2 due to the presence of the SD-event. This would confirm the cognitive impairment of spatial disorientation. This hypothesis is based on the study of Landman et al. (2022) in which the cognitive performance was worse in situations with spatial disorientation.
2. In the comparison of the pilot flying scenarios (conditions 3 and 4), an anticipation is that cognitive performance (both accuracy and reaction time) will be worse in scenarios aligned with condition 4, attributed to the presence of the SD-event. The “orientation first” principle forms the scientific foundation for this. As the control task becomes more difficult in scenarios obeying the fourth condition due to SD, less mental resources are available for the cognitive task. This would result in lower accuracy and reaction times. The impact of the SD-event can be seen in the control inputs of the participant. If these deviate from the desired flight path, it can be said that the participant has to cope with SD. If the control inputs do not deviate or have minimal deviation from the desired flight path, and the participant performs worse on the cognitive task, then this could be indicated as disorientation stress. The participant puts all resources in steering the aircraft and has little resources left for the cognitive task, resulting in a worse cognitive performance (“orientation first” principle).
3. The effect sizes of SD for the pilot monitoring scenarios (comparison conditions 1 and 2) can be compared with these of the pilot flying scenarios (comparison conditions 3 and 4). It is thought that the decrement in cognitive performance for pilot flying scenarios is larger than this decrement in pilot monitoring scenarios. This is expected, since there is an extra task in the pilot flying scenarios, which could take away more mental resources.
4. It is thought that the impact of SD on the cognitive performance is less worse for more experienced pilots. Experience is measured in the total amount of flight hours. The chance of having more experience with SD is higher when having flown more hours as a pilot. It is expected that this experience causes the impact of SD to be less on the cognitive performance.

When putting the third hypothesis in an operational context, the decrement in cognitive performance for passively flying scenarios could have a larger impact than for the actively flying scenarios. This is because these scenarios represent the role of a pilot monitoring, who has to, among others navigate and communicate. When the pilot flying becomes disoriented, he/she will have trouble with steering the aircraft, but has no other (large) cognitive tasks. Only if SD Type-I, things will become dangerous. However there is almost always another pilot to take the controls. If the pilot monitoring becomes disoriented it directly affects cognitive tasks such as navigation and communication. The pilot flying could take over these tasks, however he/she is already executing the control task.

## 6.4. Statistics

This section covers the statistical tests that will be used to determine the statistical significance of the results.

The accuracy and reaction time of the cognitive tasks between the SD and no-SD conditions will be compared for both the pilot flying and pilot monitoring roles. If the data follows a normal distribution (verified by a Shapiro-Wilk test), a paired-samples t-test will be applied. In cases of non-normal distribution, a Wilcoxon Signed-ranks test will be used. The effects and their magnitudes will be described and compared across the roles.

To examine whether some SD-events have more impact than others, a repeated-measures ANOVA with a 2xY design will be utilized. This involves the condition (SD/no-SD) as one repeated-measures factor, and the scenario (Y1, Y2, Y3) as the second factor. If a significant interaction effect is observed, further analysis will involve conducting pairwise comparisons at each time point.

To test the potential correlation between the impact of SD on cognitive performance and flying experience, Pearson correlations will be conducted between the difference in cognitive performance and the total number of flight hours.

For the pilot flying scenarios, the control inputs are analysed at moments of disorientation events, in order to check if participants were disoriented. To check this, the proportion of incorrect first control inputs (i.e., in the opposite than required direction) is compared between the SD and no-SD conditions. If the data exhibits a normal distribution (confirmed by a Shapiro-Wilk test), a paired-samples t-test will be applied. In the case of non-normal distribution, a Wilcoxon Signed-ranks test will be utilized.

Alpha is set to $p = 0.05$ for all statistical tests. Results of $p < 0.100$ are reported as marginally significant.

# 7

# Conclusion

*Numerous conclusions* can be drawn with respect to this literature study. The perception systems with the highest contribution to the process of orientation are the vestibular and visual system. The otoliths sense linear acceleration and the semicircular canals angular accelerations. The ambient visual system is related to orienting the individual in the environment. Focal vision has more to do with object recognition [15], [17].

Spatial disorientation illusions are created by false or missing visual cues and false or sub-threshold vestibular cues. Helicopter pilots mainly deal with visual illusions in which the horizon is missing due to atmospheric conditions or sand and snow (e.g. brownout or whiteout) or situations in which a false horizon is present. SD due to missing altitude cues is a frequently reported illusion too. The leans and undetected drift are commonly reported vestibular illusions amongst military helicopter pilots, in which the undetected drift is a unique illusion for helicopters. The SD-events with the most impact are related to loss of horizon due to atmosopheric conditions or sand/snow, false horizon, undetected drift, black hole approach and misleading altitude cues [7], [8], [35], [36].

Cognitive tasks in the cockpit can, in general, be summarized as *"Aviate, Navigate, Communicate"*. The cognitive tasks of military helicopter pilots depends on the type of helicopter. In (transport) helicopters with two pilots, the pilot flying does the steering and the pilot monitoring executes all the other cognitive tasks, such as communicating with ATC. However, the pilot flying still performs cognitive tasks by communicating with the pilot monitoring and executing its commands. In case of emergency, the PF should be able to perform the tasks of the PM. In attack helicopters, the pilot does all the flying and flying related cognitive tasks, while the co-pilot performs the weapon related tasks [50].

