Faculty of Aerospace Engineering

Using heave cues to increase pitch perception in ground-based simulation

Master of Science Thesis

B.N. Güngen

31 August 2022

Delft University of Technology

Challenge the future

Using heave cues to increase pitch perception in ground-based simulation

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering
at Delft University of Technology

B.N. Güngen

31 August 2022

Faculty of Aerospace Engineering · Delft University of Technology

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Delft University Of Technology
Department Of
Control and Simulation

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Using heave cues to increase pitch perception in ground-based simulation"** by **B.N. Güngen** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: 31 August 2022

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Preface

Before you lies my thesis titled *Using heave cues to increase pitch perception in ground-based simulation*, based on an experiment conducted among twenty Dutch airline pilots in the SIMONA Research Simulator. It has been written as part of the graduation requirements of the MSc Aerospace Engineering at Delft University of Technology. This master provided me the opportunity, after my bachelor in Mechanical Engineering, to learn more about aerospace and aviation, which has been an interest ever since my first flights at a young age.

I feel that the idiom *"It takes a village..."* is applicable here, as this report is a product of the continuous support of many individuals, throughout a challenging period, where our interactions suddenly took a different form over Zoom calls. It was an honour and I am very grateful to have experienced the combined knowledge of my supervisors and discuss thesis related ideas with them. Annemarie, as my daily supervisor you gave me a push when I needed it on many occasions, especially your help with statistics and writing is very much appreciated. Olaf, your ability to approach problems out of the box proved very useful, thank you for all of your guidance with my simulations and programming. René , I have come to see you as a human encyclopedia, thank you for providing insight and helping to generate a mental image of problems. Max, thank you for your always positive guidance and helping to maintain an overview of the most important matters.

Aside my supervisors I am very grateful to Dirk for all your help with DUECA. Rowenna thank you for providing your Simulink model, general advice on my thesis and encouraging words. Without Jan's help with participant recruitment and the enthusiasm of the volunteering pilots, this experiment would not have been possible. Jacomijn, thank you for your feedback. Huub, you were my foundation, both in day-to-day necessities as long evenings behind Matlab. The COVID-19 period, during which I didn't see my family for more than a year, made me extra appreciative to have such supporting parents. Those circumstances also lead to prove the importance of friendships which bring joy and inspiration no matter what.

Berna Güngen
Delft, 17 August 2022

Contents

List of Figures

List of Tables

Part I

Paper

Using heave cues to increase pitch perception in ground-based simulation

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***Abstract*—In current spatial orientation models, vertical acceleration (heave) is not coupled with pilot pitch perception, although such a coupling may be present. Therefore, in this study it is investigated whether a heave cue can increase perceived pitch in pilots. Airline pilots (n = 20) performed a pitch perception task in a hexapod simulator. A level change maneuver, with the simulator cabin pitching up and back down, was presented with different maximum pitch angles. After the maneuver, pilots indicated the maximum perceived pitch angle. This motion was presented either with or without a brief (1.25s or 1.5s) heave cue, that was timed to the onset of the pitch motion. Two timings and magnitudes of the heave cue were used to investigate these factors.**

The results indicate that the heave cue significantly increased pilot pitch perception by 1.88°, p $<$ 0.001. The maximum pitch angle was 2.69° underestimated without heave and 1.42° underestimated with heave. A higher heave magnitude, relative to a lower, resulted in a significantly larger estimation of the pitch angle, δ = 0.47°, p = 0.009. Earlier timing of the heave cue resulted in marginally significantly higher pitch perception than later timing, δ = 0.43°, p = 0.069. Interestingly, if heave was presented without pitch motion, pilots still estimated 2.66° pitch on average.

The results suggest that heave cueing increases perceived pitch in pilots, even when the heave cues are shorter in duration than cues that would be present in the actual maneuver in flight. Heave cues timed to the onset of pitch motions can thus possibly be used to enhance pilot pitch perception in hexapod simulators.

I. Introduction

Aviation is widely known as one of the safest forms of long distance transportation and travel [1]. Today, its efficiency and safety still depends on adept cooperation and integration of pilots within existing (automated) aircraft systems. Pilot (supervisory) performance and their correct interpretation of aircraft cues remains imperative to maintain safety at all times [2] [3]. Recent sector-wide scrutiny on incidents and accidents involving spatial disorientation (SD) has brought to light that this forms a serious risk which must be addressed [4] [5]. A study conducted by Boeing, covering a 20 year period from 1990 onward, noted a rate of about one fatal SD accident per year [6]. Between 2000 and 2016, six large transport aircraft accidents and three serious incidents related to SD in the pitch axis occurred, with a total of 481 lives lost. The somatogravic illusion (SGI) was considered a causal factor in these cases [5]. Even when incidents do not amount to fatal accidents, their rate of occurrence suggests a problem. A large pilot survey found that 71% had encountered SD at some point during their career and 41% of participating pilots reported to specifically have experienced the SGI [5].

In order to better understand and mitigate such situations the industry reacted by investigating, and setting up safety enhancements and operational procedures [7] [4]. A systematic approach to analysing accidents was needed in order to determine whether SD was a contributing factor. Boeing collaborated with the Netherlands Organization for Applied Scientific Research (TNO) to set up a tool which could realise such analyses by applying a spatial orientation model (SOM) [6].

Further a series of studies used ground-based simulation to approach the sensations that can be felt in a SGI. Scenarios were developed for the demonstration of SD using a hexapod simulator [8]. Researchers aimed to expose pilots to the false perception of pitch that occurs in the SGI, by introducing a deviation between the motion platform and the applied aircraft model's pitch angle during a go-around scenario [9]. In a similar way a centrifuge simulator can also be applied to create a continuous force for demonstrating SD. Participants are continuously rotated around a central axis, while facing the axis. When the rotational velocity is constant, the direction of the resultant acceleration force, which consists of a gravitational and centripetal component, is interpreted as the vertical in the steady state [10]. This gives participants an illusion as though they are tilted, which resembles the vestibular cues involved in a SGI. Variable-radius centrifugation provides circumstances wherein a sustained linear acceleration is present and the gravity vectors direction can be varied without subjecting participants to a physical tilt, all while the semicircular-canals remain un-stimulated [11]. While there are numerous ground-based methods for invoking the same sensations of a mismatched pitch illusion, research towards potential triggers of this vestibular reaction are limited. Civilian pilot ground-based training of the SGI also remains mostly limited to theoretical forms, because its replication is difficult within the limits of simulators [5].

Aircraft accident investigation of Afriqiyah Airways Flight 771, Gulf Air Flight 072, and the recent Atlas Air Flight 3591, revealed that these accidents were also caused by SD. The involved pilots made a series of unexpected nose-down inputs during go-around phases. A discrepancy is suspected by investigators, between the pilots perceived pitch and the actual pitch angle during the go-around, indicating the SGI as a cause [12] [13] [14]. A common feature of these flights is impeded visibility, due to either weather circumstances such as fog or limited lighting at that time of the day. Another frequently encountered factor is the presence of unfavorable weather circumstances such as wind gusts and micro-bursts. Such wind gusts can form a heave cue for the vestibular system and may have a profound effect on pilot perception. Current SOM do not link heave cues and the perception of pitch, while it can be reasoned that heave cues can be of influence on the vestibular system.

In the current study the aim is therefore to investigate whether a heave motion (i.e., a vertical acceleration) at a frequency that is higher than the pitch change during a go-around, can influence pitch perception in pilots. Such a heave motion may occur in-flight, for example, due to a wind gust or a micro burst. The decision to investigate a higher-frequency heave was also based on the limitation of a hexapod simulator motion space.

To outline the hypothesis that adding a higher-frequency heave cue to a pitch motion may increase the perceived pitch motion, Section II provides background information and consists of the following subsections: II-A. An introduction to spatial disorientation, our perceptual system and the SGI. II-B. An outline of reasons why a higher-frequency heave cue may cause increased pitch perception. II-C. A description of current spatial orientation models and an application of the Wada perception model to data of Atlas Air flight 3591.

A hexapod simulator experiment was performed to test whether a heave cue indeed contributes to the perceived pitch angle in pilots. Heave and pitch cues were independently manipulated. Two intensities and timings of this heave cue were tested to obtain more insight into the relation between heave cues and pitch perception. The set-up of this experiment is described in Section III and its results are presented in Section IV. The last two sections, Section V and VI, contain the discussion and conclusion of this research. The results can be used for improving SOM, and to improve hexapod-based simulation of the SGI for research and training purposes.

II. Background

A. Spatial Disorientation

Spatial orientation (SO) refers to the humans ability to continuously detect their body's correct attitude, position and motion relative to their surroundings. Spatial disorientation (SD) is defined as the situation wherein the human fails to maintain their SO.

In the case of pilots, SD occurs in the form of an incorrect perception of the attitude, position and motion of an aircraft relative to a fixed reference frame (earth) [15]. Such situations arise when a discrepancy occurs between the subjective vertical (SV) and the actual vertical. The SV is a construct based on the idea that the vestibular system creates a 'sensed horizon' as an output by combining the effect of stimuli as inputs to its vestibular organs with the estimation given by an internal model [16]. The latter is based on prior vestibular experiences and expectations.

A pilot has fewer sources to verify their SV than a human situated on the surface of earth would have. Therefore, especially under challenging flying circumstances such as poor visual cues and an increased workload, a pilot will be more likely to experience SD [17]. Additionally, when flying there are often motions that fall below the thresholds of the perceptual system. When discussing SD a distinction is made between three types of SD [18]:

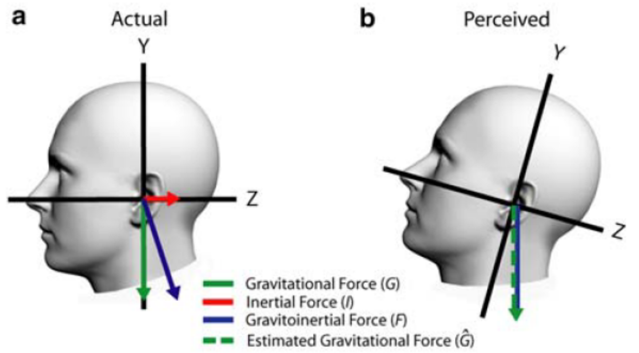


Figure 1: Somatogravic illusion and gravitoinertial force [19]

- *Type I - Unrecognised SD*: when a pilot is unaware of their SD this often results in the occurrence of an incident or accident as a result of a series of wrong decisions which are made based on an incorrect assumption.
- *Type II - Recognised SD*: when the pilot is aware of their SD and can therefore take the correct measures when adjusting the aircraft's position.
- *Type III - Incapacitating SD*: When the pilot is aware of their SD, however lacks the capacity to react. Both physical and psychological reasons may cause this 'blockage'.

Somatogravic Illusion

The somatogravic illusion (SGI) is the name given to the false sensation of body tilt that results from perceiving the direction of a non-vertical gravito-inertial force, such as the specific force vector in Eq. 1, as being vertical. This is depicted in Figure 1 [19].

The specific force is defined as the sum of motion acceleration and gravitational acceleration as given in equation 1:

$$\vec{f} = \vec{a} + \vec{g} \qquad [m/s^s] \tag{1}$$

In Figure 1-a, the actual forces present when upright and accelerating forward are presented: in red the inertial force, in green the gravitational force and in blue the resultant gravito-inertial force. In Figure 1-b the SD situation is depicted where the gravito-inertial force is falsely sensed as the gravitational force resulting in the perception of a 'pitch up' cue or up- and backwards oriented rotation.

In other words, when a constant acceleration occurs, the brain falsely translates the received information of hair-cells being bent, as a head tilt. Whereas a forward acceleration without rotational cues, while the head is kept upright, can also bend hair cells. The constant acceleration force is misperceived as a forward rotation of the gravity vector, leading to a pilots sensation of 'pitching up'. This may cause a pilot to make unintended nose-down inputs, further increasing forward acceleration, which continues or aggravates the illusion.

The human vestibular system evolved in order to cope with everyday scenarios in the natural human environment. It is based on bipedal locomotion, thus motion cues that are not self-generated such as pilots experience in aircraft, push the vestibular system beyond the limits of motion and attitude it was originally intended to handle [9].

This sensation where the specific force thus becomes the SV can be so strong and overwhelming that pilots can be deceived, possibly while forgetting to verify this sensation with their attitude indicator and other equipment [15].

B. Potential effects of heave cues

There are three possible reasons why heave cues, such as the aforementioned wind gusts and micro bursts, may lead to false pitch perception. Namely:

1) Pilot experience of pitch and heave
2) Physiology of the vestibular system
3) The rotation of the gravito-inertial force vector

1) Pilot experience of pitch and heave: One reason why a heave cue may lead to a false pitch perception is that the pilots may have learned to couple pitch control inputs with heave sensations due to often having experienced these simultaneously. In normal operations pitch control actions will always coincide with heave sensations. Pitching up from level flight will increase the load factor to a value above one whereas pitching down will decrease below unity. This load factor can be calculated by the Eq. 2, where V represents the aircraft velocity, q the pitch rate and g the gravitational constant.

$$n = \frac{Vq}{g} + 1 \qquad (2)$$

However the pitch acceleration also causes a heave cue, because the pilot is positioned a certain distance (d) in front of the centre of gravity (see Eq. 3). Here a_z represents the vertical acceleration or heave cue and $\dot{q}$ the pitch acceleration.

$$a_z = -\dot{q} * d \qquad (3)$$

When looking at commercial aircraft in its approach phase, the speed can be around 130 kts (66.8 m/s). If the pilot gives an input so that the pitch angle oscillates between $+2.86°$ and $-2.86°$ with a maximum pitch rate of $2°/s$ and a maximum pitch acceleration of $1.4°/s^2$ (see Figure 2), then according to Eqs. 2 and 3 resulting G-forces are presented in Figure 3.

If pitch inputs always lead to heave sensations that are of this magnitude, pilots may have learned to associate heave with pitch. In Figure 4 the heave motion that will lead to the same cues as the pitch motion described above is presented. Thus a heave cue that is not caused by a pitch change, but instead for example by a wind gust or a micro burst, could potentially prompt an incorrect assumption of pitch.

From Figure 3 it can be seen that the component from pitch rate has a larger theoretical effect on the heave cue than the component from pitch acceleration. So for a hypothetical linear relationship: $heave = factorK \times pitch$ would mean that $factorK_q$ from $q > factorK_{\dot{q}}$ from $\dot{q}$. If we were to translate this to a pitch angle then a larger effect of a component on heave, would result in a smaller perceived pitch angle, as the pitch angle could theoretically be obtained by dividing the heave cue by said component: $pitch = \frac{heave}{factorK}$. This would have the outcome that the heave obtained from the pitch acceleration component would theoretically be associated with a larger pitch angle than the heave obtained from the pitch rate component.

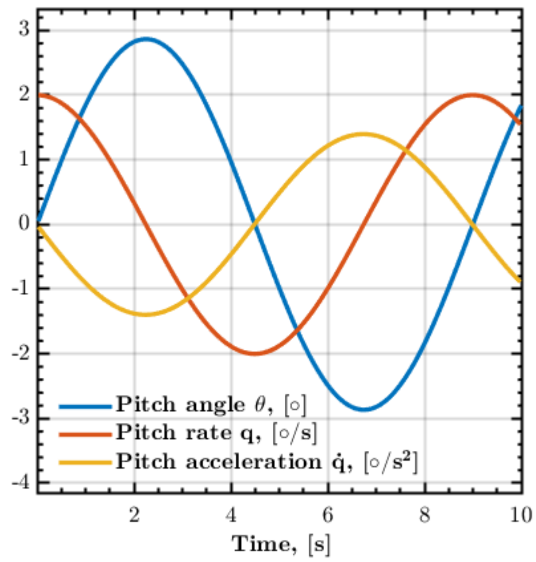


Figure 2: The pitch rate

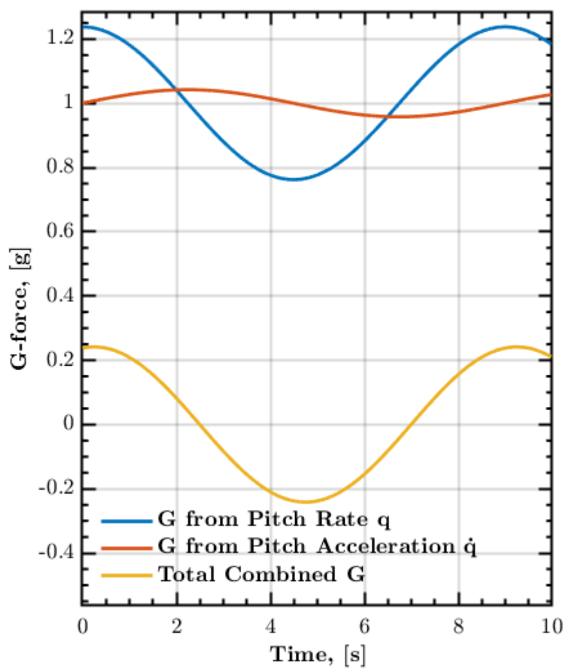


Figure 3: The total G-force obtained from combined pitch rate and pitch acceleration

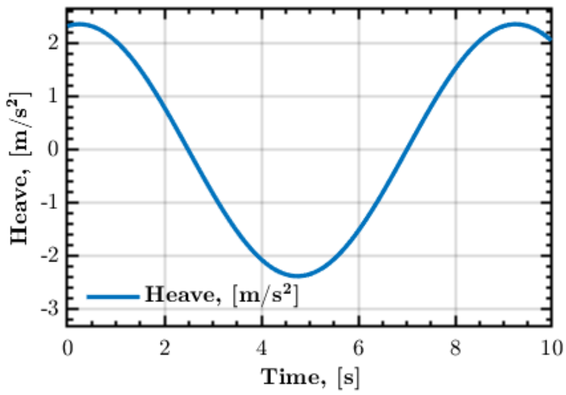


Figure 4: Heave motion that will create the same cues as the pitch inputs (described in text)

2) Physiology of the vestibular system & heave cues: A second potential reason why a heave cue may lead to a false perception of pitch, is that the utricle is tilted with respect to the horizontal. Compared to Reid's Baseline, which describes a line between the bottom of the eye socket and the centre of the ear. The utricle is tilted forward by about 30°, Reid baseline itself is tilted backward by 10° [20]. Thus this tilt with respect to the horizontal will generate a signal of backwards tilt if g-forces increase, because the otolith crystals will shear backwards relative to the organ.

Indeed several studies have shown that G-forces cause a pitch-up sensation. In a study where participants were subjected to five minutes of constant 2g, there was an average pitch up sensation of 21° in non-pilots, 19.8° in fighter pilots and 25.9° in helicopter pilots [21]. In a different experiment non-pilots also experienced on average 22.5° of pitch-up sensation when exposed to five minutes of 2g [22]. However these heave cues are of a very low frequency compared to the heave cues we are interested in. Still if we look at the group means for several time intervals in Figure 2 of [22], it appears that after 15 seconds of g-force presentation the average pitch-up sensation was already 10°.

Although the heave cue indicated a pitch, there was no corresponding signal from the semicircular canals, which means that if interpreted as pitch, this pitch would have to be very slow (i.e., sub-threshold). It is interesting that in the condition where the 2g plateau was preceded by a pitch up motion (centrifugal condition) the average pitch illusion during the first 30 seconds was already 16° instead of 10°.

Concluding, these studies show that a low frequency heave cue induces a pitch perception. But for this to work at a higher frequency, it is likely necessary to induce a signal from the SCC as well.

3) Increased rotation of the gravito-inertial force vector: The third reason why a heave cue may lead to a false pitch perception is due to the rotation of the gravito-inertial force vector. The Otolith organ perceives linear accelerations by sensing the specific force given in Eq. 1. A heave cue directed downward during the forward acceleration, would partly negate the component of gravity, resulting in an even further backward tilted resultant force vector. In this study an increased perception of pitch angle is of interest and therefore the situation wherein a heave cue directed in the opposite, upward direction is studied.

C. Spatial orientation modelling and the possible integration of heave motion from wind gusts and micro bursts

To better predict spatial disorientation and motion sickness, spatial orientation models (SOM) were developed which integrate motion cues with the vestibular system's internal model's expectations. A model was developed by Bos and Bles in 1998 and aimed to study and quantify motion sickness. The SOM's sensory information stems from combined inputs acquired from the eyes, the vestibular system and nonvestibular proprioceptors, its output is a sensed vertical in the form of a vector indicating the magnitude and direction of gravity.

The internal model that is mentioned, is the humans ability to predict self motion in the form of a subjective vertical and therefore its output is an estimation of the gravity vectors magnitude and direction based on previous experience [23]. This model was further developed [24] [25] [26].

The model is situated in the head reference system, where the x-axis is aligned with the nasooccipital axis, the y-axis is aligned with the inter-aural axis, and the z-axis is orthogonal to the latter two.

The first building block of the model 'OTO' in Figure 5, is the specific force as seen in Eq. 1 that the otoliths are sensitive to. Inertial acceleration and gravity are taken as the summation inputs for the resultant force f which is then fed into the simulated otolith organ, its transfer function is a unit matrix. [26] The next block 'SCC' in Figure 5) are simulated semi circular canals, their input is angular velocity and their transfer function is as noted in Eq. 4 [27].

$$\omega_s^i = \frac{\tau_d \tau_a s^2}{(\tau_d s + 1)(\tau_a s + 1)} \omega^i, (i = x, y, z) \tag{4}$$

(with τ_a and τ_d as time constants)

The subjective vertical is then defined from both the otolith and semi circular canal outputs as in Eq. 5

$$\frac{dv_s}{dt} = \frac{1}{\tau}(f - v_s) - \omega_s \times v_s \tag{5}$$

Here $\tau = 5s$ and is noted as LP in the model in Figure 5 [28].

The estimation for inertial acceleration, sensed vertical and angular velocity are then used as an input for the internal model together with two gains $K_a = 0.1$ and $K_\omega = 0.8$. The internal model further consists of identical otolith and semicircular canal building blocks as the vestibular system. A potential error in inertial acceleration, sensed vertical and angular velocity is handled by integration and then reintroduced as feedback with gains $K_{ac} = 1.0$, $K_{vc} = 5.0$ and $K_{\omega c} = 10.0$, respectively [29].

The difference between the modelled vestibular systems sensed vertical and the internal models estimated vertical is then found and implemented on the final outcome values of these three factors. The Hill function and Motion Sickness

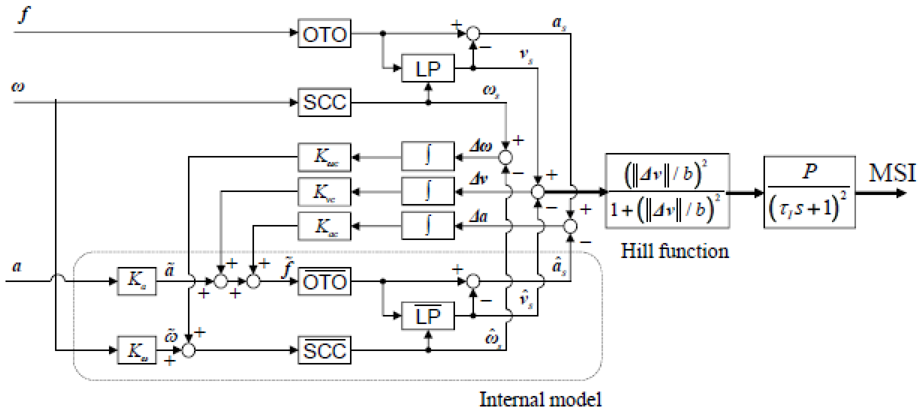


Figure 5: 6-DOF-SVC model of motion sickness incidence [26], revised from [30]

Incidence, as can be seen in the model, are not of interest for this study and will therefore not be further elaborated on.

During the analyses of SD accidents it has repeatedly come forward that many of them occur during unfavorable weather circumstances where wind gusts may have occurred. Such wind gusts can form a heave cue for the vestibular system and may have a profound effect on pilot perception. Interestingly in Atlas Air flight 3591 there was also a heave cue present before elevator inputs were initiated. If we calculate what pitch changes could correspond with such a heave cue, there could be an illusion of 5° pitch up angle, calculated as discussed in Section III-G. However the introduced SOM does not always predict the perceptual illusion, specifically in the case of the Atlas Air accident a pitch-up illusion was suspected, but this could not be found when applying the SOM. While the SOM integrates heave cues, because acceleration is a model input, no relationship is defined for the coupling of vertical acceleration to the perception of pitch. SOM's predict the greatest sudden pitch up illusion during a GA only after the pilot pitches down, this is due to the decrease in the gravitational component which then occurs. A trigger must have been present to coax this reaction from the pilot, it can be suspected that such a pilot pitch input may have been a correction on a (heave) cue. Therefore defining and integrating this relationship into SOM could improve the understanding of SD in pitch perception such as the SGI.

III. Method

An experiment was performed in which pitch and heave motion cues were independently manipulated, with the aim of investigating whether heave motion cues can indeed contribute to the pilot's perception of a pitch angle.

A. Participants

The experiment was performed by a total of 20 professional airline pilots who had flown within the last month. The pilots were all familiar with flying medium- to large-sized aircraft with their most common current flown types being Airbus and Boeing (A320, A321, A330, B737, B747, B777, B787). More information about the pilots and their experience can be found in Table I and II. The participants were recruited on voluntary basis from the researchers' own networks and from the The Royal Netherlands Aerospace Centre (NLR) pilot volunteer database. This experiment was assessed and approved by the TU Delft Human Research Ethics Committee (HREC). Before the experiment the participants were both verbally and in writing informed of their rights and each participant signed an informed consent form.

Table I: Participant information: gender and rank

	No.	%
Gender, female	2	10
Gender, male	18	90
Rank, captain	10	50
Rank, first officer	6	30
Rank, second officer	4	20
Flight instructor	8	40

Table II: Participant information: flight hours, years employed and age

	Mean	SD
Flight hours (hrs)	8809	5697
Years employed (yrs)	21.2	11.4
Age (yrs)	42.5	10.8

B. Apparatus

The experiment was conducted in the SIMONA Research Simulator (SRS) at the faculty of Aerospace Engineering of the Delft University of Technology. The simulator functions using a hydraulic hexapod motion system, with which it attains six-degrees-of-freedom full-motion simulation. The participants were seated in the right hand seat of the cockpit, all displays, the outside visuals and controls were turned off. The primary flight display was used to present information to the participants (see, Section III-E). Motion signals were directly sent to the motion system without the use of an aircraft model. Participants wore headphones on which white noise was played during the motions. Communication between the participants and researchers was realised by providing the participants with headphones. In Figures 6 and 7 the SRS and the experimental set-up within the simulator can be seen.

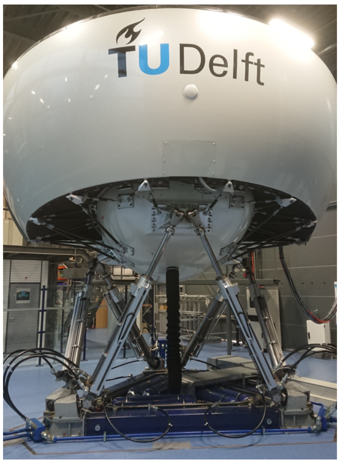


Figure 6: Simona Research Simulator (SRS)

Figure 7: Experimental set-up within the SRS

C. Motion profiles

Motion signals were developed for the pitch attitude and vertical acceleration (heave), all motion in the other axes (x,y) and angles (roll, yaw) was kept zero. When designing the motion profiles, a main focus was providing pitch motion which is similar to what can be expected during a pitch up and level-off maneuver in an aircraft. A pilot experiment gave the opportunity to test various conditions and select heave motions which blended well into the pitch maneuver.

A 7^{th} order smooth step function was chosen as a basis for both these motions, as its derivative and double derivative are zero at the start and end of the movement, ensuring a smooth motion. The signals were then mirrored and shifted in order to design an identical level-off maneuver after the peak value had been reached. Essentially, the simulator was moved up when pitching up, and it was moved down again when pitching down back to level. These equations, before mirroring and shifting, can be seen in Eqs. 6 and 7.

Pitch motion signals (pitch up section):

$$\begin{aligned} \theta &= h_0(-20h^7 + 70h^6 - 84h^5 + 35h^4) \\ q &= h_0(-140h^6 + 420h^5 - 420h^4 + 140h^3)\left(\frac{1}{h_2 - h_1}\right) \\ \dot{q} &= h_0(-840h^5 + 2100h^4 - 1680h^3 + 420h^2)\left(\frac{1}{h_2 - h_1}\right)^2 \end{aligned} \tag{6}$$

With h, h_0, h_1, h_2 factors chosen according to the desired motion characteristics and simulator requirements.

Heave motion signals (heave up section):

$$\begin{aligned} z &= k_0(-20k^7 + 70k^6 - 84k^5 + 35k^4) \\ v_z &= k_0(-140k^6 + 420k^5 - 420k^4 + 140k^3)\left(\frac{1}{k_2 - k_1}\right) \\ a_z &= k_0(-840k^5 + 2100k^4 - 1680k^3 + 420k^2)\left(\frac{1}{k_2 - k_1}\right)^2 \end{aligned} \tag{7}$$

With k, k_0, k_1, k_2 factors chosen according to the desired motion characteristics and simulator requirements.

The physical limitations in actuator extension (neutral position ±0.55m) and velocity (±0.75m/s) of the hydraulic cylinders of the SRS were used to set up boundaries for the signals. The heave motion was necessarily at a higher frequency than the pitch motion, due to the limitation of the simulator motion space.

The heave motion was also presented at two different magnitudes, or peak values. Studying the effect of a moderate versus a stronger heave motion provided the opportunity to additionally understand the extent to which heave magnitude may contribute to pitch perception. Therefore the strongest possible heave motion was designed within the given limitations and a more moderate heave cue was selected during the pilot experiment, such that it blended in with the pitch motion, but could still be perceived. The motion envelope for the upward heave signal was maximized by prepositioning the simulator 0.5m downwards. The low magnitude heave motion had a peak value of $0.58 m/s^2$ and lasted 1.5s. The high magnitude heave cue had a peak value of $0.84 m/s^2$ and lasted 1.25s. Although a higher magnitude heave motion may have more effect on pitch perception, it is also shorter in duration and therefore more distinguishable from the pitch motion.

The heave motion was presented with two different timings of its peak value. It was timed so that the peak value of heave either coincided with the peak value of the pitch rate q or with the peak value of the pitch acceleration $\dot{q}$. In reality, the maximum of the heave cue would be sensed near the maximum of q (see, 2 and 3). However, by timing it to $\dot{q}$, the start of the higher-frequency heave motion would coincide more with the start of the pitch motion, possibly making the motion feel more natural.

In Figure 8 a motion profile example can be seen of a low magnitude heave motion timed to coincide with the peak value of the pitch rate, with a maximum simulator pitch angle of 10°.

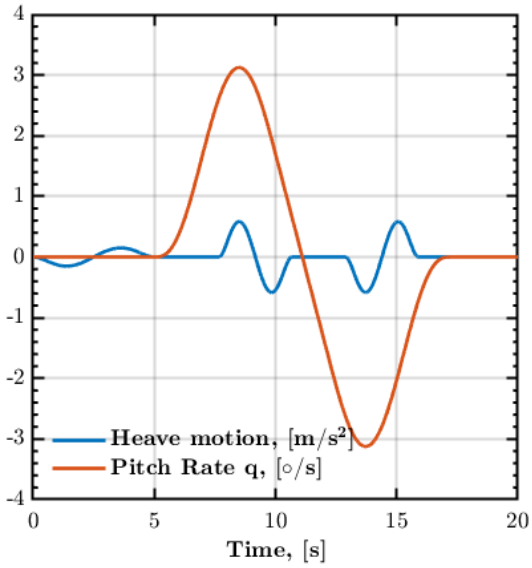


Figure 8: Motion profile example of *Scenario 13* with a maximum pitch angle of 10° and a low magnitude heave of 0.58m/s, timed to coincide with the peak value of the pitch rate.

Table III: Overview of scenarios and their details

Scenario Nr.	Pitch Angle [°]	Heave Magnitude $[m/s^2]$	Heave duration [s]	Timing heave at peak value
1	5	0.58	1.5	$\dot{q}$
2	7.5	0.58	1.5	$\dot{q}$
3	10	0.58	1.5	$\dot{q}$
4	12.5	0.58	1.5	$\dot{q}$
5	15	0.58	1.5	$\dot{q}$
6	5	0.84	1.25	$\dot{q}$
7	7.5	0.84	1.25	$\dot{q}$
8	10	0.84	1.25	$\dot{q}$
9	12.5	0.84	1.25	$\dot{q}$
10	15	0.84	1.25	$\dot{q}$
11	5	0.58	1.5	q
12	7.5	0.58	1.5	q
13	10	0.58	1.5	q
14	12.5	0.58	1.5	q
15	15	0.58	1.5	q
16	5	0.84	1.25	q
17	7.5	0.84	1.25	q
18	10	0.84	1.25	q
19	12.5	0.84	1.25	q
20	15	0.84	1.25	q
21	0	0.58	1.5	
22	0	0.84	1.25	
23	5	0	0	
24	7.5	0	0	
25	10	0	0	
26	12.5	0	0	
27	15	0	0	

In each run, a similar motion profile was presented, with five different maximum simulator pitch angles (i.e., 5° - 15° with 2.5° incremental steps) so that pilots would need to make an estimation of the correct answer. The increment of 2.5° was chosen as this is close to the smallest increment in pitch angle deviation that a human can perceive. Commercial pilots encounter a maximum of 15° during normal flying procedures, therefore this was selected as the experiments maximum pitch angle condition [31]. A dynamic maneuver needed to be developed, because pilots would otherwise directly be able to determine the pitch angle simply from the gravitational force, which would not be the case in real flight. The simulated maneuver is shown in Figure 8. In each run, the maximum pitch rate was $3°/s$, as this is in line with the standard pitch rate procedures. The maneuver was simulated both without added heave motions (baseline) and with added heave motions.

D. Independent Variables

The five maximum pitch angles × two heave magnitudes (low and high) × two heave timings (pitch rate and acceleration) plus five pitch angles without heave cues, led to 25 runs. Two extra runs were added to complete the set of 27 runs: with heave only (low and high magnitude), to test if heave could cause a pitch illusion without any pitch angle being presented. Each run was performed twice throughout the experiment. The order of the runs was counterbalanced using the Latin square method which ensured that each participant had a uniquely randomized order of the runs. In Table III an overview of the experimental conditions for each scenario, as obtained during the motion profile design phase, is presented.

E. Procedure

The effect of heave cues on pilot pitch perception was experimentally investigated by presenting the pilots with combinations of pitch and heave motion cues in 54 runs that each lasted circa 20 seconds. At the end of each run, the pilots indicated their perceived maximum pitch angle by verbally selecting one of the eight letter-labeled attitude indicators that were shown on the primary flight display (see, Figure 9). These were presented in one image, in two rows of four, with increasing pitch angles ordered from left to right, ranging between $0° - 17.5°$ and with 2.5° incremental steps.

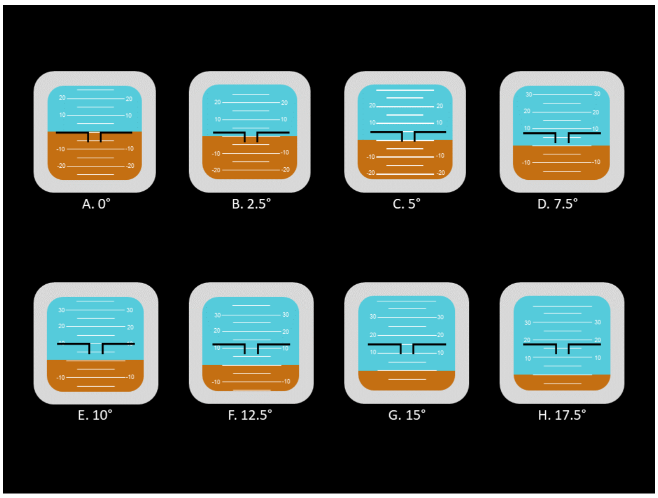


Figure 9: The attitude indicators as provided on the primary flight display for pilots to choose from

The pilots were briefed at the start about these tasks, and were shown an image of the maneuver being simulated (see, Figure 10). They were not informed about the motion cueing to ensure that the results would be unbiased. Pilots were instructed to envision they were flying on auto-throttle in a twin-jet like a B737 between 5000 and 10000ft. They were also instructed to position their head during the runs as if they were looking at the primary flight display.

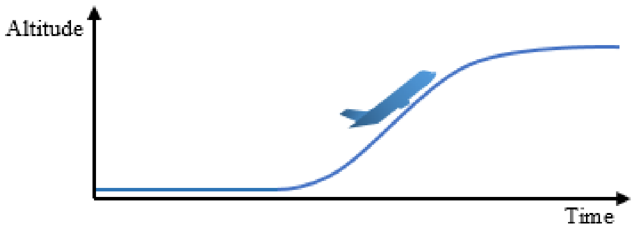


Figure 10: Depiction of the pitch up and level off movement as provided to the participants prior to the experiment in the briefing

The runs were presented in two sets of 27, with a 15-minute break in between the sets, and the opportunity for a short break between runs if the participant requested it. At the start of the first set, pilots performed five practice runs, and at the start of the second set one practice run. These were not included in the analysis.

F. Dependent Measures

The mean of each pair of two runs with the same parameters was obtained before further analysis to reduce variance in the results. The pitch perception relative to the presented simulator angle was obtained to test the effect of adding heave to different simulator angles on pitch perception. The simulator angle was subtracted from the reported perceived pitch, in order to obtain the difference between perceived- and actual angle. The consistency in answers between two runs with the same parameters is also reported, but this was not statistically analysed.

G. Hypotheses

It is hypothesized that the addition of an upward-directed heave motion to a positive pitch motion will increase a pilots estimation of a maximum pitch angle. This is based on the reasons outlined in .

A larger heave motion is in parallel also expected to result in a larger estimation of a pitch angle relative to a smaller heave motion. The larger heave motion would approach the actual heave sensation for the pitch maneuver in reality more.

Further, it is also expected that the timing of the heave motion where its peak value coincides with the moment $\dot{q}$ reaches its peak value, will result in a larger estimation relative to the heave motion timed to coincide with the peak value of q. The largest heave sensation would coincide more with the $\dot{q}$ of the maneuver in reality as described in Section III-G.

H. Statistical analysis

The analysis consisted of two parts:

Effect of Heave Motion on Pitch Perception:
To test whether heave motion increased pitch perception, a 2x5 repeated-measures ANOVA was used with the within-subject factors of heave motion (added heave or no added heave) and maximum simulator angle ($5°$, $7.5°$, $10°$, $12.5°$, $15°$), and pitch perception relative to simulator angle as the dependent variable. For this analysis, the pitch perception of different added heave intensities and timings were averaged into one condition of "added heave".

Effect of Heave Magnitude & Heave Timing:
To test whether heave magnitude and heave timing affected pitch perception, a 2x2x5 repeated-measures ANOVA was used with the within-subject variables of heave magnitude (low, high), heave timing (q, $\dot{q}$), and maximum simulator angle ($5°$, $7.5°$, $10°$, $12.5°$, $15°$), and relative pitch perception to simulator angle as the dependent variable.

Significant main or interaction effects were followed-up with post-hoc tests with Bonferroni correction. Mauchly's test of sphericity was used to check sphericity of the data, and a Greenhouse-Geisser adjustment was applied if the data did not meet the Mauchly criteria of sphericity.

IV. Results

A. General performance of the pilots

The raw data of the pitch angle estimations can be found in the appendix in Table VII. Individually most pilots performed well, as there was a tendency to only slightly underestimate the pitch angle with an average error of only $-0.55°$, *SD* $1.87°$. However, the difference between perceived pitch in two identical runs with the same parameters was on average $1.75°$, *SD* $0.43°$.

B. Effect of heave on perceived pitch

The 2×5 (heave $\times$ simulator angle) repeated-measures ANOVA revealed a significant main effect of adding heave, $F(1{,}19) = 33.44$, $p < 0.001$ and a significant main effect of simulator angle, $F(1.91{,}36.23) = 3.76$, $p = 0.039$. There was no significant interaction effect $p = 0.158$, so the effect of heave was independent from the presented simulator angle. The main effect of added heave showed that the pitch perception with heave was on average $1.88°$ higher than without added heave, *SD* 1.46. The pitch perception increased on average from $2.31°$ below the actual simulator pitch angle to $0.43°$ below the actual simulator pitch angle. For the simulator angle the post-hoc comparisons showed that there was only a significant difference between $15°$, mean = $-2.06°$, *SD* = 2.50, and $10°$, mean = $-1.06°$, *SD* = 2.01, $\delta = 1.00°$, $p = 0.002$.

All mean pitch angle differences relative to the simulator angle, both with and without added heave motion are shown in Table IV and in Figure 11. The Figure illustrates that larger angles are increasingly underestimated.

Table IV: Mean difference between the perceived pitch angle and the simulator angle, without and with heave conditions compared.

simulator angle	Mean (*SD*) without heave		with heave	
0°			2.66	(2.41)
5°	-2.06	(1.36)	0.30	(2.03)
7.5°	-2.44	(1.74)	-0.11	(2.16)
10°	-2.00	(2.20)	-0.11	(2.29)
12.5°	-2.38	(2.59)	-0.80	(2.18)
15°	-2.69	(3.12)	-1.42	(2.33)

Interestingly, the 'heave-only' motion without pitch motion also led to a mean perceived pitch of 2.66°, *SD* = 2.41. For the high magnitude heave motion the mean perceived pitch angle was slightly higher, mean = 2.81°, *SD* = 2.36, than for the low magnitude heave motion, mean = 2.50°, *SD* = 2.50.

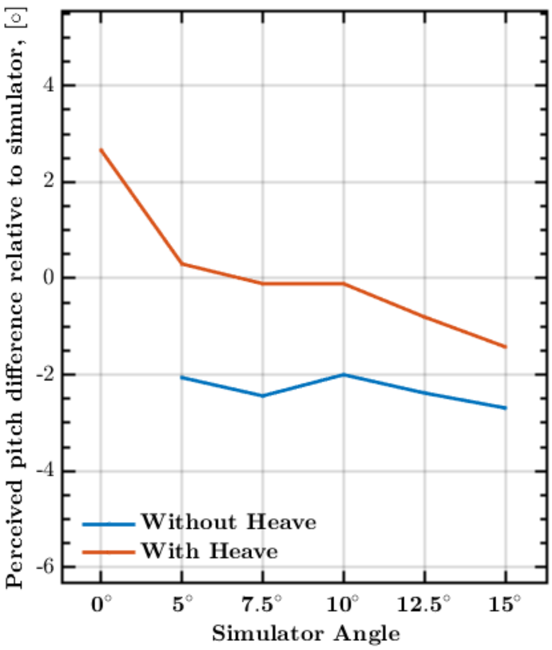


Figure 11: Mean difference between the perceived pitch angle and the simulator angle, without and with heave conditions compared.

C. Effect of heave timing and heave magnitude on perceived pitch

The 2×2×5 (timing, magnitude, simulator angle) repeated-measures ANOVA revealed a significant main effect of heave magnitude, $F(1,19)$ = 7.62, p = 0.012, a nearly significant main effect of heave timing, $F(1,19)$ = 3.87, p = 0.064, no significant main effect of simulator angle, p = 0.242, and no significant interaction effects and p's > 0.286.

The high-magnitude heave resulted in a perceived pitch mean = $-0.194°$ relative to the simulator angle, *SD* 2.13, that was higher than the low-magnitude heave, mean = $-0.663°$, *SD* 2.00, δ = 0.47°, p = 0.009. In Figure 12 it can be seen that for all simulator angles the higher magnitude heave led to a larger perceived pitch. For the lower angles (i.e., $< 12.5°$), this even led to an overestimation of the actual simulator pitch angle. At 15°, the difference between magnitudes seems to dissipate, although there was no significant magnitude×simulator angle interaction effect.

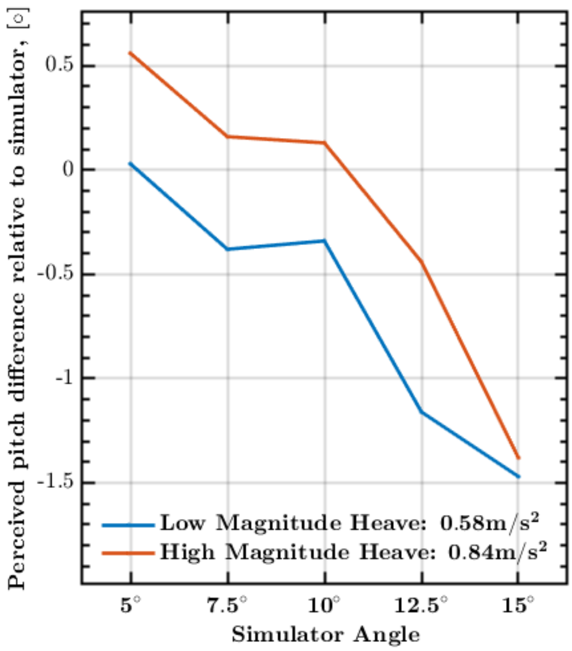


Figure 12: Mean difference between the perceived pitch angle and the simulator angle, two magnitudes of heave compared.

The marginal significant main effect of heave timing suggested that the timing of the peak of heave at $\dot{q}$ resulted in a higher perceived pitch, mean = $-0.21°$ relative to the simulator angle, *SD* = 2.21 than the timing of the peak of heave at q, mean = $-0.644°$, *SD* = 1.98, δ = 0.43°, p = 0.069. The heave cue appeared most effective when it was triggered at the beginning of the pitch motion. In Figure 13 it can be observed that this effect, like the effect of heave magnitude, was highest for the lower simulator pitch angles.

In Figure 14 and Table V an overview of the results in mean differences between the perceived pitch angle and the simulator angle per type of heave motion is summarised.

Table V: Mean difference between the perceived pitch angle and the simulator angle per type of heave motion.

simulator angle	without heave		$\dot{q}$ low		$\dot{q}$ high		q low		q high	
	Mean (*SD*)									
5°	-2.06	(1.36)	0.56	(2.55)	1.00	(2.80)	-0.50	(1.92)	0.13	(1.85)
7.5°	-2.44	(1.74)	0.00	(2.63)	0.25	(2.62)	-0.75	(2.12)	0.06	(2.52)
10°	-2.00	(2.20)	-0.25	(2.45)	0.31	(2.69)	-0.44	(2.61)	-0.06	(2.61)
12.5°	-2.38	(2.59)	-1.00	(2.49)	-0.63	(2.31)	-1.31	(2.76)	-0.25	(2.49)
15°	-2.69	(3.12)	-1.38	(2.75)	-1.00	(2.62)	-1.56	(2.66)	-1.75	(2.55)

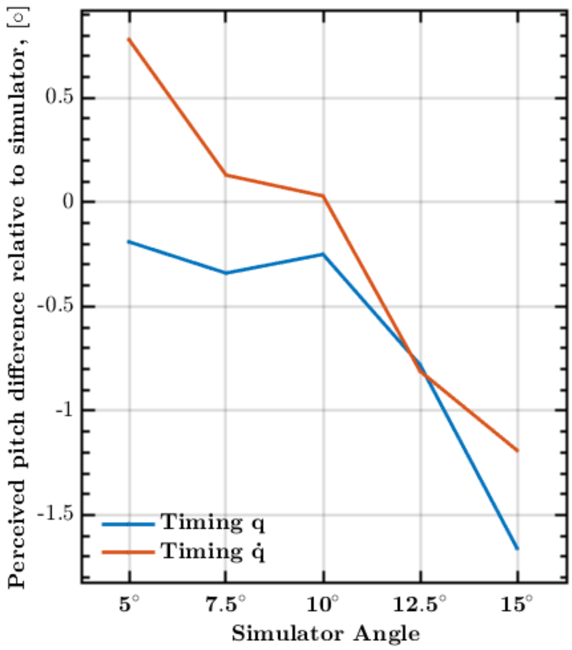


Figure 13: Mean difference between the perceived pitch angle and the simulator angle, two heave motion timing conditions, at q and $\dot{q}$, compared.