Previous studies have investigated the effect of spatial disorientation on the cognitive performance. However, these studies contained possible confounding factors. None of these studies had taken all of the following factors into account: Focus on disorientation stress; Correct target audience consisting of military helicopter pilots; Advanced simulator on which the experiment was performed; Free of confounding factors. To fill in the gap in literature, the experiment for this master thesis should be designed such that all these factors are taken into account. The experiment will consist of scenarios obeying one of four conditions, in which the presence of spatial disorientation and a control task will be the independent variables. The Mathematical Processing Task will be used as cognitive task. The experiment will be executed on the highly advanced Desdemona simulator [59]. A combination of visual (brownout, false horizon, featureless terrain, NVGs) and vestibular (somatogyral yaw illusion, the leans) will be presented to the participants.

The scenarios without control task represent the pilot monitoring role, whereas the scenarios with control task represent the pilot flying role. Based on the research of Landman et al. (2022) and the "orientation first" principle, it is expected that the cognitive performance will be worse in scenarios containing an SD-event [1].

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# Part III

## Appendices

# A

# Pre-Experiment Questionnaire

The following page contains the questionnaire that was given to participants before the start of the experiment.

PP nummer: …………………….

## ALGEMENE VRAGEN VOORAF

Leeftijd:……………………

Geslacht: M / V

Rang:……………………………………………………………

Jaren werkervaring:……………………………………………………………

Wat is uw huidige functie? (i.e., gezagvoerder/copiloot, helikoptertype, evt. nevenfuncties):

……………………………………………………………………………………………………………………………………

……………………………………………………………………………………………………………………………………

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……………………………………………………………………………………………………………………………………

Gevlogen helikoptertypes (incl. indicatie aantal vlieguren per type):

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

……………………………………………………………………………….Vlieguren:……………………………………………………

Heeft u ervaring met vliegen in VR? Ja / Nee

Heeft u ervaring als instructeur? Ja / Nee

# B

# Post-Experiment Questionnaire

The following pages contain the questionnaire that was given to participants after finishing the experiment.

PP nummer:………………………..

## VRAGEN NA HET EXPERIMENT

U heeft een aantal scenario’s gevlogen. In de helft van deze scenario’s was er een Spatial Disorientation (SD) verstoring toegevoegd. De andere helft bestond uit dezelfde scenario’s zonder die SD verstoring.

De volgende vragen gaan steeds eerst over de variant met SD verstoring, en daarna over de variant zonder die SD verstoring. Selecteer steeds één antwoord:

### 1a. Valse horizon door schuin wolkendek

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

### 1b. Hetzelfde scenario als 1A maar <u>zonder</u> schuin wolkendek.

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

### 2a. Brownout <u>met</u> verlies van zicht op horizon.

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

### 2b. Hetzelfde scenario als 2a maar <u>zonder</u> verlies van zicht op horizon.

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

PP nummer:……………………….

**3a. Vliegen boven de zee zonder golven en textuur**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**3b. Hetzelfde scenario als 3a maar met golven en textuur**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**4a. Night vision met verlies van referentie.**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**4b. Hetzelfde scenario als 4a maar zonder verlies van referentie.**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**5a. The Leans (gesimuleerd met roll cue).**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

PP nummer:……………………….

**5b. Hetzelfde scenario als 5a maar zonder extra rol cue.**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**6a. Tegenstrijdige yaw cues (verschijnend beeld draait in omgekeerde richting als gevoelde beweging)**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

**6b. Hetzelfde scenario als 6a maar met verschijnend beeld dat dezelfde kant op draait als gevoelde beweging.**

Hoe desoriënterend vond u het scenario?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

In welke mate beïnvloedde dat uw rekenprestatie?

| | | | | |
|---|---|---|---|---|
| Helemaal niet | Zwak | Matig | Sterk | Zeer Sterk |

Heeft u opmerkingen over de scenario’s? Wat zou er beter kunnen?

……………………………………………………………………………………………………………………

……………………………………………………………………………………………………………………

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……………………………………………………………………………………………………………………

PP nummer:……………………….

Heeft u in het echt wel eens SD meegemaakt? Wat gebeurde er? Welke impact had dit op u en wat deed u ertegen? (Meerdere antwoorden mogelijk)

……………………………………………………………………………………………………………………

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Als u in het verleden een head-mounted display (HMD) heeft gebruikt, heeft u hier wel eens storingen of problemen bij meegemaakt die uw werklast beïnvloedden? Zo ja, kunt u hier iets over vertellen?

……………………………………………………………………………………………………………………

……………………………………………………………………………………………………………………

……………………………………………………………………………………………………………………

……………………………………………………………………………………………………………………

# C

# Raw Data

This appendix contains figures featuring raw data obtained during the experiment.

## C.1. Error Rate

Figure C.1 shows for each condition the types of answers given in each interval. It is a accumulation of data of all 13 participants. Each bar thus represents 130 answers to the mathematical exercises during the specific interval in that condition. The bars in the No-SD condition of the “Somatogyral Illusion” scenario only contains 120 data points, because for one participant the log file was corrupted.

## C.2. Reaction Time

This section contains figures (Figures C.2, C.3, C.4, C.5, C.6, C.7) for each condition of each scenario during both Simulator Session I and Simulator Session II. Each figure represents one condition and visualizes the reaction times of all participants. For each cognitive task interval, a separate boxplot is made. The “missed” answers are not taken into account. The number of data points for each interval is given above the corresponding boxplot.

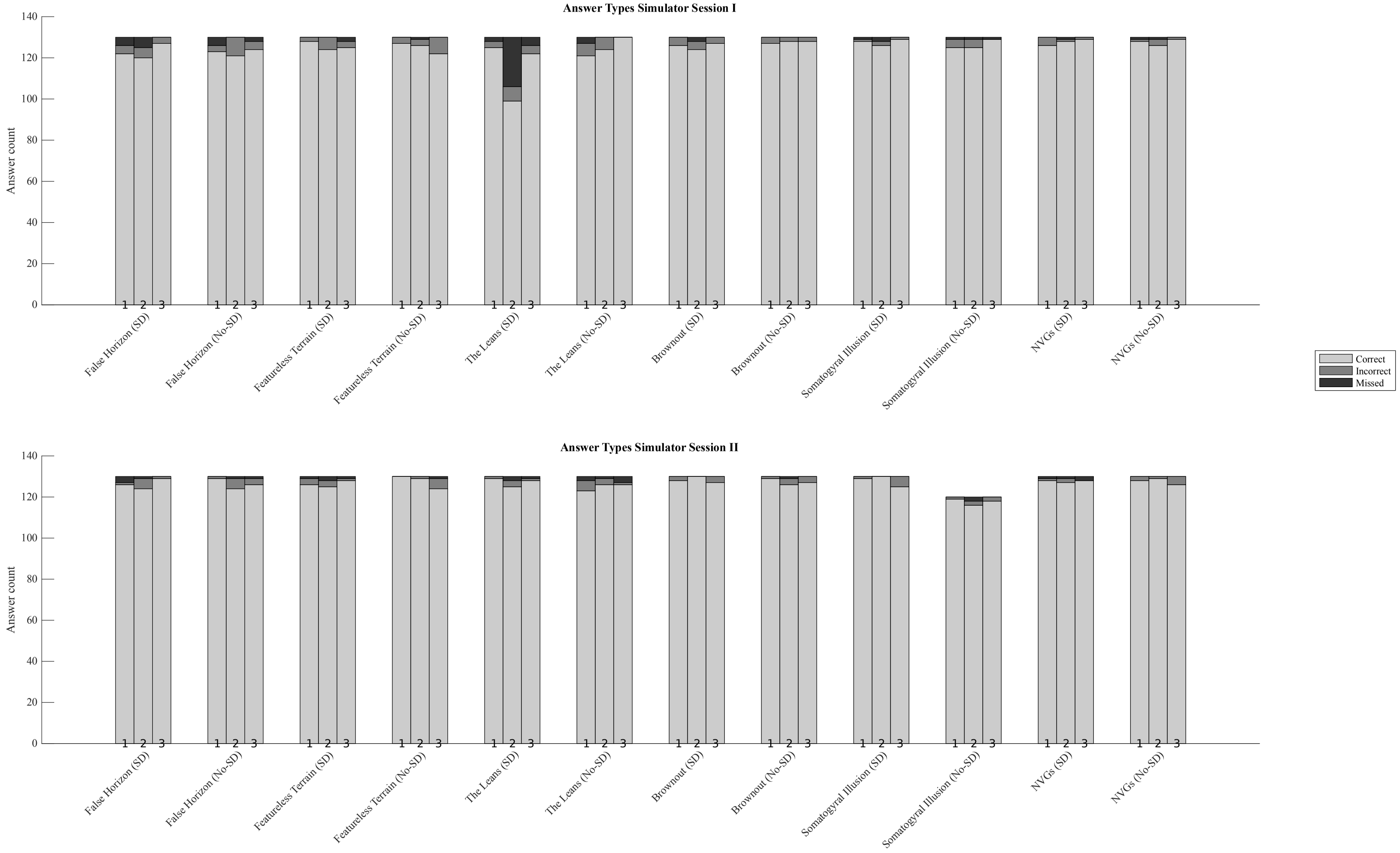
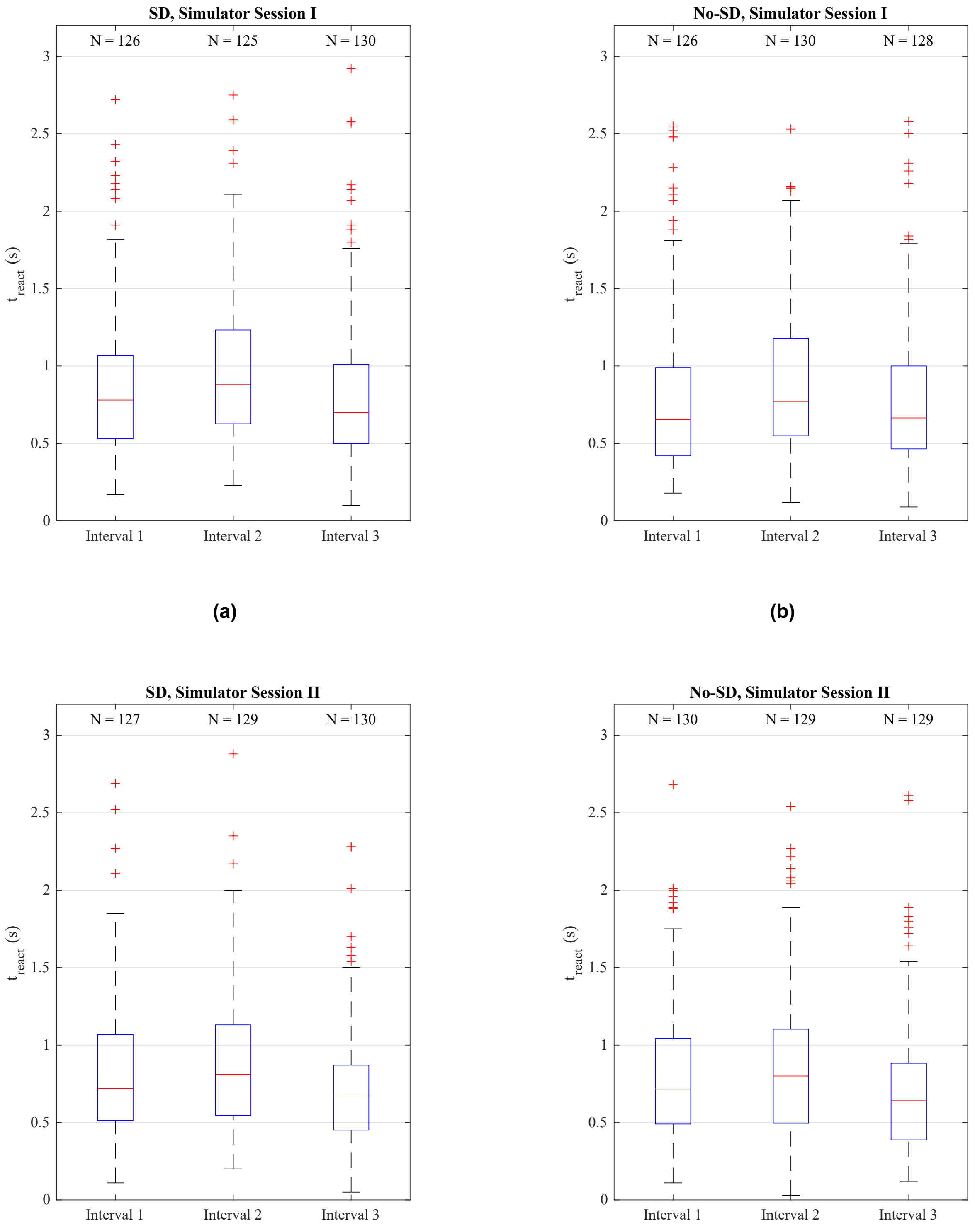