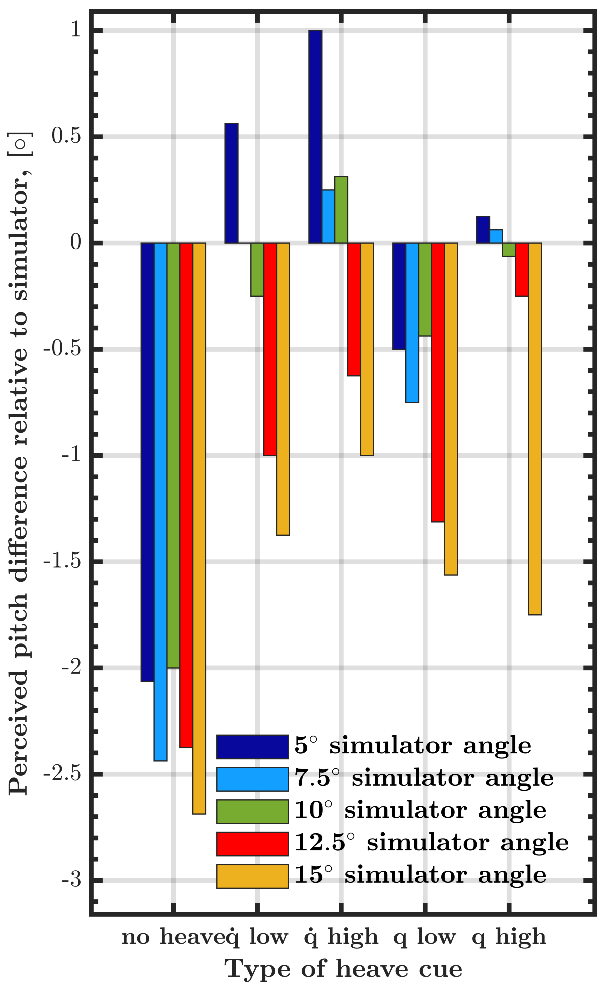


Figure 14: Mean difference between the perceived pitch angle and the simulator angle per type of heave motion.
(Please note that the mean value for a 7.5° simulator angle of type $\dot{q}$ low is zero and therefore absent in the figure.)

V. DISCUSSION

In this study the aim was to gain a better understanding of possible triggers of SD in pilot pitch perception such as the SGI, by investigating the effect of high-frequency heave motion combined with pitch motion on pilot pitch perception. An experiment was executed in which pilots underwent hexapod simulator runs in which they were exposed to independently manipulated heave and pitch motions. After each run the participating pilots were required to verbally report their maximum perceived pitch angle. In total 20 pilots underwent 2 runs each of all 27 different motion conditions, each in a unique order. The data were analyzed to assess the effect of the addition of a heave motion of different magnitudes and timings to a pitch motion such that this information may be used in future adaptation SOM and in the analyses of accidents and incidents where SD such as the SGI is suspected to have been a causal factor.

Based on experiment results it can be confirmed that the addition of an upward-directed heave motion to a positive pitch motion increases a pilots estimation of a maximum pitch angle. Such a heave motion may be caused due to a wind gust or micro burst. A reason for the increase in pitch perception may be pilot experience, wherein pitch control inputs are coupled with heave sensations, as they always coincide during normal operations (as explained in Section III-G). The physiology of the vestibular system, may also have contributed, as the tilt of the utricle can create a signal of backwards tilt if g-forces, as may be caused by a heave cue. It can also be reasoned that the specific force is rotated when a heave cue occurs, which in its turn can cause an increased pitch perception.

A finding is that pilots at average underestimate pitch angles relative to the actual simulator angle. The addition of a high frequency heave motion leads to an estimation which is, while still too low, nearer to the actual angle than when the participants are subjected to a sole pitch cue. Further the results show that larger simulator angles are increasingly underestimated. Hexapod simulation can not fully replicate all the aspects of an actual flight. During an actual flight changes in attitude and vertical velocity would naturally be accompanied by a G-force. Therefore pilots will sense the absence of G-forces and jerk that they would normally feel in a regular flight. One participant described that the absence of G-force was especially strong in larger angles and gave an unnatural feeling. Thus it is probable that pitch angles are systematically down scaled by the pilots in the SRS as a result of the absence of actual in-flight G-forces. The absence of motion in the x-axis, which would normally accompany an in-flight change in pitch attitude, is also a factor which may have contributed to decreasing the general perception of pitch attitude. Another possible explanation for the underestimation of the pitch attitude could be the Aubert effect, which states that when tilted on a side the participants estimation of verticality or their idiotropic vector is tilted toward the body tilt [32].

During debriefing many pilots also stated that in commercial flight a pitch angle of 15° is already at the maximum of the range of pitch angles that they experience, usually during take-off, leading them to perhaps 'downgrade' their perception. So if pilots really imagined themselves to be flying auto-throttle during level changes after a takeoff at about 5000 to 10000ft as stated in the experiment briefing, larger pitch motions could be found to be extreme for the described situation and the expectation of pilots would be more subtle pitch angles, leading them to report a lower angle in line with their knowledge of the situation.

An additional finding was that a 'heave only' motion still lead to an average of 2.7° perceived pitch, this could also stem from strong coupled heave-pitch perceptions from experience. The motion cueing may also be a causal factor, as it is possible that the cue from the onset of the heave motion in the simulator could be mistaken for a pitch cue by the pilots.

The hypothesis which expected a larger magnitude heave motion to result in a larger over-estimation of a pitch angle relative to a smaller heave motion can also be confirmed. However the effect was larger for the smaller angles. A possible explanation is, that for 15° there might be a possible edge or 'roof' effect, as there was only one simulator angle (of 17.5°) option above 15° made available for the participants to choose from.

The hypothesis regarding the timing of the heave motion, which stated that a heave cue coinciding with the timing of the peak value of $\dot{q}$ would result in a larger estimation relative to the heave motion timed to coincide with the peak value of $\dot{q}$ can prudently be confirmed. A marginally significant result was found, where the heave motion timed at $\dot{q}$ resulted in a higher pitch perception than the heave motion times at q. It could be reasoned that timing a heave motion with $\dot{q}$ means it coincides closer to the beginning of the pitch movement. Figure 15 provides a purely theoretical image, because heave cues accompanying pitch changes will always originate from the combination of two factors originating from q and $\dot{q}$, thus can not realistically be depicted as two separate entities. However Figure 15 can be used to illustrate the theoretical contribution of each individual factor to pitch perception, while keeping in mind that these entities actually simultaneously provide only one total pitch angle. In Figure 15 it can be seen that the induced theoretical pitch angles are instigated earlier on in the pitch movement for the heave motion timed at $\dot{q}$ relative to q. This could lead to a crossover of the perception to the semi circular canals, with a stronger perceived pitch angle as a result. From the same Figure 15, it can also be seen that the heave motion timed at $\dot{q}$ has a slightly prolonged period over which additional induced theoretical pitch angles act aside the actual pitch angle. This longer duration of additional perceived pitch angles could amount to an increased perception of pitch.

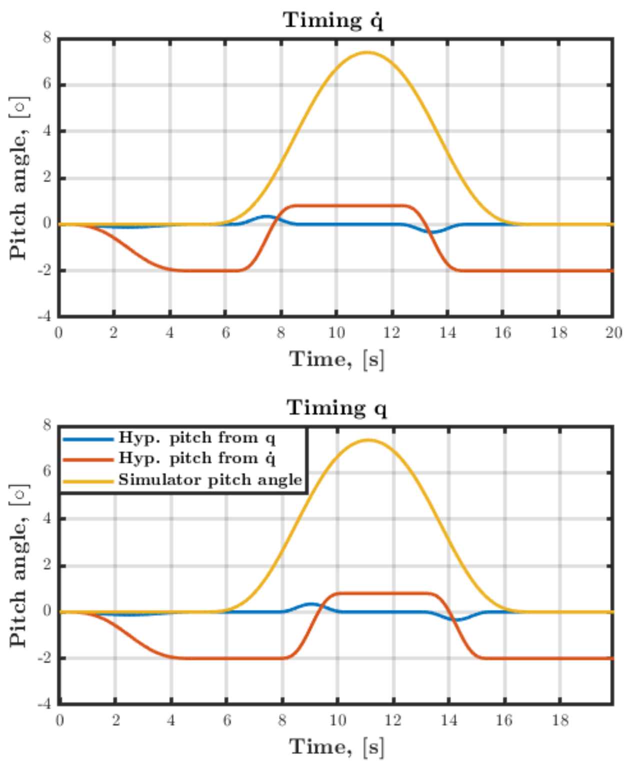


Figure 15: Overview of calculated hypothetical pitch angles from q, and from $\dot{q}$ as discussed in Section III-G. In the Figure the first 5 seconds consist of a a sub threshold prepositioning of the simulator after that the pitch and heave motions are introduced.

The main limitations of the designed experiment were the lack of g-forces and motion in the x-axis to accompany pitch and heave changes. This decreases the realism of the setting for pilots, as they are accustomed to such sensations being present from in-flight experience. The pilots only had eight angles to choose from, this meant that while there were two steps of $2.5°$ below the smallest angle of $5°$ for them to choose from, there was only one step available above the largest angle of $15°$. The headphones which the pilots wore and through which white noise was played were not fully sound proof. This was mentioned a few times during the participant debriefing and means that the pilots may to a certain extent have been able to hear the motion system of the simulator, which may have influenced their reported angles. Subsequently pilots may also have been able to sense the onset of motion. The last shortcoming may possibly have been the orientation of the pilots heads. The pilots were asked to position their head during as if they were looking at the primary flight display, however they may have moved their heads. Some studies which investigate vestibular responses, secure the participants head, as to prevent possible confounds from the idiotropic vector.

It could be interesting to perform the exact same study with regular participants which are not pilots, in order to have a reference case to compare results with. This could confirm whether the found tendencies in pitch perception are indeed coupled to a pilots associated cues learned from experience flying aircraft, or whether these cues are present in all humans and have a physiological underlying reason. An additional variation could also made with regular participants using the same motion while telling the participants to imagine the simulator is tilting. Perhaps the participants envisioned scenario situation has an influence on their estimation of the pitch angle.

Another adaptation could be made by reproducing a similar experiment around another axis. If the same increasing effects of heave on pitch perception are found for a surge movement on the yaw perception or of a sway movement on the roll perception, the findings can be detached from a pilots learned association between certain movements.

Performing a similar experiment with an alternative motion where there is a pitch down with a heave down followed by an identical motion up, a level off with a heave up, could be interesting. It could provide information as to whether the same, pitch perception increasing, effect can be seen with a pitch down maneuver.

The investigation of the relationship in between the different forms of coupled pitch control input with heave sensations would allow to better understand the extent to which the pitch angle, originating from the load factor and from the distance to the centre of gravity, respectively influence the perception of the actual pitch angle.

A further suggestion is the adaptation of the motion to include a longer lasting heave motion using a simulator with a larger range of motion. Extreme forms of wind gusts can last up to 20s [33]. Thus extending the duration of the applied heave motion could provide the opportunity to investigate whether an extreme form of wind gust also has the same increasing effect on pilot pitch perception or whether it is more easily distinguishable from a pitch angle as its longer duration may not allow it to 'blend' in with a pitch motion.

Current perceptual models do not integrate the presence of heave cues. The findings in this study suggest that there is reason to investigate how heave motion can be integrated into existing SOM. An updated SOM could then be applied to further understand the occurrence of the specific form of SD, the SGI, as it was found that turbulent weather with wind gusts (i.e. heave motion) was often present right before the on set of the illusion. Finally these findings could be used to improve pilot awareness and training.

VI. Conclusion

A hexapod simulator experiment was performed to test whether a heave cue contributes to the perceived pitch angle in pilots. Heave and pitch cues were independently manipulated. Two intensities and timings of the heave cue were tested to obtain more insight into the relation between heave cues and pitch perception. It was found that a heave motion, as may be induced during a flight by a wind gust or burst, increases pitch angle perception under pilots. The resultant pitch angle overestimation may be a trigger for SD and specifically the SGI. The combination of pitch angles with larger magnitude heave motions, will result in a larger discrepancy between the pilots perceived pitch angle and the actual pitch angle. Timing the heave motions peak value to coincide with the peak of pitch acceleration $\dot{q}$ can trigger a larger overestimation of the pitch angle than timing it with the peak of pitch rate q. The results can be used for improving perceptual models, and to improve hexapod-based simulation of the SGI for research and training purposes.

References

[1] Airbus, "Statistical analysis of commercial aviation accidents 1958-2016," 2017.

[2] R. Amalberti, "The paradoxes of almost totally safe transportation systems," *Safety science*, vol. 37, no. 2-3, pp. 109–126, 2001.

[3] L. Bainbridge, "Ironies of automation," in *Analysis, design and evaluation of man–machine systems*. Elsevier, 1983, pp. 129–135.

[4] B. d'enquêtes et d'Analyses pour la sécurité de l'aviation civile, "Study on aeroplane state awareness during go-around," BEA, Le Bourget, France, Report 1, 2013.

[5] S. Ludlow, "Reducing the threat of the somatogravic illusion," *Flight Safety Foundation International Air Safety Summit (IASS)*, 2016.

[6] R. J. Mumaw, E. Groen, L. Fucke, R. Anderson, J. Bos, and M. Houben, "A new tool for analyzing the potential influence of vestibular illusions," in *ISASI Forum*, vol. 49, no. 1, 2016, pp. 6–12.

[7] "Notice of proposed amendment 2017-06, loss of control or loss of flight path during go-around or other flight phases," European Aviation Safety Agency, Report RMT.0647, 2017-06.

[8] D. H. Klyde, A. K. Lampton, and P. C. Schulze, "Development of spatial disorientation demonstration scenarios for commercial pilot training," in *AIAA Modeling and Simulation Technologies Conference*, 2016, p. 1180.

[9] ——, "Evaluation of a steep turn spatial disorientation demonstration scenario for commercial pilot training," *AIAA Modeling and Simulation Technologies Conference*, p. 1079, 2017.

[10] G. Clément, S. T. Moore, T. Raphan, and B. Cohen, "Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight," *Experimental Brain Research*, vol. 138, no. 4, pp. 410–418, 2001.

[11] B. J. Correia Grácio, K. N. De Winkel, E. L. Groen, M. Wentink, and J. E. Bos, "The time constant of the somatogravic illusion," *Experimental Brain Research*, vol. 224, no. 3, pp. 313–321, 2013.

[12] A. H. Rupert, B. McGrath, and F. Guedry, "Tgulf air flight gf-072 perceptual study," Naval Aerospace Medical Research Laboratory, 280 Fred Bauer St. Building 1811 Pensacola, FL 32508-1046 United States, Report Appendix E, 2000.

[13] "Afriqiyah airways flight 771," https://aviation-safety.net/database/record.php?id=20100512-0, accessed: 2020.11.30.

[14] T. B. C. Robert J. McIntosh, Director Product Safety, "Boeing submission to the national transportation safety board for atlas air 767-300bcf n1217a accident trinity bay, tx,23 february 2019," *NTSB*, vol. 1, no. DCA19MA086, February 07,2020.

[15] F. H. Previc and W. R. Ercoline, *Spatial disorientation in aviation*. American Institute of Aeronautics and Astronautic, 2004, vol. 203.

[16] J. Bos and W. Bles, "Modelling motion sickness and subjective vertical mismatch detailed for vertical motions," *Brain Research Bulletin*, vol. 47, no. 5, pp. 537–542, 1998.

[17] C. Lessard, R. Matthews, and D. Yauch, "Effects of rotation on somatogravic illusions," *IEEE Engineering in Medicine and Biology Magazine*, vol. 19, no. 2, pp. 59–65, 2000.

[18] T. J. Lyons, W. Ercoline, K. O'Toole, and K. Grayson, "Aircraft and related factors in crashes involving spatial disorientation: 15 years of us air force data," *Aviation, space, and environmental medicine*, vol. 77, no. 7, pp. 720–723, 2006.

[19] P. R. MacNeilage, M. S. Banks, D. R. Berger, and H. H. Bülthoff, "A Bayesian model of the disambiguation of gravitoinertial force by visual cues," *Experimental Brain Research*, vol. 179, no. 2, pp. 263–290, 2007.

[20] J. Corvera, C. Hallpike, and E. Schuster, "A new method for the anatomical reconstruction of the human macular planes," *Acta oto-laryngologica*, vol. 49, no. 1, pp. 4–16, 1958.

[21] A. Tribukait and O. Eiken, "Flight experience and the perception of pitch angular displacements in a gondola centrifuge," *Aviation Space and Environmental Medicine*, vol. 83, no. 5, pp. 496–503, 2012.

[22] A. Arne Tribukait and O. Eiken, "Semicircular canal influence on the visually perceived eye level during gondola centrifugation," *Aviation Space and Environmental Medicine*, vol. 77, no. 5, pp. 500–508, 2006.

[23] N. Kamiji, Y. Kurata, T. Wada, and S. Doi, "Modeling and validation of carsickness mechanism," *Proceedings of the SICE Annual Conference*, pp. 1138–1143, 2007.

[24] T. Wada, S. Fujisawa, K. Imaizumi, N. Kamiji, and S. Doi, "Effect of driver's head tilt strategy on motion sickness incidence," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 11, no. PART 1, 2010.

[25] T. Uefune, T. Wada, and K. Sonoda, "Computation of the Vestibulo-Ocular Reflex for eye closure based on the 6DOF-SVC model," *2016 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2016 - Conference Proceedings*, no. October, pp. 1285–1290, 2017.

[26] T. Wada, S. Fujisawa, and S. Doi, "Analysis of driver's head tilt using a mathematical model of motion sickness," *International Journal of Industrial Ergonomics*, vol. 63, no. January, pp. 89–97, 2018.

[27] D. M. Merfeld, "Modeling the vestibulo-ocular reflex of the squirrel monkey during eccentric rotation and roll tilt," *Experimental Brain Research*, vol. 106, no. 1, pp. 123–134, 1995.

[28] J. E. Bos and W. Bles, "Theoretical considerations on canal–otolith interaction and an observer model," *Biological cybernetics*, vol. 86, no. 3, pp. 191–207, 2002.

[29] T. Uefune, T. Wada, and K. Sonoda, "Computation of the vestibulo-ocular reflex for eye closure based on the 6dof-svc model," in *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2016, pp. 001 285–001 290.

[30] N. Kamiji, Y. Kurata, T. Wada, and S. Doi, "Modeling and validation of carsickness mechanism," *Proceedings of the SICE Annual Conference*, pp. 1138–1143, 2007.

[31] D. Owens, "The Go Around Procedure," *Safety First - The Airbus Safety Magazine*, vol. 12, no. July, pp. 1–8, 2011.

[32] H. Aubert, "Eine scheinbare bedeutende drehung von objecten bei neigung des kopfes nach rechts oder links," *Archiv für pathologische Anatomie und Physiologie und für klinische Medicin*, vol. 20, no. 3, pp. 381–393, 1861.

[33] P. Cheng and W. Bierbooms, "Extreme gust loading for wind turbines during operation," *J. Sol. Energy Eng.*, vol. 123, no. 4, pp. 356–363, 2001.

VII. RAW DATA

Table VI: Raw Data / Experimental Results: average pitch angle choice for two runs of the same scenario, (the participant order is randomised for privacy reasons)

Scenario Nr.	Simulator Pitch Angle [°]	Pitch Angle Choice [°] Pilot 1	Pilot 2	Pilot 3	Pilot 4	Pilot 5	Pilot 6	Pilot 7	Pilot 8	Pilot 9	Pilot 10
1	5	2.5	10	3.75	10	2.5	3.75	3.75	5	7.5	5
2	7.5	3.75	10	6.25	11.25	6.25	7.5	3.75	5	6.25	10
3	10	6.25	11.25	10	13.75	8.75	10	5	6.25	10	12.5
4	12.5	6.25	12.5	10	13.75	11.25	10	7.5	8.75	11.25	13.75
5	15	8.75	17.5	13.75	16.25	15	12.5	7.5	12.5	11.25	15
6	5	1.25	7.5	3.75	7.5	5	5	2.5	3.75	5	8.75
7	7.5	2.5	11.25	7.5	10	7.5	8.75	3.75	6.25	6.25	12.5
8	10	5	11.25	7.5	12.5	10	10	6.25	8.75	10	13.75
9	12.5	7.5	13.75	11.25	13.75	11.25	11.25	6.25	11.25	10	16.25
10	15	10	16.25	12.5	17.5	15	15	8.75	11.25	12.5	16.25
11	5	1.25	6.25	3.75	6.25	2.5	3.75	2.5	6.25	3.75	8.75
12	7.5	3.75	7.5	6.25	10	7.5	7.5	2.5	6.25	6.25	12.5
13	10	5	12.5	10	15	8.75	6.25	6.25	7.5	8.75	12.5
14	12.5	7.5	16.25	8.75	16.25	11.25	10	5	11.25	10	11.25
15	15	8.75	15	13.75	17.5	15	10	6.25	12.5	12.5	15
16	5	2.5	5	3.75	7.5	3.75	5	2.5	6.25	3.75	8.75
17	7.5	2.5	10	10	10	6.25	6.25	2.5	8.75	5	11.25
18	10	5	15	8.75	13.75	7.5	8.75	5	10	7.5	12.5
19	12.5	6.25	17.5	12.5	15	12.5	8.75	11.25	12.5	10	12.5
20	15	7.5	16.25	12.5	15	13.75	12.5	8.75	11.25	11.25	16.25
21	0	0	2.5	1.25	5	2.5	2.5	0	2.5	1.25	5
22	0	0	0	1.25	5	3.75	2.5	0	1.25	1.25	3.75
23	5	2.5	5	2.5	3.75	2.5	3.75	2.5	2.5	2.5	3.75
24	7.5	2.5	6.25	3.75	6.25	5	5	2.5	3.75	5	5
25	10	5	11.25	7.5	8.75	10	6.25	6.25	5	6.25	10
26	12.5	5	11.25	7.5	10	11.25	10	7.5	6.25	10	10
27	15	6.25	15	11.25	15	15	11.25	12.5	6.25	11.25	12.5

Scenario Nr.	Simulator Pitch Angle [°]	Pitch Angle Choice [°] Pilot 11	Pilot 12	Pilot 13	Pilot 14	Pilot 15	Pilot 16	Pilot 17	Pilot 18	Pilot 19	Pilot 20
1	5	5	6.25	11.25	6.25	5	5	7.5	5	2.5	3.75
2	7.5	10	10	12.5	7.5	8.75	7.5	7.5	2.5	6.25	7.5
3	10	11.25	12.5	13.75	10	11.25	7.5	10	8.75	7.5	8.75
4	12.5	15	13.75	15	11.25	12.5	10	8.75	13.75	13.75	11.25
5	15	15	17.5	13.75	15	11.25	15	10	15	16.25	13.75
6	5	6.25	8.75	13.75	7.5	7.5	7.5	6.25	5	5	2.5
7	7.5	7.5	8.75	12.5	8.75	6.25	6.25	8.75	8.75	5	6.25
8	10	12.5	12.5	16.25	13.75	8.75	8.75	8.75	10	10	10
9	12.5	13.75	12.5	15	13.75	11.25	11.25	12.5	11.25	12.5	11.25
10	15	17.5	15	17.5	16.25	15	11.25	12.5	11.25	13.75	15
11	5	5	5	7.5	5	3.75	3.75	5	5	1.25	3.75
12	7.5	6.25	6.25	7.5	7.5	6.25	5	6.25	8.75	5	6.25
13	10	11.25	8.75	12.5	10	8.75	10	8.75	10	6.25	12.5
14	12.5	13.75	12.5	11.25	11.25	13.75	10	7.5	12.5	11.25	12.5
15	15	16.25	15	12.5	13.75	13.75	15	12.5	16.25	13.75	13.75
16	5	5	5	8.75	7.5	5	5	6.25	3.75	3.75	3.75
17	7.5	8.75	8.75	11.25	6.25	8.75	6.25	7.5	6.25	8.75	6.25
18	10	10	10	12.5	11.25	11.25	10	7.5	10	11.25	11.25
19	12.5	13.75	13.75	15	10	11.25	11.25	11.25	12.5	15	12.5
20	15	15	13.75	15	11.25	15	16.25	10	15	15	13.75
21	0	2.5	2.5	11.25	2.5	2.5	2.5	2.5	1.25	0	0
22	0	2.5	3.75	10	2.5	5	5	3.75	2.5	1.25	1.25
23	5	5	0	2.5	5	0	2.5	2.5	3.75	2.5	3.75
24	7.5	8.75	5	6.25	5	5	2.5	8.75	5	3.75	6.25
25	10	11.25	8.75	10	8.75	7.5	7.5	3.75	7.5	11.25	7.5
26	12.5	13.75	11.25	13.75	11.25	11.25	8.75	7.5	8.75	15	12.5
27	15	16.25	13.75	16.25	12.5	11.25	11.25	6.25	12.5	15	15

Part II

Preliminary Report

Please Note: This part has already been graded under Literature Review (AE4020)

Chapter 1

Introduction

On February the 23rd 2019 Atlas Air flight 3591 a Boeing 767-300BCF entered a rapid descent from 6,000ft and crashed into a bay just 34 miles from its destination, George Bush Intercontinental Airport (IAH), Houston, Texas. The two pilots and one jump-seat pilot were fatally injured. The domestic cargo flight, was in its approach phase when ATC requested to fly a deviation around local bad weather. Shortly after complying, a series of irregular events happened in the cockpit. Unexpectedly and abruptly, the pilot flying reacted by giving a series of nose down inputs, which ultimately lead to a situation which was not salvageable. The aircraft crashed in to the bay [16]. But what led this pilot to react as he did? And most importantly, what can be done to prevent such accidents from happening in the future?