**Figure C.1:** Visualization of the types of answers given in each cognitive task interval for each condition. The data of all 13 participants is taken into account.



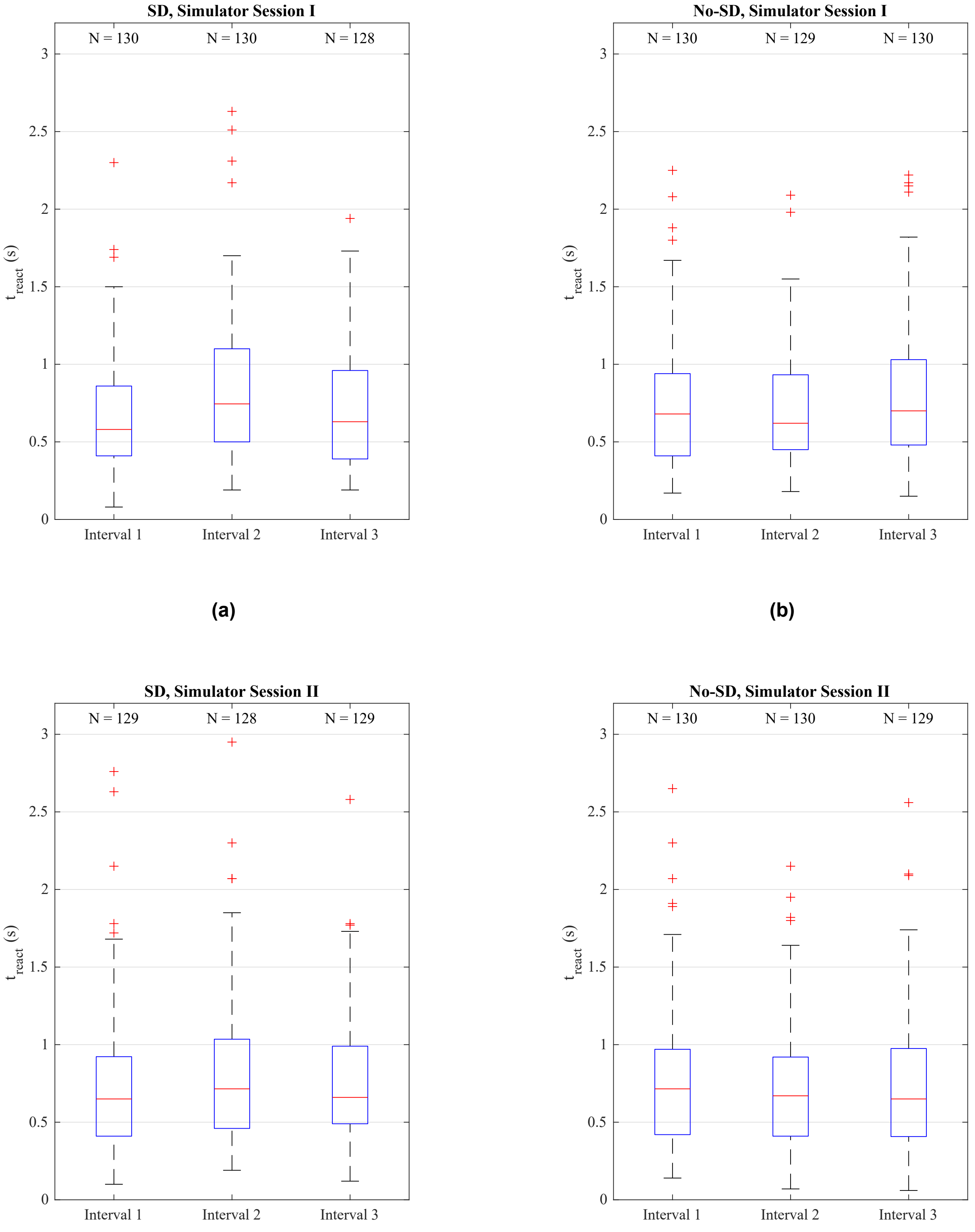
(a)

(b)

(c)

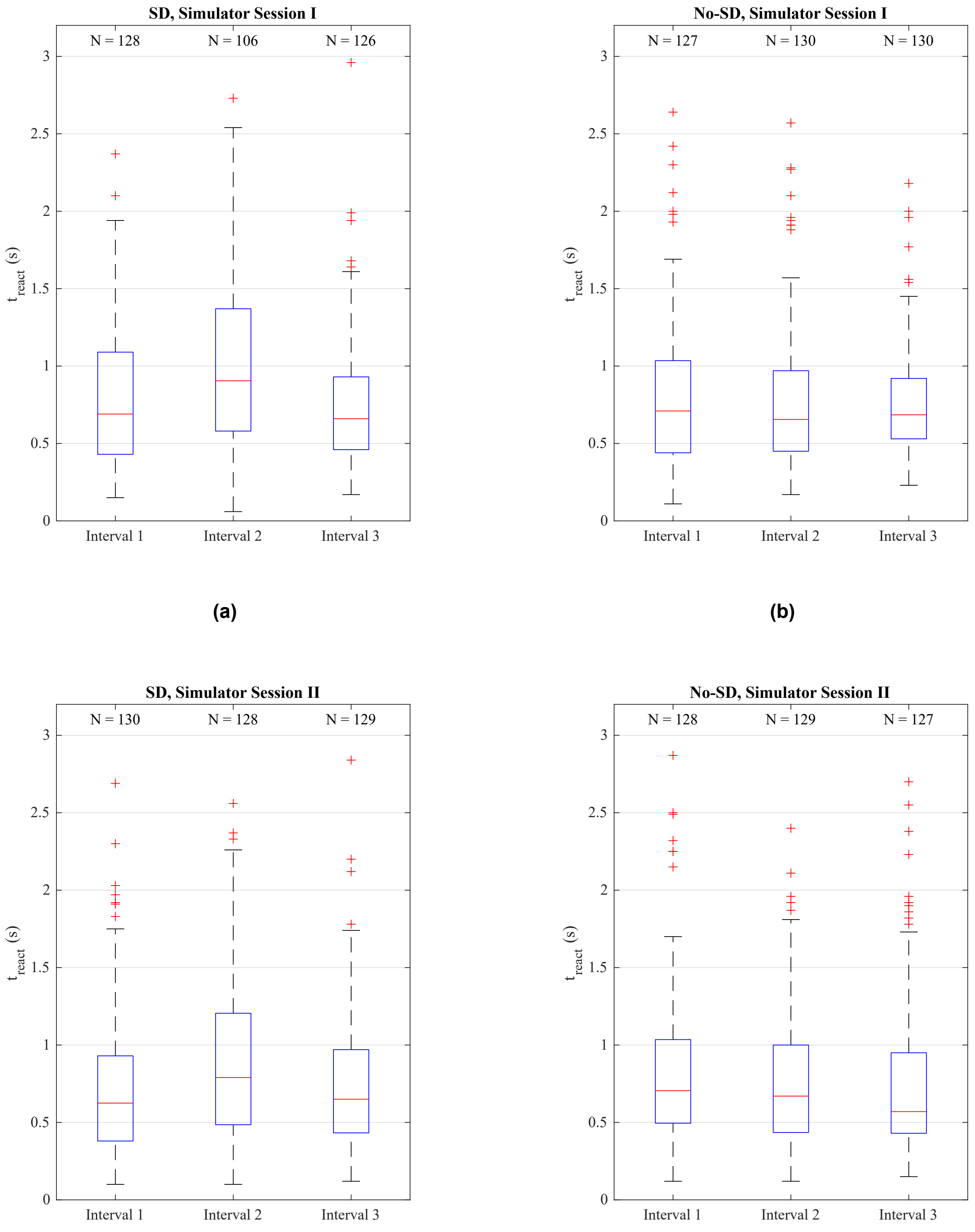
(d)

**Figure C.2:** Reaction times for the “False Horizon” scenario.



**(a)** **(b)** **(c)** **(d)**

**Figure C.3:** Reaction times for the “Featureless Terrain” scenario.



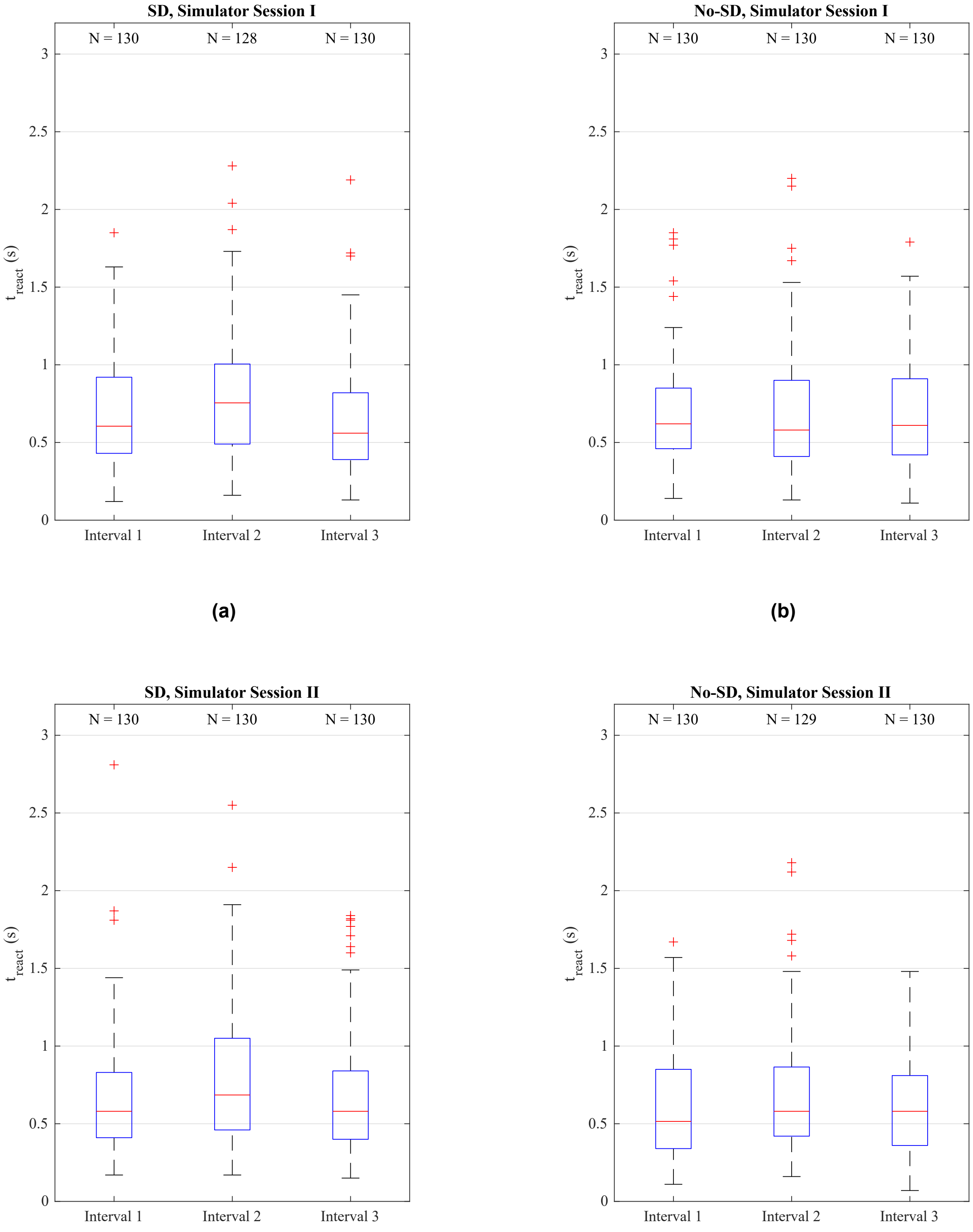
(a)

(b)

(c)

(d)