It is thought that 25 to 33% of all aircraft incidents can be attributed to spatial disorientation (SD), although the actual impact of this phenomenon could be higher as not all incidents are correctly identified and reported as such [17]. Of these, the somatogravic illusion (SGI) is one of the most prevalent and fatal forms of spatial disorientation.

A study conducted by Boeing, covering a 20 year period from 1990 onward, noted a rate of about one fatal spatial disorientation accident per year. Specifically the SGI accounts for a considerable number of accidents. Figure 1-1, presents a timeline with all the accidents over the period 1991-2016 which are suspected to have SD as a cause.

Between 2000 and 2016, six large transport aircraft accidents and three serious incidents related to the SGI occurred, with a total of 481 lives lost. Since then, the rate of accidents has steadily continued. One factor has repeatedly come forward during the analyses of these accidents: nearly each of them occurred during the go-around phase of flight.

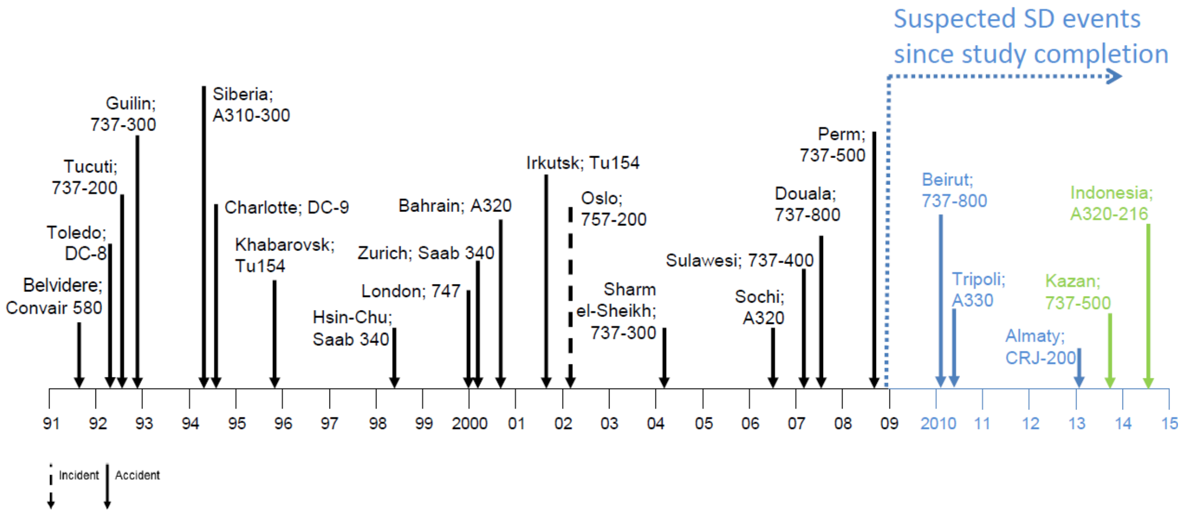


Figure 1-1: Timeline of all suspected SD events between 1990 and 2016 from [1]

Although a number of tools have been developed to identify and analyse SGI and its causes and prevalence amongst pilots have been investigated, there still remain gaps in the understanding of factors influencing this phenomenon's occurrence. That is why we are specifically interested in finding and reproducing the possible triggers that lead up to SGI such as in Atlas Air flight 3591. In this study we aim to investigate one of the potential triggers, which is the occurrence of a heave motion (e.g. due to an upward wind gust). This is done by analysing accidents involving the SGI, as well as the literature with a focus on preexisting experimental methods to invoke the SGI.

1-1 Research question

The main aim of this study can be summarised with the following research question:

Research question

Can a heave cue due to a wind gust lead to an additional pitch-up sensation?

The research question was further subdivided into sub-questions which address the main associated factors which together can lead to an approach for investigating the main question. In Section 3-4 the concepts leading towards these sub questions will be described in more detail and summarised.

Sub questions

1. *What are the causal pathways through which heave cues may cause a pitch-up illusion during a go-around manoeuvre?*
2. *Are there signs that there was a heave cue present just before pilot nose-down inputs in go-around accidents that are attributed to the somatogravic illusion?*
3. *Does the addition of a heave cue to a pitch cue in a hexapod simulator increase the estimated pitch angle in pilots?*

1-2 Report Structure

In order to answer the research question preliminary research was conducted, which will be presented as follows: In Chapter 2 the research context will be elaborated on by introducing the vestibular system and its components followed by a description of SD and SGI. A section will then focus on the prevalence of the somatogravic illusion will be discovered by studying pilot interviews, accident reports. The section will be concluded with a section on the various forms of pilot training conducted to prevent SGI.
In the next stage potentially aggravating factors including specific types of SGI, environmental circumstances and psychological characteristics will be analysed followed by a section on the prevalence of the somatogravic illusion using surveys and accident analyses. Chapter 3 will present an overview of previous research that is relevant for this study and is structured as follows: ground-based simulation of SGI, methods for measuring spatial orientation in a participant, modelling of spatial orientation, the go-around procedure and finally a conclusion will be made on potential gaps in knowledge.
In Chapter 4 the potential effects of heave cues through: the pilots experience,the physiology of the vestibular system, the rotation of the gravito-inertial force vector and potentially the elevator illusion are analysed. This is followed by an analysis of the 2019 Atlas Air flight 3591 accident using the perceptual model that has been introduced earlier on. Finally the method for an experimental approach to further investigation of the research question will be presented.

Chapter 2

Research Context

In this chapter the background knowledge, necessary for understanding this study, will be introduced. The functioning of the vestibular system 2-1 and its main components, the semicircular canals 2-1-1 and the otolith organs 2-1-2, will first be outlined. In the next sections the concept of spatial disorientation 2-2 will be introduced, followed by an in depth description of the somatogravic illusion 2-3 and potentially aggravating factors 2-6. In the final section of this section 2-4 the prevalence of the somatogravic illusion will be studied through a series of pilot surveys 2-4-1, accident analyses 2-4-2. This will be followed by a subsection on employed training methods 2-5-1 for pilots to become familiar with the SGI. The chapter will be ended with a section 2-6 on potentially aggravating factors.

2-1 The Vestibular System

Every healthy human has a system which determines their spatial orientation. This complex system is a multi-sensory integration of a visual system, vestibular system and somatosensory system. The main functions of this system are to maintain postural balance, spatial orientation and to enable gaze stabilization.

The vestibular system, named the labyrinth, is located in the head behind the ear and can be described as three circular ducts packed together on a cluster together with a snail shaped particle, the cochlea, Figure 2-1.

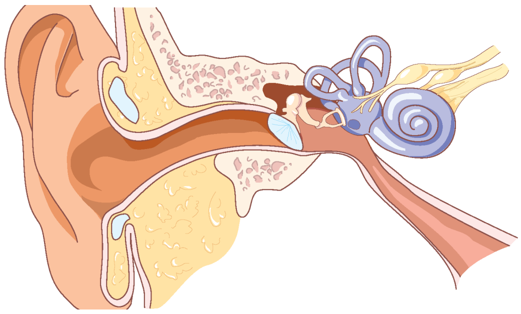


Figure 2-1: The vestibular system as situated behind the ear. Adapted from: www.neura.edu.au

2-1-1 Semicircular Canals

The duct-shaped sensors are named "*Semicircular canals*" and are sensitive to angular motion or rotational acceleration of the head. The three canals are situated in orthogonal planes (see Figure 2-2), which enables them to sense rotations around the three axes. A fluid called endolymph is situated within the canals and moves in opposite direction relative to the heads rotations due to inertia. A thicker part, situated at the root of each canal, is called the cupula. The cupula covers the crista ampullaris, the main sensory organ of rotation, which contains hair cells. These hair cells are bent as a result of the endolymph moving against the cupula, and then send an output signal to the brain via the vestibular nerve. In essence the semicircular canals are human angular accelerometers [18].

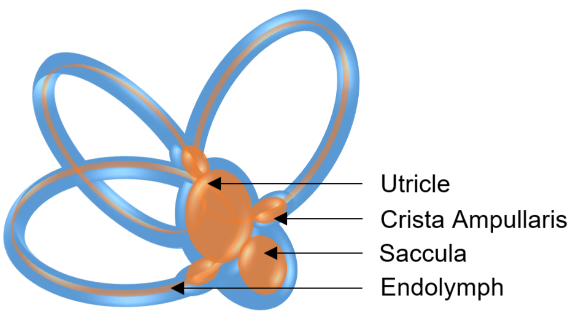


Figure 2-2: Semicircular canals, note that cochlea has been omitted in this figure

2-1-2 The Otolith Organs

In complement, the otolith organs are the linear motion sensors of the human body. They are located in the saccula and utricle, which are positioned right at the location where the semicircular canals are connected to the rest of the vestibular organ (see Figure 2-2). More specifically, "Otolith" is the name given to a collection of calcite crystals located on a gelatinous substance which contains embedded sensitive hair cells (see Figure 2-3). During linear accelerations, the relative movement of the otoliths with respect to the head stimulates the hair cells. This information is then transmitted to the brain via the nerve fibers that receive signals from the hair cells. The saccula has vertical sensitivity and the utricle horizontal sensitivity. However, the otolith organ is not just sensitive to acceleration, but actually to specific forces in general. The specific force is defined as the sum of inertial acceleration and gravitational acceleration as given in Eq. 2-1:

$$\vec{f} = \vec{a} + \vec{g} \qquad [m/s^s] \tag{2-1}$$

When there are no accelerations, the specific force enables the human to construct a subjective vertical, an estimation of their attitude relative to the horizon. The subjective vertical is then an estimation of the gravity vector consisting of a magnitude and direction. Thus, the otolith is not only an accelerometer, but also a sensor of head orientation.

The human brain combines information using its internal model, which is based on a combination of the sensed vertical, visual information, motor commands, proprioceptive information and eventually cognitive inputs. The result is an estimation constructed from sensed information and the humans prior expectations [19].

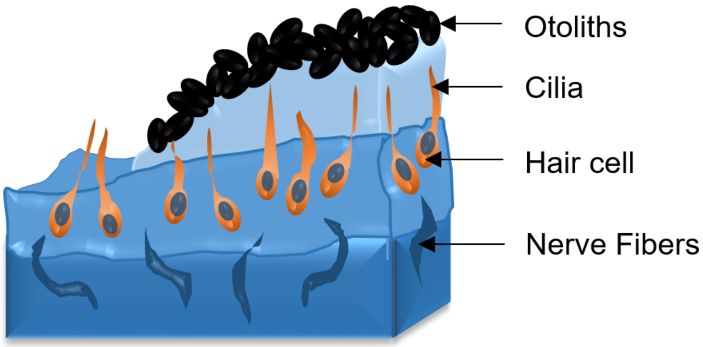


Figure 2-3: The otolith organs

2-2 Spatial Disorientation

In this section Spatial Disorientation (SD) will be defined, by first explaining the concept of its antonym spatial orientation (SO). SO refers to the human ability to continuously detect their body's correct attitude, position and motion relative to their surroundings. SD is defined as the situation wherein the human fails to maintain SO.

In the case of pilots, SD occurs in the form of an incorrect perception of the attitude, position and motion of an aircraft relative to a fixed reference frame (earth) [5]. Such situations arise when a discrepancy occurs in between the subjective vertical (SV), the sense of attitude relative to the gravity vector, created by the vestibular system and the actual direction of the vertical.

A pilot has less sources to verify their SV than a human situated on the surface of earth would have. Therefore, especially under difficult flying circumstances such as poor visual cues and an increased workload, a pilot becomes more prone to SD [20].

When discussing SD a distinction is made between three types of SD [21]:

- **Type I - Unrecognised SD**: when a pilots is unaware of their SD this often results in the occurrence of an incident or accident as a result of a series of wrong decisions which are made based on an incorrect assumption.
- **Type II - Recognised SD**: when the pilot is aware of their SD and can therefore take the correct measures when adjusting the aircraft's position.
- **Type III - Incapacitating SD**: When the pilot is aware of their SD, however lacks the capacity to react. Both physical and psychological reasons may cause this 'blockage'. In Section 2-6-1 the latter possibility will be elaborated on.

2-3 Somatogravic Illusion

The somatogravic illusion is the name given to the false sensation of body tilt that results from perceiving the direction of a non-vertical gravitoinertial force, such as the specific force vector Eq. 2-1, as being vertical, depicted in Figure 2-4. The SGI can mainly be categorised as a Type I - unrecognised form of SD. In Figure 2-4-a the actual forces present when upright and accelerating forward are presented: in red the inertial force, in green the gravitational force and in blue the resultant gravitoinertial force. In Figure 2-4-b the SD situation is depicted where the gravitoinertial force is falsely sensed as the gravitational force resulting in the perception of a 'pitch up' cue or up- and backward rotation. In Figure 2-4-c and the plane defined by the X, Y and Z axes and originating in the centre of the head can be seen while in Figure 2-4-d the zone within which the resultant force can come pared with noise is presented.

In other words, when a constant acceleration occurs, the brain falsely translates the received information of hair-cells being bent, as a head tilt. Whereas a forward acceleration without rotational cues, while the head is kept upright, can also bend hair cells. The constant acceleration force is misperceived as a forward rotation of the gravity vector, leading to a pilot sensation of 'pitching up'. This may cause a pilot to make unintended nose-down inputs, further increasing forward acceleration, which continues or aggravates the illusion.

The human vestibular system evolved in order to cope with everyday scenarios in the natural human environment. It has angular acceleration thresholds for rotation of around $0.14°/sec^2$ about the yaw axis and $0.5°/sec^2$ about the roll and pitch axes, for linear motions the perceptual threshold is about 0.005g in the respective planes of the otoliths [18]. This system is based on bipedal locomotion, thus a three dimensional motion such as pilots experience in aircraft, pushes the vestibular system beyond the limits of motion and attitude it was originally intended to handle [7].

This sensation where the specific force thus becomes the subjective vertical can be so strong and overwhelming that pilots can act solely upon it, incidentally forgetting to verify this sensation with their attitude indicator and other equipment [5].

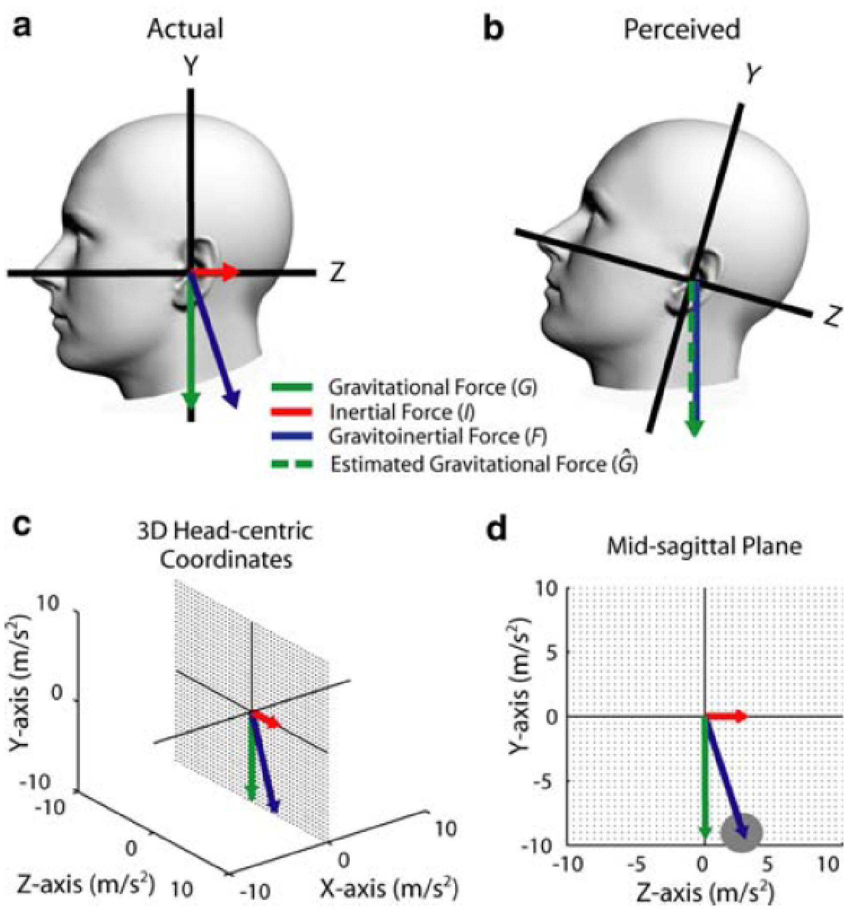


Figure 2-4: Somatogravic illusion and gravitoinertial force [2]

2-4 Prevalence of the somatogravic illusion

In this section the prevalence of the SGI will be studied as follows: first a series of accidents 2-4-2 will be observed, next pilot experiences 2-4-1 will be introduced from surveys.

2-4-1 Pilot Experiences with SGI

In 2013 the BEA conducted a survey among 831 pilots with varying levels of experience [22]. Most of these pilots hold or have held A320 type rating. (Further: A330-A340, B737, B777 and B747 families of aircraft.)

In a first instance the survey focused on quantifying the number of GA a pilot experiences, it was found that:

- Between two and four GAs per one thousand flights are recorded each year.
- A medium-haul flight crew performs on average one GA a year.
- A long-haul flight crew performs on average one GA every 5 to 10 years.

Of all interviewed pilots eight had never performed a GA when flying. As PF 57% had performed fewer than 5 and 31 pilots had never performed a GA as PF. As PNF 71.5% had performed fewer than 5 GAs and 53 had never performed a GA as PNF. This underlines how infrequent the procedure is, which means that when it occurs it does not necessarily compare well to other standard procedures in how accustomed pilots are to performing it.

On average, 60% of the pilots indicated that they had encountered difficulties during a GA. An overview of the specific difficulties they reported to have experienced can be seen in Figure 2-5.

The main difficulties indicated by the pilots were capturing the stabilisation altitude and auto-system management. Whereas instructors observed difficulties in capturing the stabilisation altitude (81%), auto-system management (72%) and pitch angle capture and maintaining (69%). More than half of the instructors also saw difficulties relating to visual scan management and decision making.

One factor that pilots also mentioned as unfavourable was the obligation, on certain aircraft, to select full thrust when performing a GA.

Ludlow et al performed a survey under 585 pilots, their mean level of experience was 10,165 hours. In total, 71% stated that they had at some point encountered SD during their career and 41% of participating pilots reported to specifically have experienced the SGI [23].

Difficulties expressed	***not or a little difficult as a %ge***	***difficult or very difficult as a %ge***	***no answer as a %ge***
Getting and maintaining pitch angle	66.8	11.6	21.6
Thrust management	53.2	28.8	18.0
Horizontal flight path management	48.9	28.8	22.3
Vertical flight path management: go-around altitude capture	35.2	49.0	15.8
Aircraft configuration management	44.2	38.5	17.3
Autosystem management	36.5	46.2	17.3
Trim management	61.3	4.9	33.8
CRM: decision making	51.4	26.9	21.7
CRM: task sharing	61.4	15.9	22.7
CRM: compliance with SOP	47.9	32.6	19.5
Visual scan management/focussing	39.7	37.3	23
Coping with acceleration-related spatial disorientation	58.9	14.2	26.9
Coping with the modification of the flight path on ATC request	38.9	37.8	23.3

Figure 2-5: Specific difficulties encountered by pilots during GA

2-4-2 Accidents (commercial, general, military aviation)

The classical example of any Aerospace Human-Machine Systems course, is the inconceivable scenario wherein highly experienced military pilots take-off from an aircraft carrier vessel and directly dive nose down into the sea. Unfortunately such a scenario is not limited to the military sector, in fact the past decade has seen an increase in what we know to be spatial disorientation (SD) incidents in commercial aircraft. Recent aircraft accident investigations have shown a series of SD incidents where pilots have made a series of nose-down inputs right after the start of a go-around mode, which led to loss of control. Amongst others, Afriqiyah Airways Flight 771, Gulf Air Flight 072, and the recent Atlas Air Flight 3591 have in common that a discrepancy is suspected by investigators, between the pilots perceived pitch and the actual pitch during the go-around.

Gulf Air Flight 072, 2000 Gulf Air Flight 072 was approaching Bahrain International Airport in 2000 when it aborted landing and initiated a go-around. It was evening at that time and the lighting circumstances were very limited. During the sudden increase in acceleration the auditory flap overspeed warning was activated. Immediately thereafter a series of nose-down inputs were made by the pilot, which resulted in ground proximity warnings being sounded as the aircraft descended and shortly thereafter impacted the sea just 3 miles northeast of Bahrain [24].

Afriqiyah Airways Flight 771, 2010 In 2010 Afriqiyah Airways Flight 771 was descending for approach of Tripoli International Airport. The weather circumstances indicated fog at that time, which lead to a non precision approach as the crew of this Airbus A330-202 did not manage to obtain visuals of the runway. After a GPWS 'too low terrain' was sounded the go-around mode was activated. This was swiftly followed by a series of nose-down inputs by the captain, which together with the contributing lack of clear visibility due to weather circumstances, lead to the steep descent and finally impact of the aircraft with the ground [25].

Atlas Air flight 3591 The most recent amongst numerous SD induced accidents, was Atlas Air flight 3591 in 2019. The Boeing 767-300BCF aircraft was operating as a domestic cargo flight for Amazon Air and heading to George Bush Intercontinental Airport in Houston, Texas for landing. According to weather reports the aircraft was expected to have met weather conditions of light to moderate turbulence in the area. During the flight's final phase, while descending for approach, the go-around mode was activated, the communication and voice recordings indicate that the activation was most likely undeliberate. Shortly thereafter a Warning went off and nose-down inputs were recorded, although the pilots tried to correct this manoeuvre a shortly thereafter, it was already too late, the aircraft crashed in Trinity Bay, Texas fatally injuring its two pilots and one passenger [26].

In Figure 2-6 it can be seen that there are many more accidents of which the sommatogravic illusion was assumed to be a causal factor.

Common features of these flights

This brings us to think about the common factors of flights where the SGI is suspected to have played a role. It has become evident that the large majority of accidents and incidents, were instigated during the go-around phase [27]. This might have to do with the physical nature of

No.	Flight ID	Aircraft	SD Description
1	FOS 55	SF-340B	Somatogravic/somatogyral, false perception of attitude during turns and/or postroll tendency to roll back into a turn.
2	TIA 261	A-310-200	Somatogravic, false sensation of pitch (no details).
3	THY 5904	B-737-400	SA issue, no direct SD evidence.
4	LAK 6316	MD-11F	SA issue, no direct SD evidence.
5	TEJ 725	DC-9-30	Somatogravic, false sensation of pitch (no details).
6	KAL 8509	B-747-2B5F	Somatogravic, false perception of attitude during turns.
7	SWR 498	SF-340B	Somatogravic/somatogyral, false perception of attitude during turns and/or postroll tendency to roll back into a turn leading to a graveyard spin.
8	DAL 106	B-767-332	No discernible horizon led to somatogravic, false perception of attitude during turns.
9	GFA 72	A-320-312	Somatogravic, false sensation of pitch.
10	ETA4 1000	SA-226TC	SA issue, visual SD possible.
11	JEK PF	BE-200	Not a conclusive SD event.
12	N405PC	CE-501	Possible visual SD event.
13	VLK 352	Tu-154M	Somatogravic/somatogyral, false perception of attitude during turns and/or postroll tendency to roll back into a turn.
14	AJI TW	LR-25	Somatogravic, false sensation of pitch.
15	SKK 621	BE-1900C	Somatogravic, false sensation of pitch (no details).
16	FLT 101	SA-226-AT	Not a conclusive SD event.
17	EGU 220	CE-560	Possible Somatogravic, false sensation of pitch (no details).
18	ICE 662	B-757-200	Not a conclusive SD event.
19	9XRRB	Let-410-UVP	Not a conclusive SD event.
20	AFN 642	CV-580F	Not a conclusive SD event.
21	FLS 604	B-737	Somatogravic/somatogyral, false perception of attitude during turns and/or postroll tendency to roll back into a turn leading to a graveyard spiral following bank angle recovery.
22	N280AT	IAI-1124	Not a conclusive SD event.
23	MEP 490	MD-90-200	Not a conclusive SD event.
24	AHY 217	An-140-100	Possible visual SD event.
25	RNV 967	A-320-211	Somatogravic, false sensation of pitch.
26	DHI 574	B-737-4Q8	Somatogravic, false perception of attitude during turns.
27	KQA 507	B-737-8AL	Somatogravic/somatogyral, false perception of attitude during turns and/or postroll tendency to roll back into a turn leading to a graveyard spin.
28	DJQ BP	CE-550	Not a conclusive SD event.
29	VHOZA	SA-227-AC	Not a conclusive SD event.
30	AFL 821	B-737-505	Visual SD leading to somatogravic, false perception of attitude during turns leading to a graveyard spin.
31	CFS 8284	ATR-42-320	Not a conclusive SD event.
32	AOE 301	CE-650	Possible Somatogravic/somatogyral roll event.
33	AFR 447	A-330-203	Not a conclusive SD event.
34	IYE 626	A330-324	Possible visual SD event.
35	ETH 409	B-737-8AS	Possible visual SD event.
36	TIE 039C	CE-550B	Possible visual SD event.
37	AAW 771	A-330-202	Somatogravic, false sensation of pitch.
38	AFR 006	A-380-860	Somatogravic, false sensation of pitch.