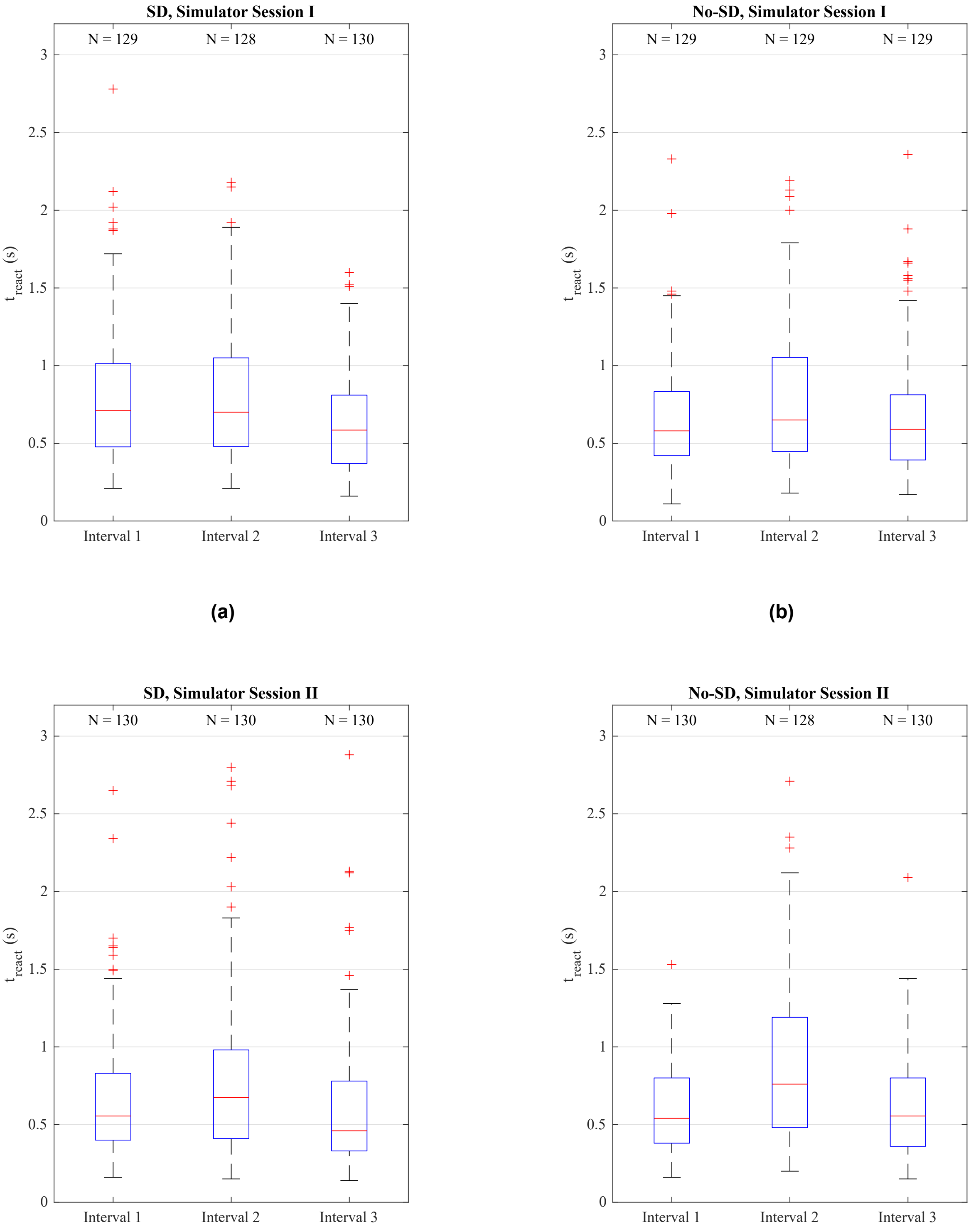
**Figure C.4:** Reaction times for “the Leans” scenario.



(a) (b)

(c) (d)