Figure 2-6: List of accidents, amongst many of which the Somatogravic illusion was assumed to be a causal factor[3]

the the go-around procedure, but the high mental workload that arises in such situations may very well also be a contributing factor. The psychological aspect will be further investigated in Section 2-6 and the standard go-around procedure will be presented in Section 2-5. Further it is clear that critical weather circumstances such as the presence of wind gusts is often noted when SGI is suspected of causing an accident. While the visual system is incorporated in human perception it can be noted that bad lighting and low visibility such as present in some of the accidents, can form contributing factors.

2-5 The go-around procedure

In Section 2-4 it became clear that most accidents where the SGI is suspected to be a causal factor occurred during the go around procedure. In light of this it is essential to understand how a standard go-around is performed.

For this section an in-house Airbus procedure list was used, between aircraft manufacturers there may be slight variations between exact go-around steps according to the aircraft's systems [4].

During approach pilots are expected to already mentally be prepared in the case a situation arises in which a go-around procedure is necessary. Such a situation can be a 'missed approach', a malfunction, ATC request, an alert of any form, or any other urgency.

While setting TOGA thrust, the pilot flying must also announce *"Go Around Flaps!"* and depending on the aircraft's setting, the pilot closely observes the autopilots reaction or steers the aircraft into a pitch target (ranging from 15° to 12.5° depending on aircraft type). The Flight Mode Annunciator must be checked and all instructions of the Speed Reference System must be executed in order to maintain the target pitch angle. The pilot not flying retracts the flaps by a step as soon as the go-around is announced.

Once the aircraft has reached the thrust reduction altitude the pitch may be lowered and the procedure must be finalized. During the entire operation it is the pilot not flying's task to monitor all systems and communicate any inconsistencies.

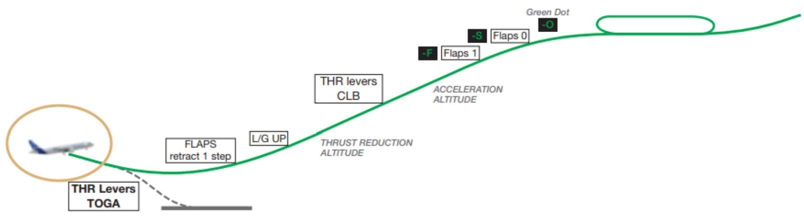


Figure 2-7: Schematisation of the Airbus Go-Around Procedure [4]

2-5-1 Pilot Training

In this section the question how pilots are currently trained for the SGI and subsequently for go-arounds will be answered.

SGI Training Ludlow et al investigated current civilian pilot training [23]. All ICAO CPL training syllabi have an element of SD training with at very least, a description of SGI. This may be taught in the classroom, read in the study notes or may also appear as questions in the student's practice examinations. Testing is by written examinations using multi-choice questions. But in general very little focus seems to be laid on the SGI when training commercial pilots. Military pilots are trained more thoroughly, a NATO agreement underlines this. For example In the UK, RAF trainee pilots attend a week- long aeromedical course with an exam, and a training session in a motion based SD training device which can demonstrate the SGI.

GA Training In the before mentioned Section 2-4-1 BEA survey, pilots indicated that they were sufficiently well trained in GA's with one engine out (85%) -however, almost half of the pilots indicated that they were not sufficiently well trained in GA'S with all engines in operation. The pilots also suggested adjustments in a number of procedures and systems involved. It was stated 'Improve flight simulators'. Most notably they see an importance in increasing the frequency of training of GAs in simulators with all engines in operation. They also indicated that training for GA's where there is a change of configuration and of plan of action could be beneficial, as well as conducting training in actual GA'S during aeroplane training [22].

2-6 Potentially aggravating factors

In the case of the SGI a multitude of factors exist which may contribute to its occurrence. In this Section 4-1-4 the elevator will be introduced followed by a study of the startle, surprise and distraction factors in Section 2-6-1.

2-6-1 Startle, surprise, distraction

As can be seen in Figure 2-8 from Previc & Ercoline's book on SD in aviation, there are a multitude of other factors influencing a pilot's SO besides vestibular cues. Aside the vestibular system, the brain combines auditory, visual (which can be very dominant), tactile and internal models to form a subjective vertical.

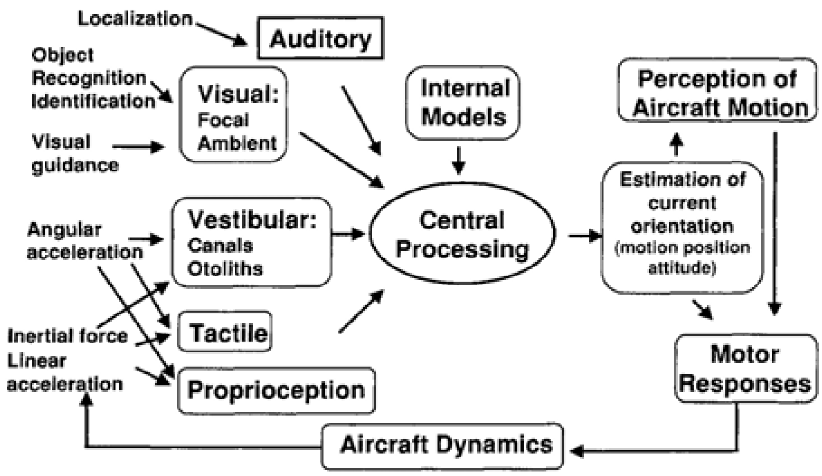


Figure 2-8: Schematic diagram of the mechanisms of spatial orientation in flight, Adapted from: [5]

However, as we are dealing with humans, one of the most important factors which is always present and can be of great influence, is perhaps the psychological factor. In this section we will therefore discuss the effects of startle, surprise and distractions and how they can be of influence for the SGI.

Startle is a short and fast reaction to a sudden stimulus which expresses its self in a highly physiological way. Its appraisal is fast. Whereas surprise has a slower appraisal and causes an emotional and cognitive response. In Figure 2-9 a conceptual model of startle and surprise [6] can be seen within a certain logical and coherent context called a frame. The model demonstrates that startle and surprise can each occur separately but a startle effect can also activate the surprise loop.

The startle and surprise factors can occur during GAs because of the nature of the manoeuvre which automatically comes paired with distractions. GAs always occur because of some unexpected factor interrupting the usual approach procedure. From a BEA study on Aeroplane State Awareness during GA's [22] it was found that 70 to 80% of the time the main factors triggering a GA are:

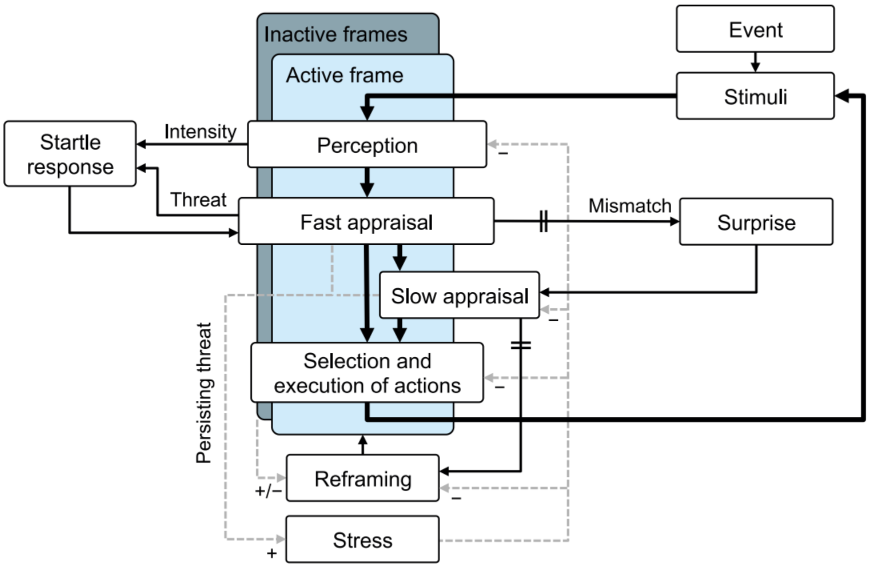


Figure 2-9: Conceptual model of startle and surprise (Adapted from: [6])

- Meteorological conditions (tailwind, wind shear, turbulence),
- Conduct of flight (Unstabilised approach, GPWS warning),
- ATC (runway occupied, separation, ATC request for GA).

Each of these factors could potentially lead to a startle or surprise effect.

The activation of the GA mode is preceded by some action on board not going according to the flight plan or an air traffic controller communicating an issue, this means that a GA always starts with a potential distraction. However there is no place for distractions in the short amount of time pilots have from announcing the procedure they are going to perform and then setting-up the aircraft and prompting the right cues to perform the GA.

Pilots are taught to never solely trust their mental image of SO but instead always use their instruments as a main source of information. However, in the case of distractions it can happen that a pilot briefly forgets to scan their instruments which increases the risk of a SGI as they will be more likely to act upon their vestibular system.

"*The pilots indicated that they quickly assimilated the operational consequences of the go around, sometimes to the detriment of monitoring the fundamental parameters of the GA.*" [22] The GA mode directly comes paired with a strong thrust, which is perhaps greater than needed, as large aircraft are much lighter at the end of their flights. This sudden increase of thrust nearly always instigates a startle effect for the pilot.

2-6-2 Other factors contributing to the somatogravic illusion

Fatigue Fatigue is an element in the background which can contribute to SGI. According to the Ludlaw et al. survey [23] respondents mentioned fatigue as a factor when they experienced SD. It is also stated that "*As many SGI events occur at night, which often coincides with the end of a crew's duty, it appears that these events can be partially attributed to fatigue.*"

Pilot experience & age It is a given that more pilot experience could potentially be a mitigating factor. However not fully proven, two studies were found which underline the likelihood of a lack of pilot experience being a contributing factor for SGI. A study by the Australian BASI of 18 pilots involved in dark night take off accidents, most holding an instrument rating, could not directly link their hours of flying time logged to the accident rate as their experience ranged from 189 to 19,006 hours [28]. The average age of this group of pilots was however relatively young. In their 2007 survey Previc et al linked older age in pilots to a possible better resolution of SD. conflicts.

Degraded external visual reference points When the visibility is low, pilots can no longer factor in their vision as an extra reference point for verifying their orientation (aside their instruments). Subsequently pilots form their SO with one less factor which means the likelihood of an error increases. This is in line with the large number of SD accidents and incidents that have occurred during the nighttime.[23]

Chapter 3

Previous research and relevant literature in the field of the Somatogravic Illusion

In the last Chapter 2 it has become evident that there exist a multitude of factors both vestibular and non-vestibular that can lead to a somatogravic illusion and that while the SGI is prevalent, there is not yet a strong training procedure in place for its prevention. In this Chapter 3 an overview of literature relevant to the exploration of circumstances surrounding the occurrence of SGI is described. In Section 3-1 the ground-based simulation of the SGI will be discussed first by observing previous studies wherein hexapod and centrifuge simulators were used. Next the shortcomings of ground-based simulation will be described. Methods of measuring the perceived spatial orientation will be introduced. This will then be followed by Section 3-3 wherein the development of models aimed at simulating the SGI will be presented. Finally potential gaps in light of the previous research will be discussed.

3-1 Ground-based simulation of the somatogravic illusion

3-1-1 Hexapod

In 2016 under instruction of the Federal Aviation Administration (FAA) a research group led by Systems Technology, Inc published a paper in which they presented scenarios which were created to demonstrate SD for pilot training. The purpose of these scenarios was to increase pilot recognition of SD situations. The scenario development was done at the NASA Ames Research Center using a FAA Certified Level D hexapod simulator for a B747-400 [3]. The simulators CAE 600 series motion system enables six-degree of freedom using hydraulic cylinders further it is equipped with state-of-the-art visual displays.

For scenario development for the pitch axis a focus was laid upon exposing pilots to the false sensation of pitch that occurs in the SGI with changing longitudinal accelerations during a GA situation.

The designed scenario was sought to be representative of existing training scenarios. For the visuals a 'degraded visual environment' was created using a cloud layer between 400-1000ft and a 1.5nm visibility. The research group chose these experimental conditions in order to be representative of common circumstances that came forward from their analyses of cases of SD. Specifically, 'night time' and 'no discernible horizon' are stated as such circumstances, this is inline with the contributing factors presented in Section 2-6-2.

Pilots were asked to perform the standard procedure for a missed approach/go-around with four engines operating in a B747-400. In the developed scenario, the motion platforms pitch attitude exceeded the aircraft models pitch attitude after TO/GA. This effect was obtained by increasing the tilt gain, or the angle of the motion platform to 2.44 times the angle of the applied aircraft model and reducing the pitch filter damping ratio, further the aircraft model's landing rate was adjusted to 450000 pounds. The tilt gain was triggered with the TO/GA and held throughout the climb out.

Further a figure presenting a test pilots column inputs during this scenario, shows that the pilot responded with a large 'nose down' input followed by a series of strong inputs which exceed what would be needed for keeping the aircraft steady.

The scenario developed in [3] was tested by a group of 14 commercial pilots, and the results were published in a 2017 paper [7]. In Figure 3-1 the perceived pitch angle of two pilots can be seen as a response to the developed SD demonstration scenario for SGI.

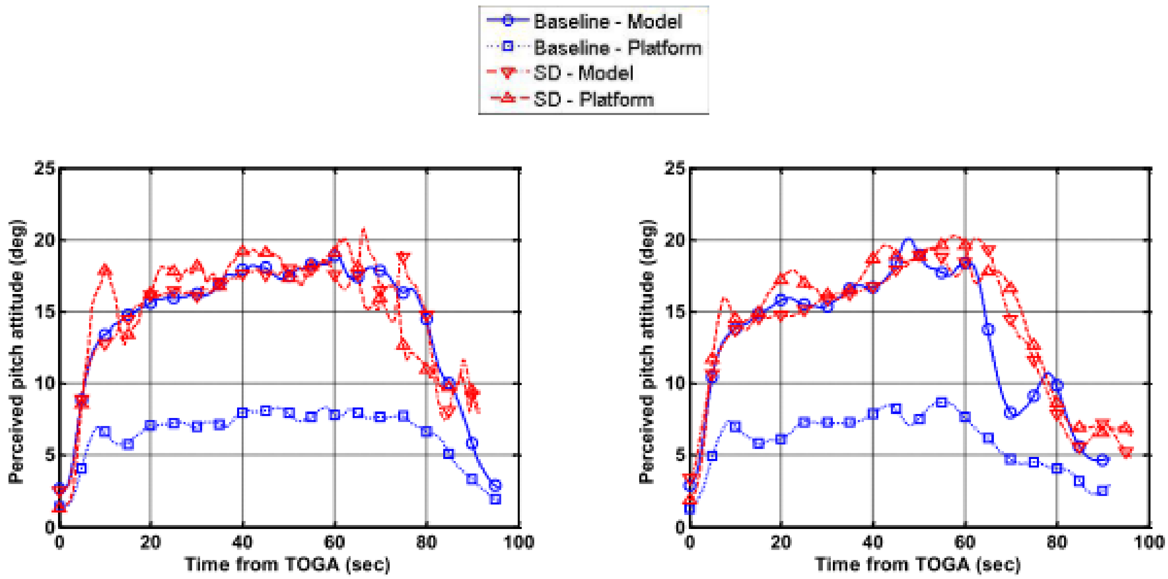
The perceived pitch attitude was calculated using the Eq. 3-1.

$$\theta_{per} = \tan^{-1}\left(\frac{a_x}{-a_z}\right) \tag{3-1}$$

And a perceptual lag was taken into consideration with following Eq. 3-2:

$$\frac{s}{s+0.5} \tag{3-2}$$

The perceived attitude of the platform closely follows the true pitch attitude of the platform. The perceived pitch attitude of the model is also smoothed, but does not follow the actual



a) Pilot A

b) Pilot B

Figure 3-1: The perceived pitch attitude of pilot A and B for the developed SD demonstration scenario for SGI [7]

pitch attitude closely. This deviation is a sign of the false sensation of pitch that would be seen in the aircraft during a TO/GA maneuver. When the motion to demonstrate SD is added, the perceived pitch attitude for the platform more closely matches that of the model, suggesting that this demonstration scenario is effective at mimicking the perception of a SD illusion during TO/GA. While both pilots had the same experiment set-ups pilot A was affected much more strongly by than pilot B, which can be seen in his more aggressive column inputs. These were the reactions of the pilots: “It felt like different levels of wind shear in which pitch attitude was affected from outside forces beyond input. I definitely had to consciously fight the pitch up sensation and fly the instruments on the go-around.” – Pilot A

“I believe my experience as a Flight Safety Officer in the military, accident investigation experience, and Master’s degree with emphasis in human factors definitely helped me prepare/be diligent for spatial disorientation events.” – Pilot B

As a final note, in their companion study for a go around with a steep bank a ‘startle effect’ similar to what pilots experience during actual GA’s was created by “failing” the pilot flying’s primary flight display just as the aircraft is returning to wings level. In this studies experiment, the startle effect was the fact that no mention of spatial disorientation was made prior to the runs.

This study represents a method of demonstrating and mimicking SD circumstances in the pitch axis using a hexapod simulator. However it can be argued that it is successfully fooling participants, but this seems to be a rather physically indirect form of representing the somatogravic pitch up illusion as the pilots are being ‘fooled’ from the beginning. It would perhaps be interesting to have a situation where there is also a baseline without the pilots being 'fooled'.

3-1-2 Centrifuge

A centrifuge can be applied to continuously rotate seated human participants on an mechanical arm around a central axis. When the rotational velocity is constant, the direction of the resultant acceleration force, which consists of a gravitational and centripetal component, is interpreted as the vertical in the steady state [8]. This gives the participants an illusion as though they are tilted. Variable-radius centrifugation provides circumstances wherein a sustained linear acceleration is present and the gravity vectors direction can be varied without subjecting participants to a physical tilt, all while the semicircular-canals are remain un-stimulated [9]. An approach to SD, specifically to the SG can be made using these facts.

Tilt perception experiment using a centrifuge
In *'Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight'* the authors describe a such experiment performed during the 1998 Neurolab STS-90 space mission where the participants were four astronauts and the apparatus was a short-arm centrifuge built by the European Space Agency [8].

During the experiment participants were seated in three ways: with their left ear facing outward relative to the central axis, with their right ear facing outward and lying on their back with their head facing outward. They were subjected to a constant acceleration or deceleration of $26°/s^2$. The participants limbs and head were secured and their so called 'Reid's Baseline' was aligned with the gravitational horizontal on earth. The centrifuging took place in complete darkness. Participants were tested both on earth and in microgravity. Participants were frequently asked to verbally report their sensation of tilt in angular degrees, they were also asked to report linear motion in m/s. A static tilt in increments of 15° up until 19° was used to measure a reference for the participants perception when no motion was in place.

The researchers also compared the participants answers with somatosensory reports, which were obtained by providing the participants a joystick with which they could indicate their perception.

For the positions where the participants were seated upright, participants were subjected to $254°/s$ and $280°/s$ rotations, which resulted in 1g and 0.5g centripetal acceleration. For the position where the participants were lying on their backs, they were subjected to $223°/s$ and $158°/s$ rotations, which again resulted in 1g and 0.5g centripetal acceleration. In Figure 3-2 the positions in which the participants are placed together with the expected perception per position can be observed.

Their studies resulted in illusions being induced in all three positions. The positions where the participants were seated upright, induced perceived roll-tilt perceptions of 20° and 34° for the 1g and 0.5g centripetal accelerations respectively. The lying on the back position induced perceived backward pitches of 5° and 15° respectively. A summary of these results, can be seen in Figure 3-3.

Tilt perception time constant study using a centrifuge
In another study, researchers used the Desdemona research simulator as a variable-radius centrifuge to study the time constant of the somatogravic illusion [9]. Participants were

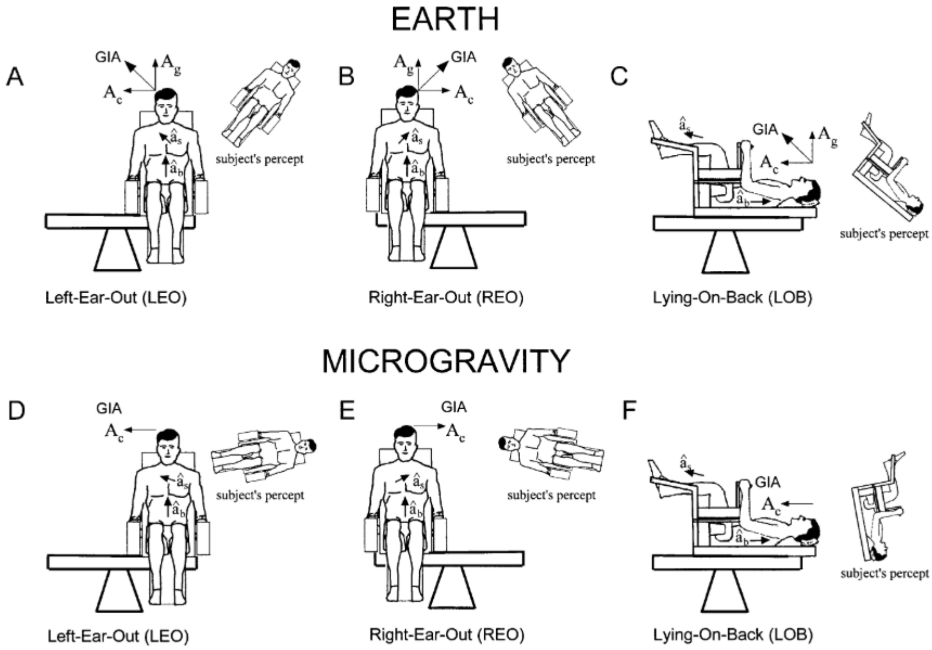


Figure 3-2: Centrifuge configurations as used in the Neurolab STS-90 mission [8]

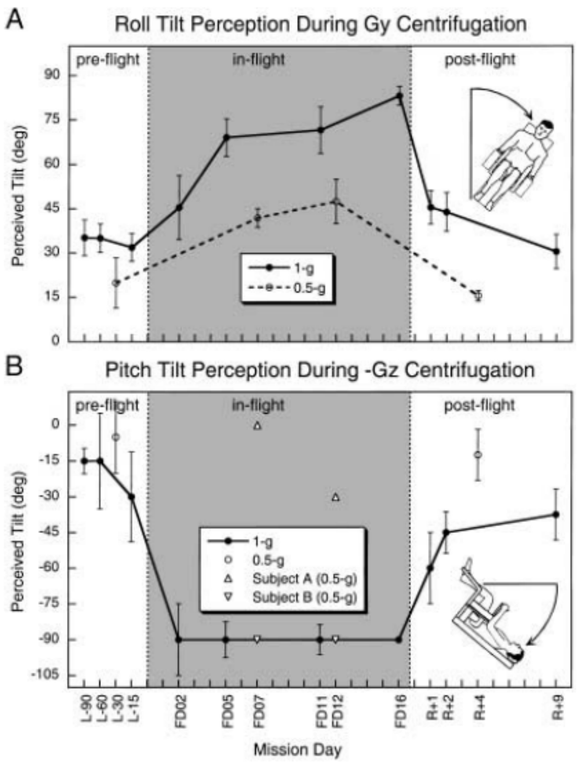


Figure 3-3: Perceptual results of the Neurolab STS-90 mission [8]

subjected to a centripetal acceleration of $4.1 m/s^2$, which resulted in a 22.5° tilt of the specific force vector, furthermore the rotational velocity was kept constant at $80°/s$. The velocity profile was obtained by using a raised-cosine and resulted in a centripetal acceleration as given in Eq. 3-3, where R describes the distance of simulator cabin on the centrifuge arm.

$$a_c(t) = \omega^2 R(t) \tag{3-3}$$

Three different frequencies of 0.05, 0.1 and 0.2 Hz were applied for the cosine motion. The participants were provided with a joystick so that they could constantly indicate their perceived roll-tilt during the outward motion of the cabin by rotating it in the same direction as their perception. For the variable-radius centrifugation the somatogravic illusions time constant was found to be around 2 seconds and the frequency of the motion profiles was found to have a strong effect on the time-constant. In Figure 3-4 an overview of the participants mean joystick responses per different frequency of motion profile can be seen.

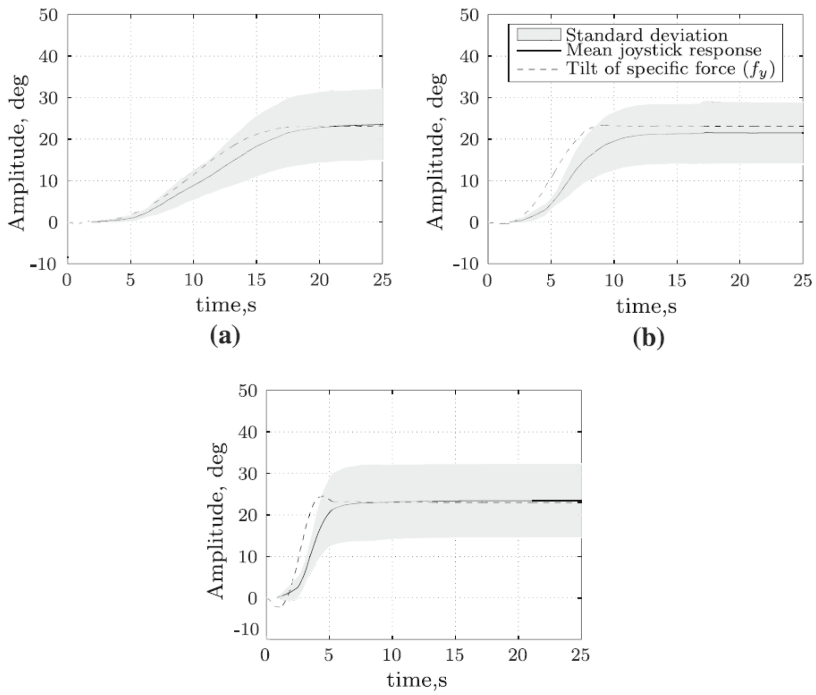


Figure 3-4: Mean joystick response of the participants, for a)0.05Hz, b)0.1Hz, c)0.2 Hz [9]

Such experiments where centrifugation is applied are interesting because it isolates the linear perceptual inputs for observation. On the other hand centrifugation is not the most accessible form of experimentation, as not all humans and therefore pilots are suitable to participate.

3-1-3 Difficulties with ground-based simulation for demonstrations

The conditions that lead to a SGI are very difficult to replicate, which makes training pilots properly difficult. The numbers of accident reports which identify SGI as a causal factor indicate that current training is far from effective and it remains a significant threat to flight safety.

Unfortunately it is difficult demonstrating the somatogravic illusion with conventional hexapod simulators because of the physical limitations in actuator extension and velocity. Further hexapod simulators do not have the capability to generate sustained linear and angular accelerations[3]. The latter limitation can be bypassed by making use of a centrifuge.

Ludlow states: "They replicate longitudinal acceleration by pitching the pilot up while maintaining visual and instrument attitudes. They cannot realistically replicate SGI if the vestibular system is already being used to convince a pilot they are accelerating by utilising the mechanism which is responsible for the illusion in the first place.“ [23]

BEA states: "Simulators do not correctly represent the phenomenon of somatogravic illusion during a GA. The pitch and accelerations present in the simulator are not those felt during a real GA... In addition, experienced pilots rarely carry out real GA and it is statutorily possible that recently qualified co-pilots have never been subject to somatogravic illusions prior to carrying out scheduled flights during line-oriented flight training." [22]

3-2 Methods for measuring and registering the perceived spatial orientation of a participant

The somatogravic illusion can be measured in various ways when experimenting with participants, in this section a short summary is made of all known methods.

Verbally Verbal reports of over a microphone are the most simple method for registering a participants perception. This method is frequently applied [8] [29].

Visual Bar The visual bar method lets participants align a visual bar with their perceived horizontal. This method originates from the oculogravic illusion wherein similar to the somatogravic illusion in the vestibular system, the visual horizon is perceived to be tilted as a reaction to a rotated gravitational acceleration vector[30].

Joystick A joystick or a somatosensory bar, gives participants a physical method of (continuously) rotating a rod according to their perceived spatial orientation [9].

3-3 Modeling the human perception of spatial orientation: the Wada model

Human spatial orientation models (SOM), have been developed in order to better understand and predict the interpretation of motion cues by the vestibular system. Such models can also be used to predict spatial disorientation in pilots, which makes them a potentially useful tool for the analysis of flights where it is suspected that the sommatogravic illusion played a role.

In this section the spatial orientation models that was initially set-up by TNO and then further developed by various parties [31] will be introduced. The model will be described in detail and include all adaptations that were made to reach the final format of the model which will be used further on in this research.

The initial model was developed by J.E. Bos and W. Bles in 1998 and aimed to study and quantify motion sickness. The authors discovered that previous research did not yet include any vestibular basis and intended to develop a model which took this into consideration. A primary assumption was adopted that motion sickness occurs as a result of an "*accumulation of the difference between sensory information from the vestibular system and the estimated sensory information from the internal model* [19]." In their publications the researchers refer to this notion as subjective vertical conflict (SVC).

The sensory information stems from combined inputs acquired from the eyes, the vestibular system and nonvestibular proprioceptors, its output is a sensed vertical in the form of a vector indicating the magnitude and direction of gravity. The internal model that is mentioned, is the humans ability to predict self motion in the form of a subjective vertical and therefore its output is an estimation of the gravity vectors magnitude and direction based on previous experience. [31]

The model is situated in the head reference system, where the x-axis is aligned with the nasooccipital axis, the y-axis is aligned with the inter-aural axis, and the z-axis is orthogonal to the latter two. In Figure 3-5 the head reference systems positive directions can be seen.

The first building block of the model (OTO in Figure 3-6) is the specific force as seen in Eq. 2-1 that the otoliths are sensitive to. Inertial acceleration and gravity are taken as the summation inputs for the resultant force f which is then fed into the simulated otolith organ, its transfer function is a unit matrix.[11] The next block (SCC in Figure 3-6) are simulated semi circular canals, their input is angular velocity and their transfer function is as noted in Eq. 3-4 [32].

$$\omega_s^i = \frac{\tau_d \tau_a s^2}{(\tau_d s + 1)(\tau_a s + 1)} \omega^i, (i = x, y, z) \tag{3-4}$$

(with τ_a and τ_d as time constants)

The subjective vertical is then defined from both the otolith and semi circular canal outputs as in equation 3-5

$$\frac{dv_s}{dt} = \frac{1}{\tau}(f - v_s) - \omega_s \times v_s \tag{3-5}$$

Here $\tau = 5s$ [33] and is noted as LP in the model3-6.

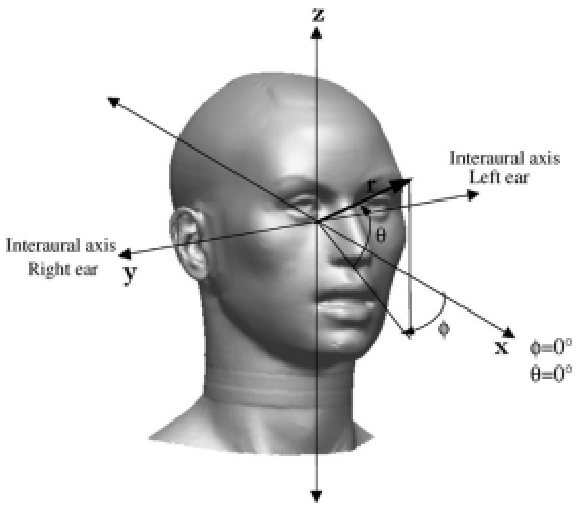


Figure 3-5: The head reference frame, with x,y and z positive directions defined as: the front, left and top of the head[10]

The estimation for inertial acceleration, sensed vertical and angular velocity are then used as an input for the internal model together with two gains $K_a = 0.1$ and $K_\omega = 0.8$. The internal model further consists of identical otolith and semicircular canal building blocks as the vestibular system. A potential error in inertial acceleration, sensed vertical and angular velocity is handled by integrating and then through feedback with gains $K_{ac} = 1.0$, $K_{vc} = 5.0$ and $K_{\omega c} = 10.0$, respectively [34].

The difference between the modelled vestibular systems sensed vertical and the internal models estimated vertical is then found and implemented on the final outcome values of these three factors. The Hill function and Motion Sickness Incidence, as can be seen in the model, are not of interest for this study and will therefore not be further elaborated on.

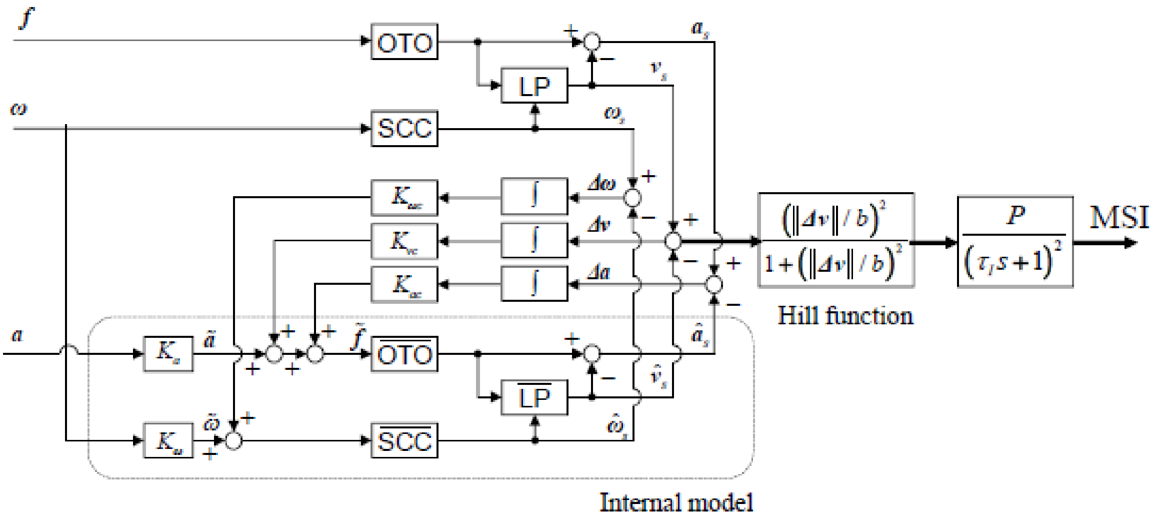


Figure 3-6: 6-DOF-SVC model of motion sickness incidence[11], revised from[12]

The introduced vestibular model can be applied in order to model different outcomes of spatial disorientation and also to analyse flight data and estimate how pilots perceived the motion. In the next chapter the Wada model will be used for an analysis of the effect of a heave motion as well as for investigating the 2019 Atlas Air accident.

3-4 Potential gaps in current knowledge & sub questions

For some accident cases, the spatial orientation models do not clearly predict the SGI, whereas the pilots' actions do suggest it took place. It thus appears that the understanding of the illusion is still lacking. From the literature study, it is clear that further investigation in triggers or factors that may exacerbate the a SGI would be interesting. From the accident reports and other literature on the prevalence of the SGI it became clear that the presence of heave cues, or vertical accelerations is frequent in such situations and may very well form a trigger to instigating or strengthening the illusion.

This leads us back to the research question of this study. **Research question**

Can a heave cue due to a wind gust lead to an additional pitch-up sensation?

The research question can be further explored by subdividing it into sub-questions which address the main associated factors which have come forward throughout the literature study as addressed and which together can lead to an approach for investigating the main question.

Sub questions

1. *What are the causal pathways through which heave cues may cause a pitch-up illusion during a go-around manoeuvre?*
2. *Are there signs that there was a heave cue present just before pilot nose-down inputs in go-around accidents that are attributed to the somatogravic illusion?*
3. *Does the addition of a heave cue to a pitch cue in a hexapod simulator increase the estimated pitch angle in pilots?*

Chapter 4

Current Experiment

In this section an initial experimental approach is made to explore the enquiry that was made on the type of cues that lead up to a somatogravic illusion. The majority of accidents that were analysed, where a SGI seems to have occurred took place after a go-around mode was engaged, another common factor is often seen to be bad visual and meteorlogical conditions. These factors were taken into consideration in the experimental approach. In order to answer the research question *'Can adding a heave cue during a go-around manoeuvre in a large aircraft lead to an additional pitch-up sensation?'*, four sub questions were defined:

- *To what extent do pitch changes in normal operations lead to heave cues?*
- *Are there signs that there was a heave cue present just before pilot nose-down inputs in go-around accidents attributed to the somatogravic illusion?*
- *If a heave cue (for instance due to a wind gust) is present during a go-around, can this be incorrectly interpreted as a pitch cue?*
- *Does the expectation of a pitch change increase the likelihood of misinterpreting the heave cue as a pitch cue?*

An initial approach to answering these questions was done in two stages. In a primary stage flight simulations of regular go-arounds and go-arounds with added heave cues were performed in The Delft University Environment for Communication and Activation (DUECA) and analysed with the spatial orientation model previously introduced in Section 3-3. In the secondary stage an investigation of Atlas Air Flight 3591 was conducted with the spatial orientation model and all factors that could have been a cue causing the occurrence of the SGI were observed.

4-1 Potential effects of heave cues

There are three possible ways in which we hypothesise that heave cues can lead to false pitch perception. Namely: 1. Pilot experience of pitch and heave 2. Physiology of the vestibular system 3. The rotation of the gravito-inertial force vector.

In the next sub sections we will elaborate on each of these potential causes.

4-1-1 Pilot experience

One hypothesised reason why a heave cue may lead to a false pitch perception is that the pilots may have learned to couple pitch control action with heave sensations due to experiencing these two events simultaneously.

In normal operations pitch control actions will always coincide with heave sensations. Pitching up from level flight will increase the load factor to a value above one whereas pitching down will decrease it below unity. This load factor can be calculated:

$$n = \frac{Vq}{g} + 1 \tag{4-1}$$

However the pitch acceleration also causes a heave cue, because the pilot is positioned a certain distance (d) in front of the centre of gravity:

$$a_z = -\dot{q} * d \tag{4-2}$$

When looking at commercial aircraft in its approach phase, the speed can be around 130 kts (66.8 m/s). If the pilot gives an input so that the pitch angle oscillates between $+2.86°$ and $-2.86°$ with a maximum pitch rate of $2°/s$ and a maximum pitch acceleration of $1.4°/s^2$ (see Figure 4-2), then according to Eqs. 4-1 and 4-2 the resulting G-forces are shown in Figure 4-1.

If pitch inputs always lead to heave sensations that are of this magnitude, pilots may have learned to associate the one with the other. In Figure 4-3 the heave motion that will lead to the same cues as the pitch motion described above is presented.

Thus a heave cue that is not caused by a pitch change, but instead for example by turbulence, could potentially prompt an incorrect assumption of pitch.

Interestingly, in Atlas Air flight 3591 there was also a heave cue present before elevator inputs were started, from which the perceptual model does not predict a pitch illusion. However, if we calculate what pitch changes could correspond with such a heave cue, there could be an illusion of about 5° pitch up angle.

4-1-2 Physiology of the vestibular system & heave cues

A second potential reason why a heave cue may lead to a false perception of pitch, is that the utricle is tilted with respect to the horizontal. Compared to Reid's Baseline, which describes a line between the bottom of the eye socket and the centre of the ear (Figure 4-4).

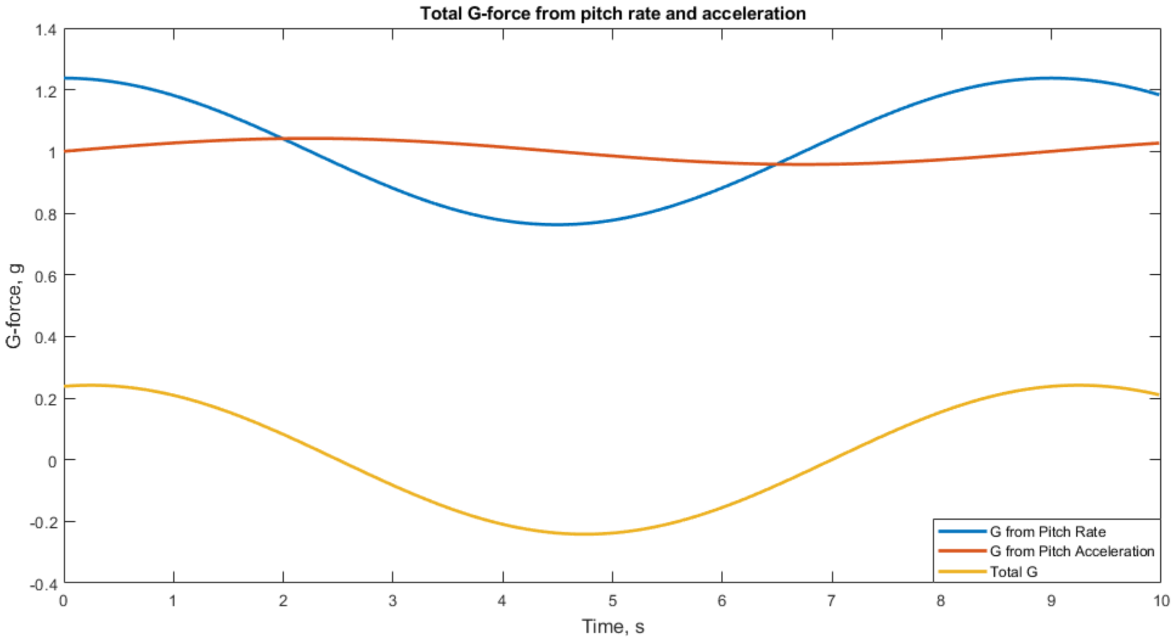


Figure 4-1: The total G-force obtained from combined pitch rate and pitch acceleration

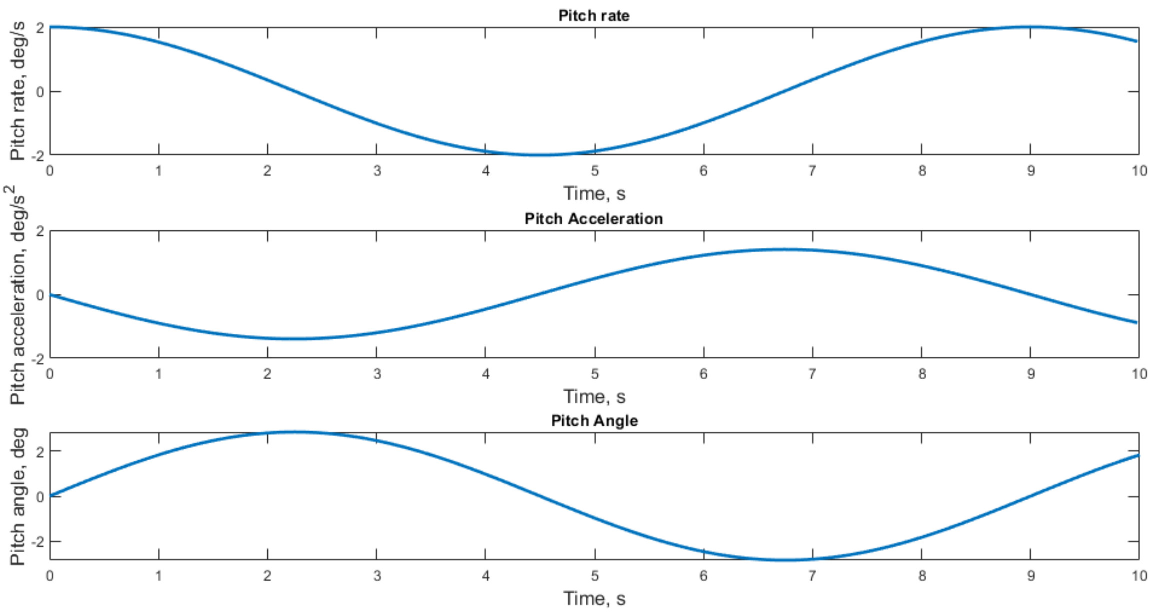


Figure 4-2: The pitch rate

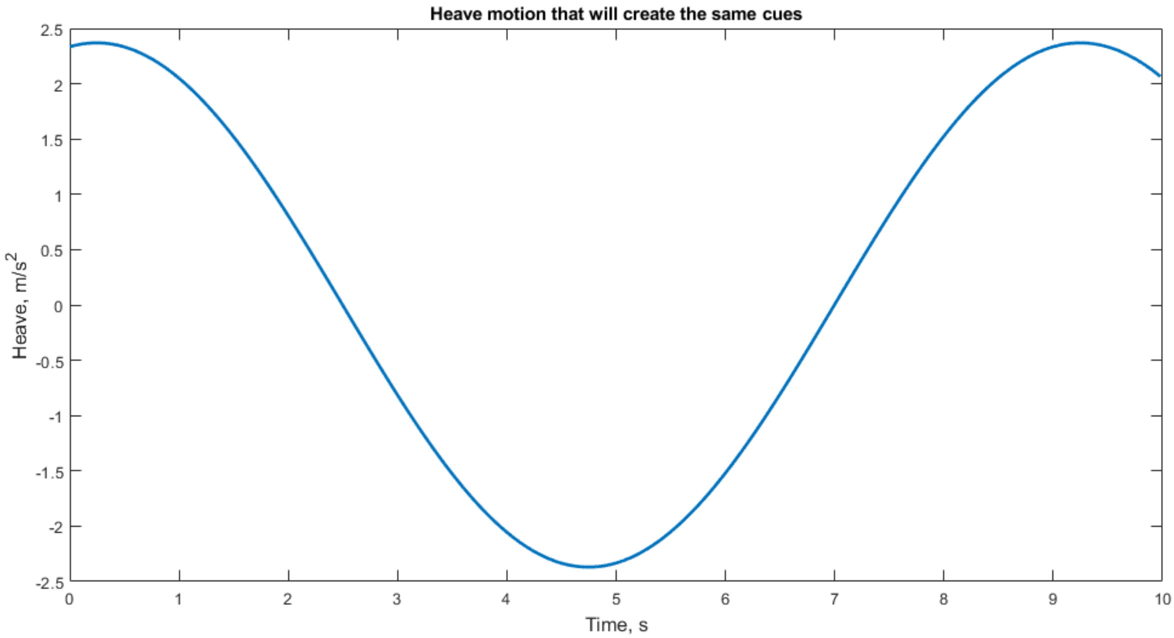


Figure 4-3: Heave motion that will create the same cues as the pitch inputs (described in text)

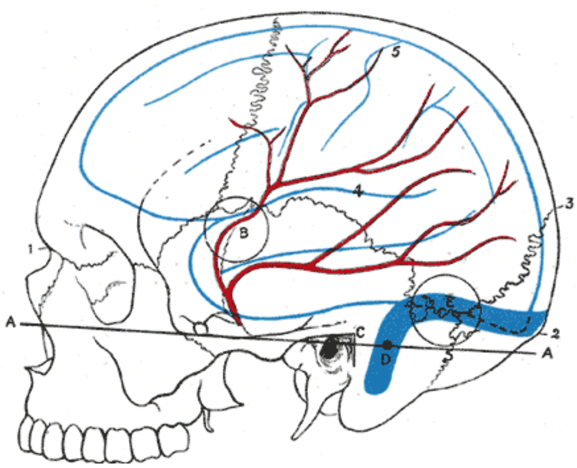


Figure 4-4: Reid's Baseline A-A [13]

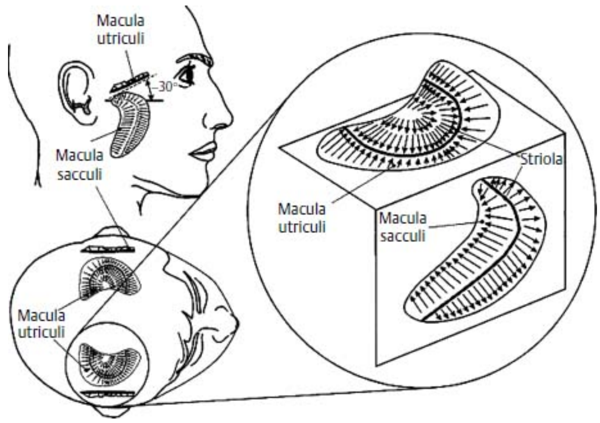


Figure 4-5: Orientation of the ottolith organ, Adapted from: entokey.com

The utricle is tilted forward by about 30°, Reid baseline itself is tilted backward by 10° [35]. Thus this tilt with respect to the horizontal will generate a signal of backwards tilt if g-forces increase, because the otolith crystals will shear backwards relative to the organ (see Figure 2-3).