**Figure C.5:** Reaction times for the “Brownout” scenario.



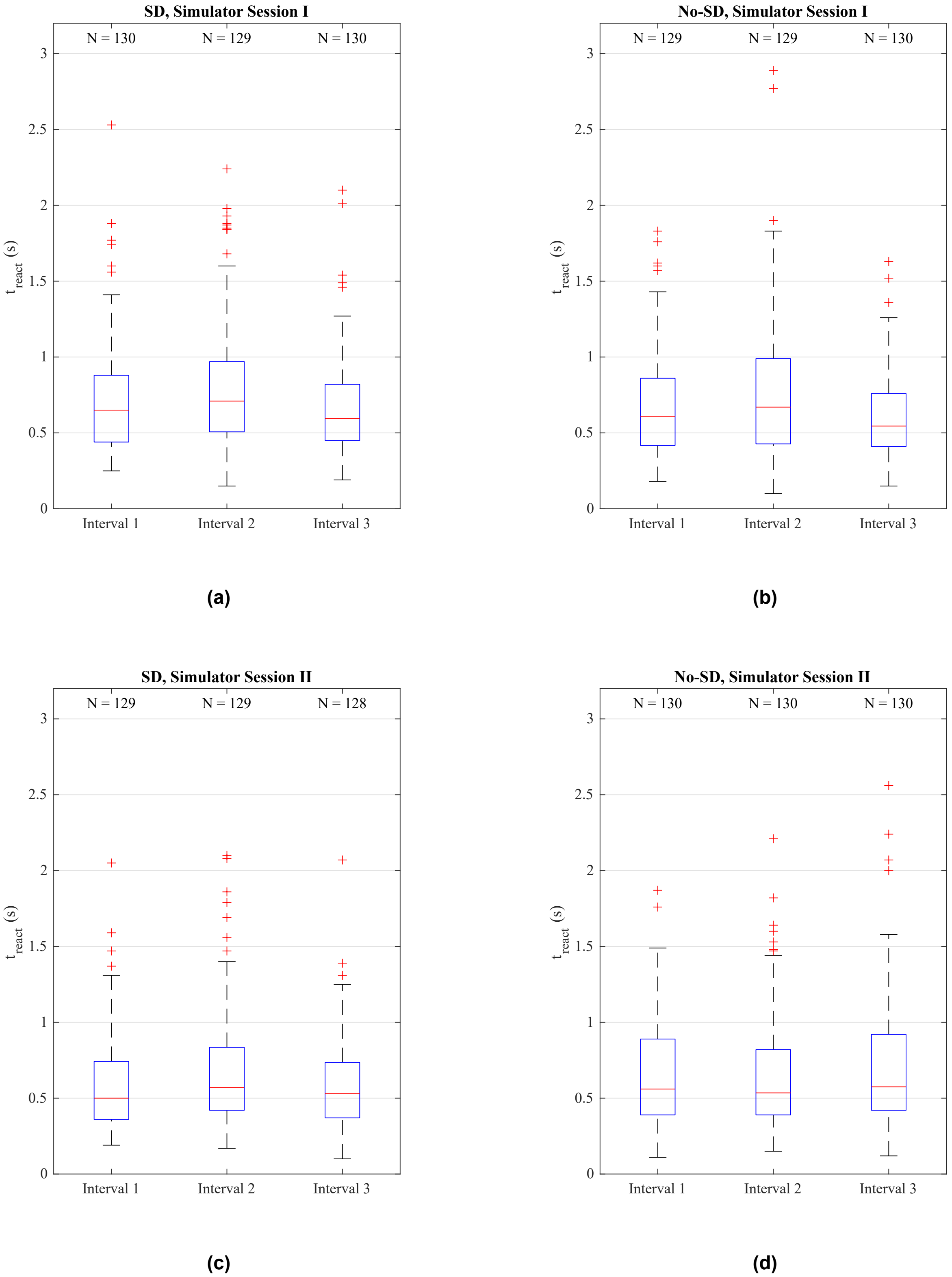
(a)

(b)

(c)

(d)

**Figure C.6:** Reaction times for the “Somatogyral Illusion” scenario.



(a)

(b)

(c)

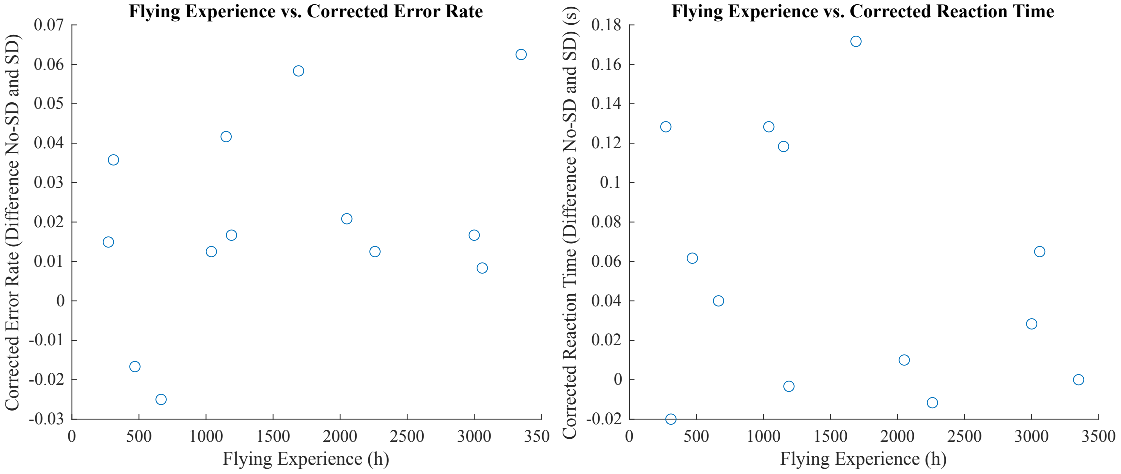
(d)

**Figure C.7:** Reaction times for the “NVGs” scenario.

# D

# Correlation Flying Experience and Impact SD

This appendix contains figures visualizing the correlation between the flying experience of participants and the cognitive impact of SD in terms of reaction time and error rate. For both the corrected reaction times and error rates, the difference between SD and No-SD conditions was determined. These values were used to test whether there was a relation between flying experience and the impact of SD. No significant correlation was found.



**(a)** Relation between flying experience of participants and the impact of SD on the corrected error rate.

**(b)** Relation between flying experience of participants and the impact of SD on the corrected reaction time.

**Figure D.1:** Relation between flying experience and the cognitive impact of SD.