Indeed several studies have shown that G-forces cause a pitch-up sensation. In a study where participants were subjected to five minutes of constant 2g, there was an average pitch up sensation of 21° in non-pilots, 19.8° in fighter pilots and 25.9° in helicopter pilots [36].

In a different experiment non-pilots also experienced on average 22.5° of pitch-up sensation when exposed to five minutes of 2g [37].

However these heave cues are of a very low frequency compared to the heave cues we are interested in. Still if we look at the group means for several time intervals in Figure 2 of [37], it appears that after 15 seconds of the plateau the average pitch-up sensation was already 10°.

When participants were facing forward of backward with regard to the centrifuge acceleration direction. Although the heave cue indicated a pitch, there was no corresponding signal from the semicircular canals, which means that if there was a pitch, it could only be a slowly developing pitch. It is interesting that in the condition where the 2g plateau was preceded by a pitch up motion (centrifugal condition) the average pitch illusion during the first 30 seconds was already 16° instead of 10°.

Concluding, these studies show that a low frequency heave cue induces a pitch perception. But for this to work at a higher frequency, it is likely necessary to induce a signal from the SCC as well.

4-1-3 The rotation of the gravito-inertial force vector & heave cues

The third hypothesized reason why a heave cue may lead to a false pitch perception is the rotation of the gravito-inertial force vector. In Section 2-1-2 we explained how the Otolith organ perceives linear accelerations by sensing the specific force given in Eq. 2-1. When there is a sustained change in linear acceleration, such as a strong forward acceleration during a go-around manoeuvre, the otolith organs cannot distinguish this vector from the gravity vector, the result is the incorrect interpretation of the gravito-inertial force vector as a tilt backwards. If for example due to turbulence, a heave cue directed upward were to be present during this forward acceleration this could result in an even further tilted resultant force vector.

4-1-4 The elevator illusion

The elevator illusion, a false sense of being in a climb, is insinuated by the occurrence of a sudden vertical acceleration directed upward, for example a wind gust, which causes the pilots vision to momentarily be directed downward. When the vision is directed downward, the visual scene is moved upward. Weightlessness as a result of accelerations can also be a trigger of the elevator illusion [5]. If a pilot were to abruptly level off during a descent they may similarly experience their eyes being directed downward by the gravity-force, which can visually create a sense of being in a climb. Reciprocally the same effect can be obtained with a constant rate climb which is leveled off, then the eyes are moved upward (Figure 4-6). The visual system is known to dominate the human's SO-mechanism [38], therefore this sensation can be especially strong. The response to this illusion can be a correction of the sudden false sense of manoeuvre by steering the nose of the aircraft down.

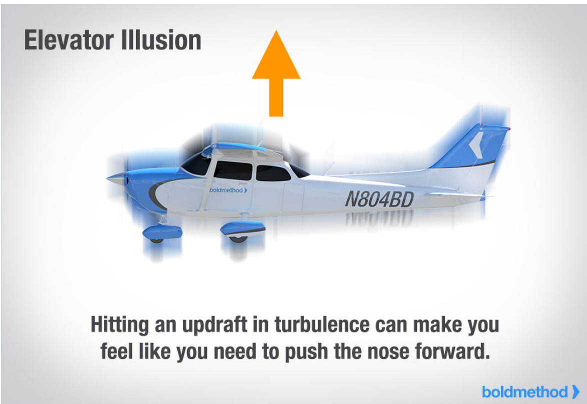


Figure 4-6: Elevator Illusion, Adapted from: Boldmethod.com

4-2 Atlas Air Flight 3591 Analysis

In this section the 2019 Atlas Air accident will be studied in depth, with a focus on the presumed occurrence of spatial disorientation.

On February 23, 2019 Atlas Air Flight 3591 suddenly made a rapid descent and crashed in Trinity Bay, Texas, fatally injuring its two pilots and one passenger. The aircraft was a Boeing 767-375BCF registered N1217A and was operating as a domestic cargo flight for Amazon Air and heading to George Bush Intercontinental Airport in Houston, Texas. Prior to the events after which the flight took a fatal turn, it had a normal, incident free take off and flight from Miami International Airport in Miami, Florida. The accident took place during the flight's final phase as it was descending for approach.

According to weather reports the aircraft was expected to have met weather conditions of light to moderate turbulence in the area. During the flight's final phase, while descending for approach, the go-around mode was activated, the communication and voice recordings indicate that the activation was most likely undeliberate. Shortly thereafter a Warning went off and nose-down inputs were recorded, although the pilots tried to correct this manoeuvre, shortly thereafter it was already too late, the aircraft crashed in Trinity Bay, Texas fatally injuring its two pilots and one passenger [26].

Final phase of flight 3591
The aircraft was cruising at 34,000ft when it started its initial descent at 12:25 CST. Six minutes later the crew contacted the Houston Approach and received instructions to fly to runway 26L. Another four minutes passed and the ATC informed the crew of 'light to heavy' precipitation and gave them a heads-up for possible extra instructions regarding the weather that might follow. At 12:36:35 CST the aircraft reached an altitude of 10,000 ft. Just before reaching this altitude, the captain spoke on the radio to the ATC approach controller. The ATC controller indicated the required vectors to approach runway 26L and inquired what route and measures the crew was planning to undertake around the weather. Just a few seconds later the FO mentions a phonetic sound 'F' attributed by the NTSB as a concern with a display, this was quickly followed by a switch to the captain as pilot flying. Meanwhile the first officer informed ATC that they would be flying west of the weather. ATC responded by urging the crew to remain at 3,000 ft west of the weather and after that go northbound. The crew correspondingly selected 3,000 ft in the mode control panel. Next the speed brake handle was manually moved to UP position. [14][15][26]

Just a few seconds later the first officer mentioned the Electronic Flight Instruments button and then swiftly said "*I got it back*". At 12:37:16 CST, just two minutes before the end of the recordings, the ATC instructed the crew to turn to a heading of 270, which was executed about 10 seconds later. At 12:37:25 the first officer once again was set in charge as pilot flying. Subsequently the flight crew discussed the Flight Management Computer (FMC) inputs required for their final approach to the runway. The captain moved the flap handle to 'position 1'. Around 12:38:26 CST, as the aircraft descended through 6,500 ft, an increased amount of perturbations can be noted when observing airspeed, angle of attack and accelerations. These perturbations and control inputs correspond to the aircraft entering turbulence.

Just a few seconds later at 12:38:31, as the aircraft passed through 6,300 ft, a click can be heard on the cockpit voice recorder and from the Flight Data Recorder (FDR) it can be seen that this was consistent with the activation of the auto-throttle go-around (GA) mode. Neither crew nor ATC made prior remarks with an incentive to engage the GA mode and the crew did not directly react as would be expected in the case of a conscious selection of this mode. In Figure 4-7 the location of the GA switches in an exemplary Boeing 767 can be seen. From all the reports provided it is estimated that this was a non deliberate activation of the (GA) mode. This could be an explanation as to why the pilots voice recordings make them appear to be startled right after the click was heard.

Figure 4-7: Location of GA switches, the red circle indicates the left GA switch. Photo taken of exemplar B-767 by NTSB investigators on February 27, 2019 [14]

Six seconds later the speed-brake handle is manually retracted to ARMED position and the engines reach GA power settings. From this moment onward forward deflections of the control column are registered and both a Master Caution as well as a autopilot caution go off. At 12:38:44 CST the CVR registers the first officer voicing surprise as he seems to focus on the aircraft's speed. Within two seconds the thrust levers are manually brought to an idle position and then re-advanced, at this time the pitch attitude was rapidly increasing and a vertical g was noted to be negative for a duration of 11 seconds. Hereafter the captain shortly communicated with ATC. The two pilots seem to be giving varying elevator inputs during a period of 10 seconds as a split between the two elevators positions occurs. At this time the FO makes a remark about stalling, while there is no evidence that this was the case. At 12:38:50 the captain literally expresses confusion: "*What's going on?*" as airspeed exceeds the maximum operating speed of 360 knots. Meanwhile the Master Warning and Over-speed discrete parameters as well as the aural Siren warning alert are issued. In the final seconds before the aircraft crashes the elevator positions become symmetric and the airplane gets out of GA mode. From then on full nose-up inputs are given until the very end of the recordings at 12:39:03CST. The final path of the flight from 10,000ft to the end of recording can be seen in Figure 4-8.

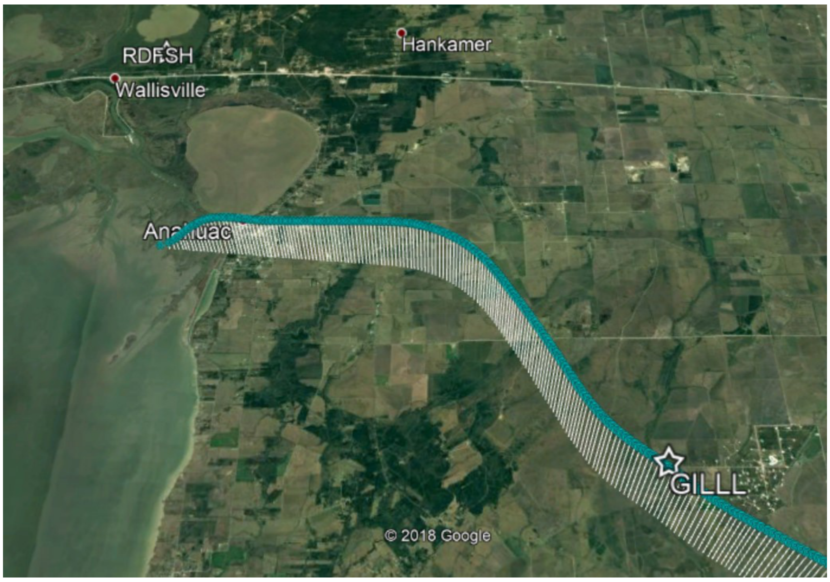


Figure 4-8: The final flight path of Atlas Air 3591 from 1000ft to the end of recording [15]

Weather circumstances

On the day of the accident a cold front was present at the accident site [26]. This induced moderate strength convective weather, which in turn caused turbulence, however the aircraft did not directly traverse the location of the convective weather [16]. Furthermore there were strong winds present from the southwest. As mentioned in 4-2 the crew received vectors to guide them around the front. Their exact route, including the weather at that time can be seen in Figure 4-9.

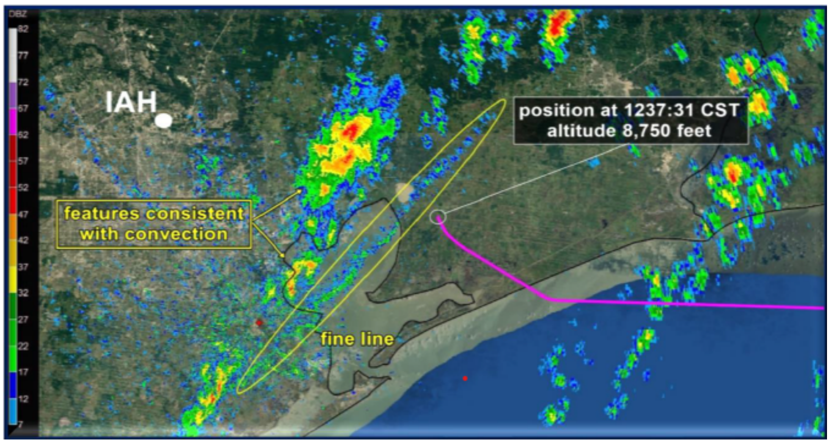


Figure 4-9: The flight path as carried out from ATC weather avoiding vectoring instruction [16]

The so called 'fine line' that can be seen in Figure 4-9 represents small birds and bugs that are being lifted and moved around as a result of wind gusts originating from the weather front behind it. Although it is difficult to determine in hindsight, the aircraft may have undergone the same lifting wind gusts around the time it was close to this area. At 11:13 CST Automatic Terminal Information Service (ATIS) showed winds 320 at 18 knots with gusts of 42 knots.

The visibility was noted to be about 8 miles, including mist and scattered clouds at 1,600ft as well as broken clouds at 2,000ft [15]. In the next paragraphs a perceptual analysis of of the flight details will be performed, in that section we will also try to distil any possible effects of these weather circumstances on the pilot perception.

Accident analysis

An accident report stated the following: "*It is unclear whether the First Officer's disorientation occurred before or because of the activation of GA mode.*" [39] In this report an attempt is made at further analysing the circumstances of the accident by using flight 3591's FDR information as an input for the perceptual model introduced in Section 3-3.

The data that was directly available from the FDR, provided a specific force, so the model was adjusted such that specific force was directly an input to the otolith block instead of acceleration. The gravity vector was determined by usage of the aircraft's rotation angles ϕ, θ and ψ and performing a quaternion vector rotation. First the rotation angles are transformed into quaternions q_0, q_1, q_2, q_3 (Eq. 4-3).

$$q = \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} cos(\theta/2) \\ sin(\theta/2)\mu_x \\ sin(\theta/2)\mu_y \\ sin(\theta/2)\mu_z \end{bmatrix} \tag{4-3}$$

Where μ_x, μ_y and μ_z represent the unit vector $[1, -1, -1]$ about which the quaternions rotation takes place.

As angular velocity was not directly available from the data, this was calculated by performing a matrix multiplication of a rotation matrix, with derivatives of each angle, as can be seen in Eq. 4-4 [40].

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & 0 & -sin(\theta) \\ 0 & cos(\phi) & cos(\theta)sin(\phi) \\ 0 & -sin(\phi) & cos(\theta)cos(\phi) \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \tag{4-4}$$

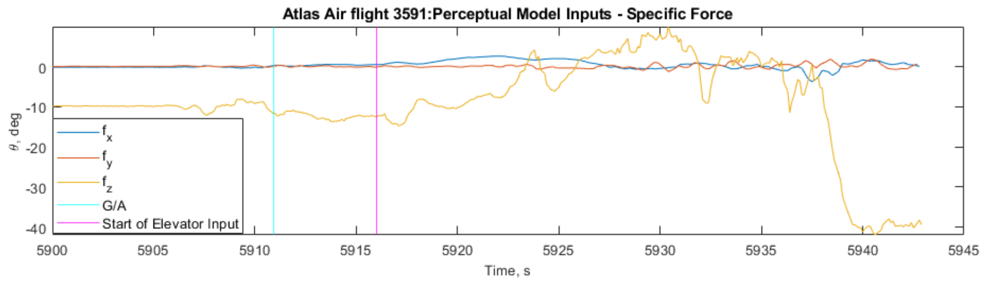
The perceived pitch angle θ_{sensed} was obtained by applying Eq. 4-5 to the sensed x and z factors from the obtained subjective vertical.

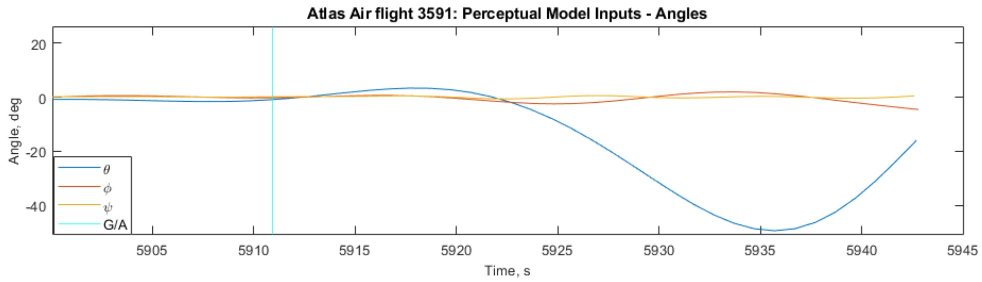
$$\theta_{sensed} = \arctan\left(\frac{x}{z}\right) \tag{4-5}$$

In the appendix in Figure A the adaptations of the applied perceptual model in Simulink can be seen, including a detailed view of the gravity block in Figure A.

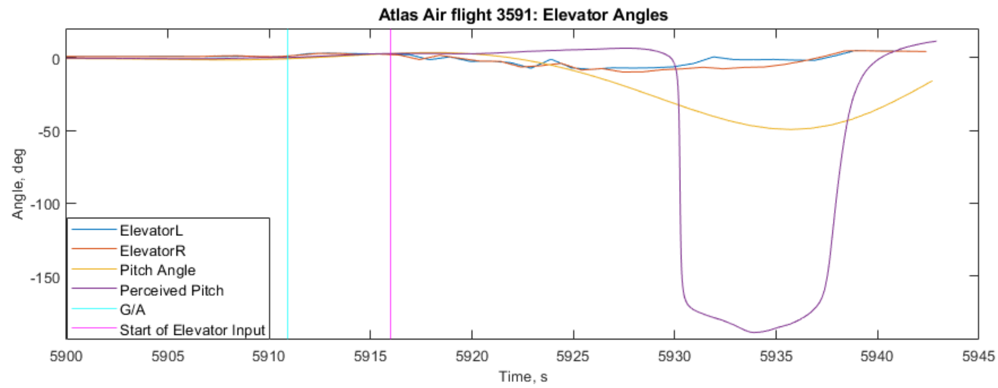
Figure 4-2 displays the inputs of the perceptual model, above the specific forces in x, y and z direction can be seen and below the ϕ, θ and ψ angles are presented, these values have been obtained from the FDR and filtered in order to achieve noise free signals. The beginning values of all figures have been omitted from the graphs, as they were observed to be steady and we are interested in the short time-span right before the go-around was initiated and the period immediately after, which lead to the accident.

In Figure 4-2 the outcome of the perceptual model can be seen in purple as the 'perceived pitch', the yellow line presents the actual value of the pitch angle further the elevator inputs



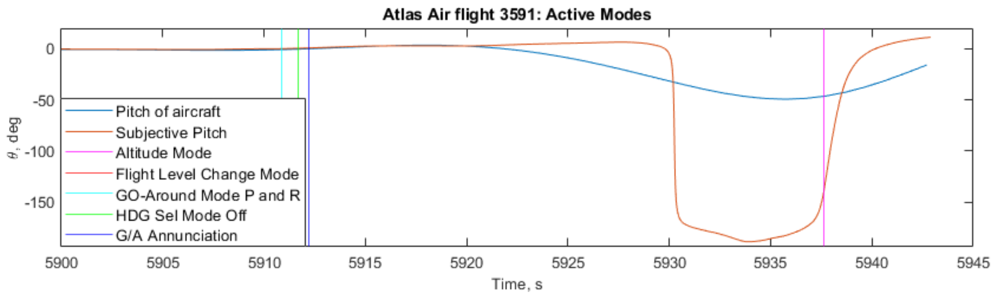


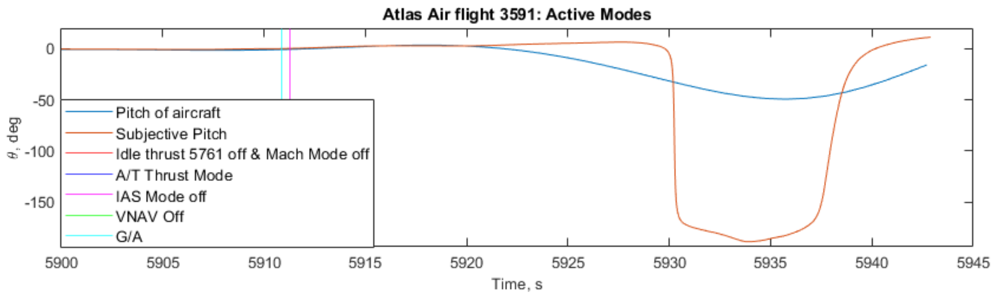
can be observed, with the left elevator in blue and the right elevator in red. At 5916s the pilots start giving elevator inputs, these two inputs are not entirely parallel, which could indicate confusion between pilots. The perceptual model does not simulate a large perceived pitch angle right after the go-around, as would be expected due to an increase in thrust. Instead the perceived pitch angle seems to slowly increase, with a slight lag relative to the actual pitch angle and then it plummets right after the actual pitch takes an extreme drop.

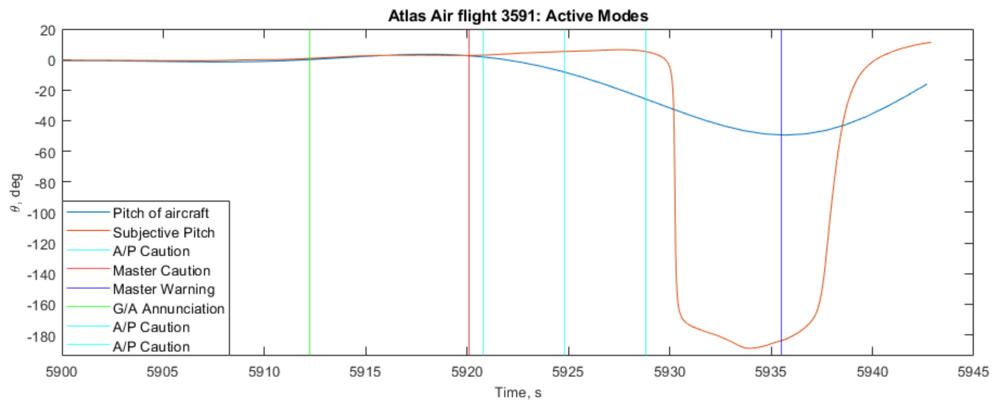


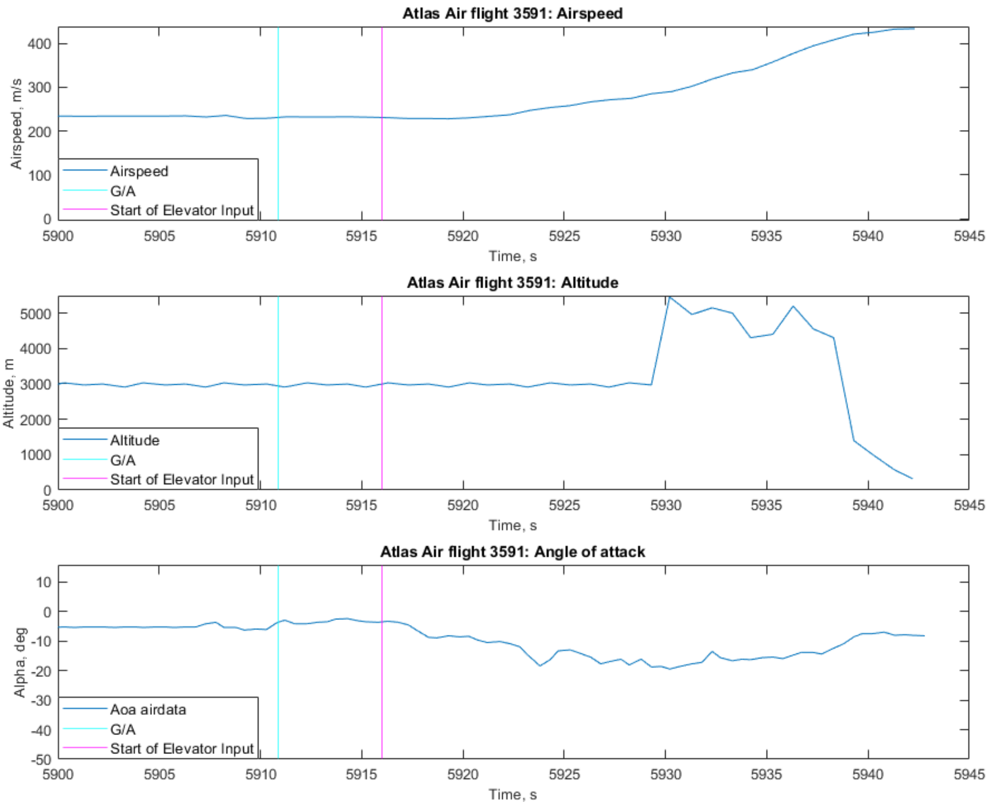
In order to better understand the circumstances of surrounding the air crash we can observe the activated aircraft modes in Figure 4-2 and the alerts in Figure 4-2. The idle thrust and Mach modes are switched off at an earlier moment in the flight, which is not included in the figures, a while later the A/T thrust mode is engaged and remains so until the final stage of the flight, whereas the VNAV mode is switched off. Right after the go-around is activated, the heading select and IAS modes are switched off, quickly followed by the go-around annunciation. About 8 seconds after the G/A annunciation has taken place, the master caution is activated and is successively followed by a series of A/P cautions, at the moment the actual aircraft pitch angle is at its maximum a master warning is sounded. From the elevator inputs and the then again climbing aircraft pitch angle it can be seen that the pilots made an attempt to correct their attitude but unfortunately their situation awareness set in too late. In Figure 4-2 the airspeed, altitude and angle of attack of the flight can be seen. After the go-around activation the airspeed slowly climbs, but it takes a while for the altitude change.

Many facts, including the reaction and inputs, as well as the attempt to recover situation awareness by the pilots suggests the their are convincing signs of a somatogravic illusion being a causal factor. However this does not come forward when observing the outcome of the perceptual model. Therefore the question arises, whether the perceptual model may be missing a form of input and its analysis. The weather circumstances may very well have been of a large influence on the pilots' perception, however this model does not include weather options such as a wind gust as an input. Visual matters may also be of an influence as seen in literature, but are not included in this perceptual model. This leads us to investigate further upon the influence of weather factors and specifically wind gusts on pilot perception.








Atlas Air flight 3591: Airspeed
Airspeed, m/s
Airspeed
G/A
Start of Elevator Input
Time, s
Atlas Air flight 3591: Altitude
Altitude, m
Altitude
G/A
Start of Elevator Input
Time, s
Atlas Air flight 3591: Angle of attack
Alpha, deg
Aoa airdata
G/A
Start of Elevator Input
Time, s

4-3 Wind gust during go-around analysis in DUECA Airbus A320 environment

DUECA provides the opportunity to perform virtual flight simulation in an adaptable environment. An Airbus A320 Model was provided by DLR and forms a solid basis to approach the large commercial aircraft in which pilots have experienced somatogravic illusions as seen in the previous chapters.

The A320 model's DUECA output is in the body reference frame, which originates in the aircraft centre of gravity and is defined with the positive x-axis in line with the aircraft's longitudinal axis, the y-axis in the lateral direction facing to the right of the aircraft and the z-axis facing down as can be seen in Figure 4-10

Figure 4-10: The aircraft body reference frame

In a primary approach towards the perception of go arounds and wind gusts, the perceptual model as presented in Section 3-3 was connected to the output of a DUECA A320 simulated go-around procedure. As the models original inputs are an output of the DUECA A320 model, no adjustments were made. The effect of various strengths and types of wind gusts was examined.

Regular go-around condition without wind

In first instance a regular go-around was performed without the addition of any wind gusts. In Figure 4-11 the perceptual models output can be observed aside the simulated go-arounds angle of attack and its vertical speed. It must be noted that because the DUECA simulation is in the body reference and the perceptual model in the head reference, all representations of DUECA outputs have an opposite sign, as a positive 'z axis' for the perceptual model is on the opposite direction. From 4-11 it can be seen that directly after the go-around is initiated both the vertical speed and the angle of attack start increasing. The orange line is the perceptual models output, or in other words the pitch angle of the subjective vertical. The red line is purely there for verification reasons, and is the pitch angle as directly calculated from the specific forces.

From now on the orange line or the 'pitch as perceived from subjective vertical will only interest us. The go around manoeuvre results in a fast increase (of high frequency) of the perceived pitch angle, which is higher in both value and frequency than the actual pitch of the simulated flight. This illustrates the gravito-inertial vectors false interpretation effect as reported in previous sections of this report. It can be remarked that the perceived pitch does not very closely follow the line of the actual pitch once the go-around has been initiated. In Figure 4-12 the strong sharp increase of the linear acceleration can be seen aside the perceived pitch.

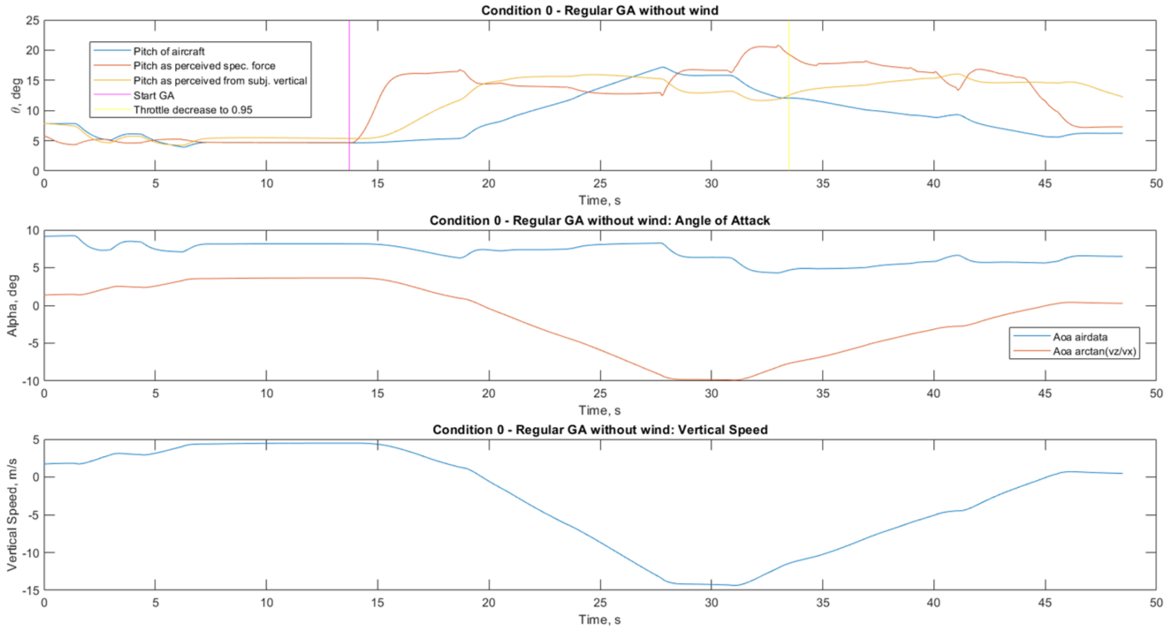


Figure 4-11: Regular DUECA A320 go-around without wind as input for perceptual model, angle of attack and vertical airspeed

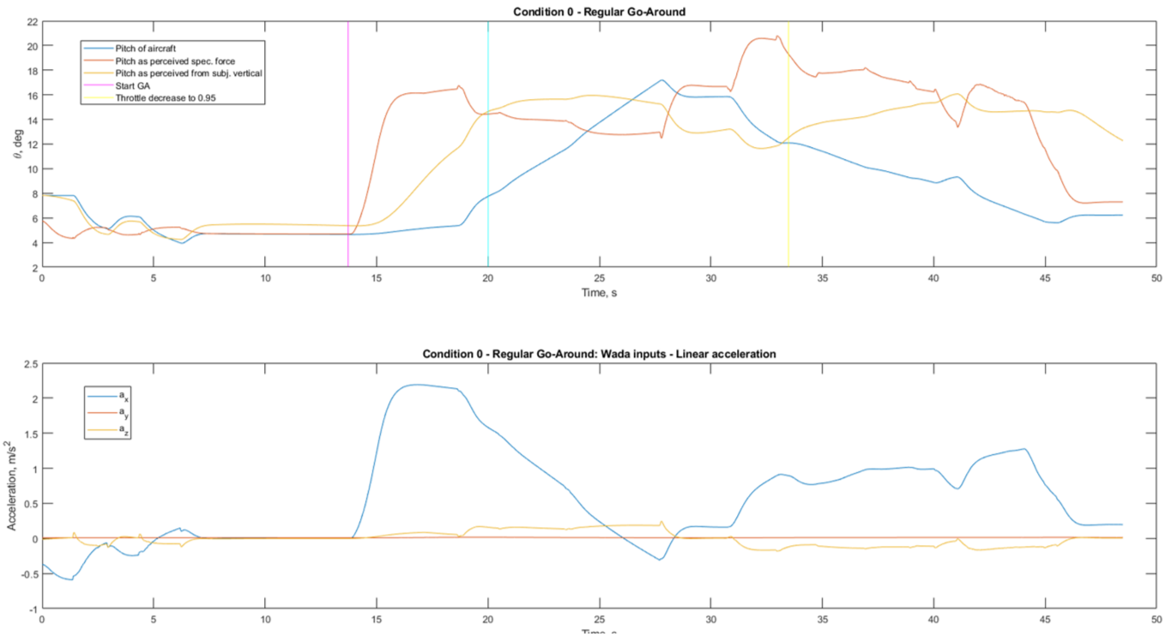


Figure 4-12: Regular DUECA A320 go-around without wind as input for perceptual model, linear acceleration

As stated in the research question we are interested in the addition of a wind gust or heave cue. Therefore the same go-around was performed, while two heave peaks of 17.5kts were included in the simulated flight circumstances. In Figure 4-13 the wind gusts can be seen aside the output of the perceptual model. While 17.5kts is a substantial intensity, the wind gusts only seem to have a very small effect on the perceived pitch angle. In Figure 4-14 the angle of attack and vertical speed for the manoeuvre with the wind gusts can be seen.

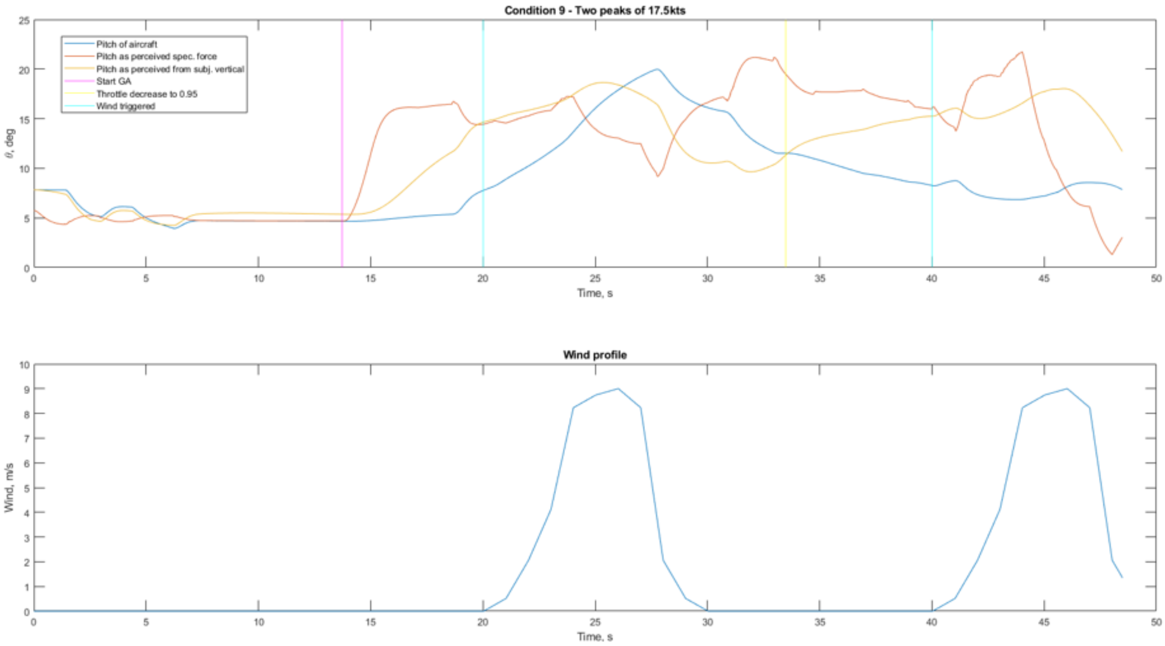


Figure 4-13: DUECA A320 go-around with two 17.5kts wind gusts as input for perceptual model, model output and representation of the wind gusts

A side by side comparison of the perceptual models outputs for the go-around with and without wind-gusts is interesting to make. We have already observed that the perceived pitch angle is influenced by a go-around by increasing beyond the actual simulated flights angle. In Figure 4-15 it can be seen that after the wind gusts begin the perceived pitch is slightly increased compared to the situation without wind. Around 25s the perceived pitch reaches a peak value, which is also around the same timing that the actual wind gust reaches its peak value. The second wind gust results in a very similar output of the perceptual model. In Figure 4-16 angles of attack of both these simulated go-arounds can be seen as a reference. While the perceptual model does react on the wind-inputs it is interesting to see that its output of perceived pitch is quiet moderate. It is interesting to further investigate this, as it is a possibility that the perceptual model does not incorporate heave cues sufficiently yet, or wind-gusts may simply not result in a significant vestibular reaction of perceived pitch. The next section will therefore propose a method for the further exploration of this notion.

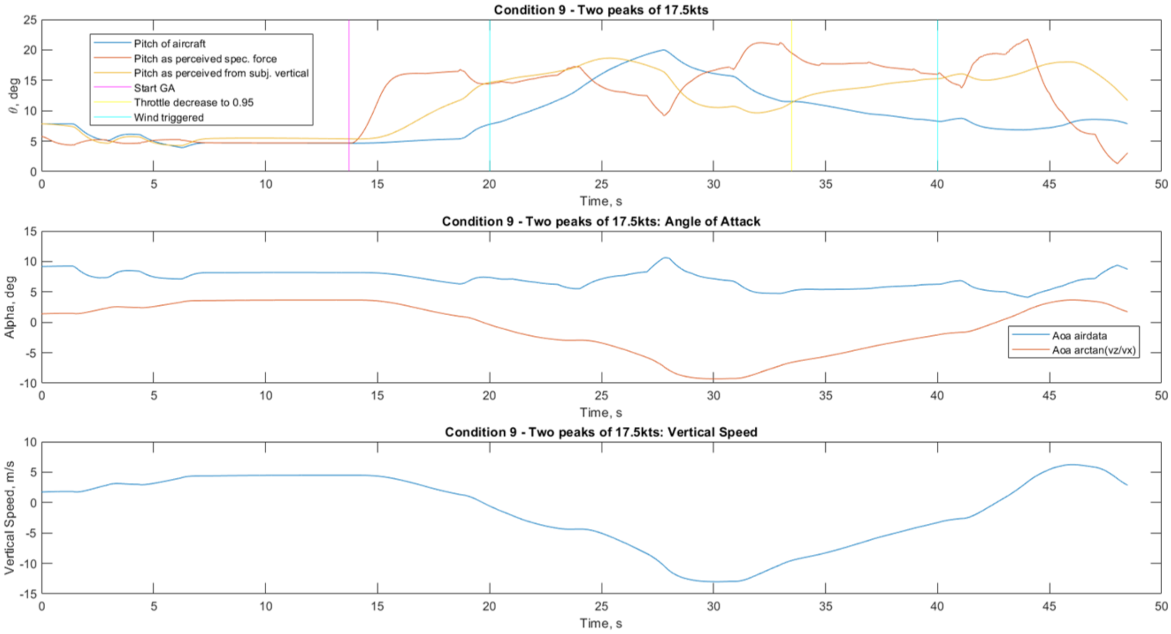


Figure 4-14: DUECA A320 go-around with two 17.5kts wind gusts as input for perceptual model, angle of attack and vertical airspeed

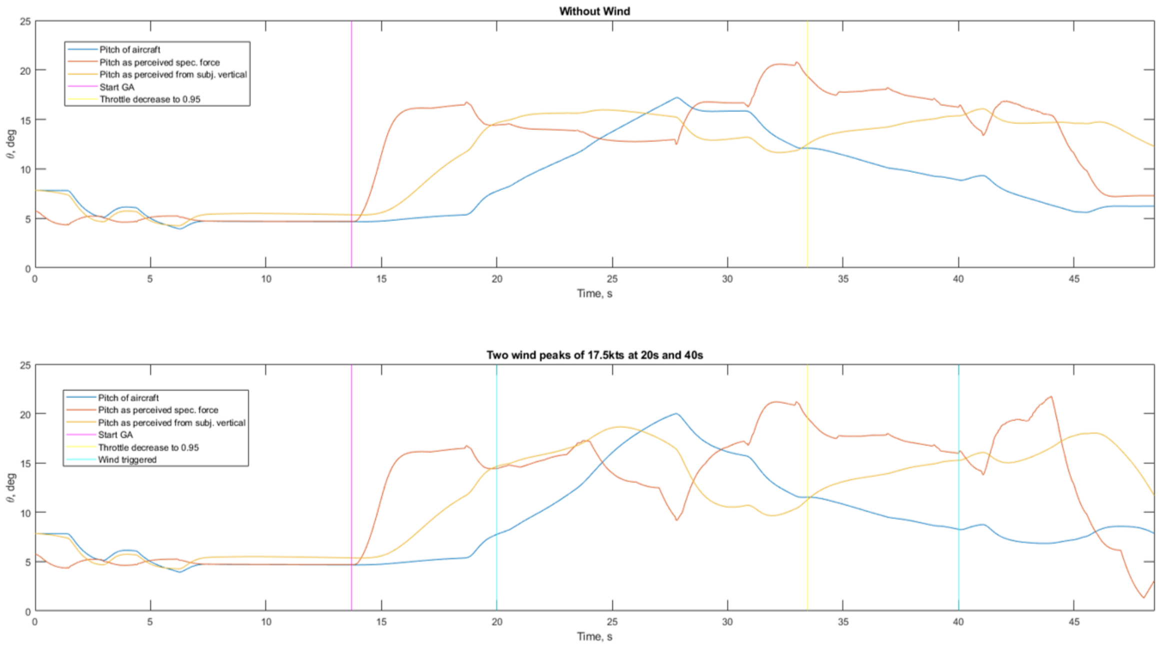


Figure 4-15: Comparison of DUECA A320 go-arounds with and without two 17.5kts wind gusts as input for perceptual model

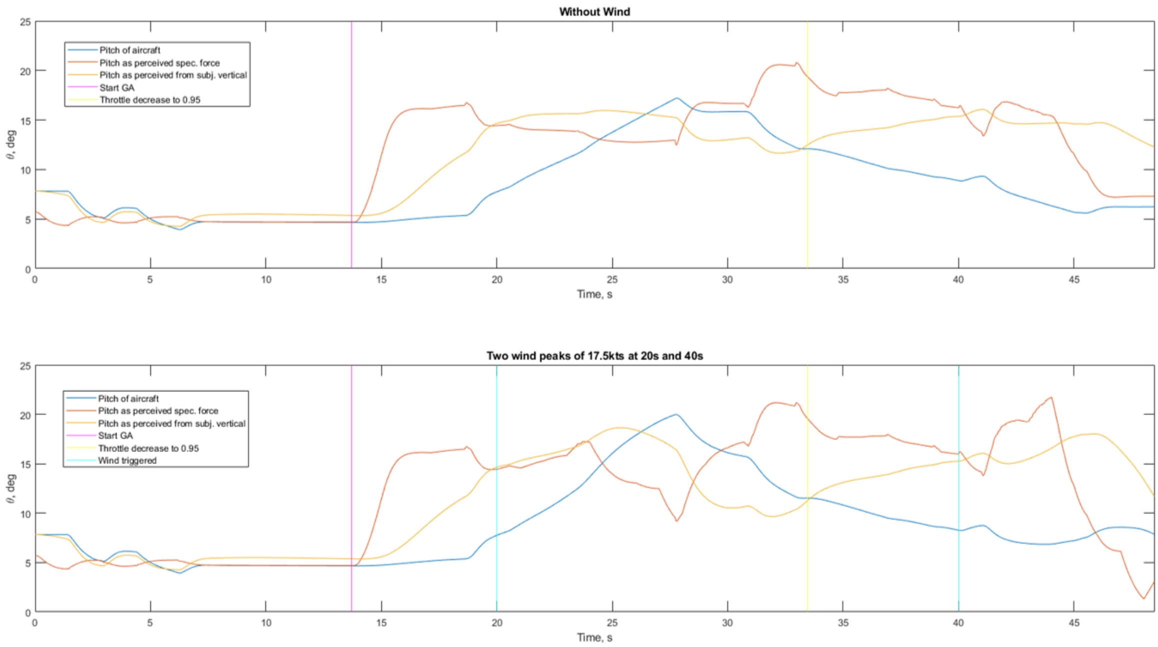


Figure 4-16: Comparison of DUECA A320 go-arounds with and without two 17.5kts wind gusts as input for perceptual model, angles of attack

4-4 Proposed Method

In this section the experimental approach to answering the research question and sub questions will be introduced. During experiment development specifically a focus was made on investigating the effect of the combination of a heave cue with a pitch cue. In a primary stage motion profiles were developed and tested, this scenario development stage will be described, next the participants and apparatus will be specified and finally the experimental procedure and the participants task will be described.

4-4-1 Participants

A total of 10 to 20 currently professionally active airline pilots with experience in large aircraft will be recruited for participation in a within-subject experiment.

4-4-2 Apparatus

The experiment will be conducted in the SIMONA Research Simulator (SRS) at the faculty of Aerospace Engineering of the TU Delft. This simulator functions using a hydraulic hexapod motion system with which it attains six-degrees-of-freedom full-motion simulation. The pilots will be seated in the right hand seat of the cockpit, all displays and controls will be turned off. The primary fight display will be used to present an image consisting of an overview of 8 different attitude indicators each adjusted at a different pitch angle of: $0°, 2.5°, 5°, 7.5°, 10°, 12.5°, 15°, 17.5°$. For this experiment the motion signals will directly be programmed into the motion system, allowing for more freedom of motion by not applying an aircraft model. Participants will wear headphones with masking sounds in order to cover any sound induced by the actuators. Any communication with the participants will be done through the headphones with the researchers. In Figures 4-17 and 4-18 the SRS and the experimental set-up within the simulator can be seen.

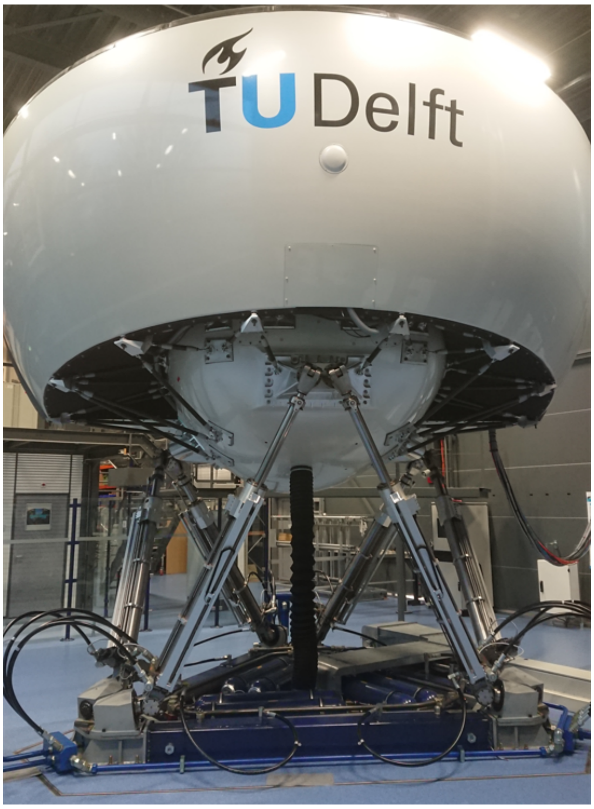


Figure 4-17: SIMONA Research Simulator (SRS)

Figure 4-18: Experimental set-up within the SIMONA Research Simulator (SRS)

4-4-3 Motion profile design

A motion profile was designed such that a heave cue and pitch cue as stated in the sub questions in Section3-4 could simultaneously be triggered in a hexapod simulator. For both pitch and heave signals a 7^{th} order smooth step function was chosen, as its derivative and double derivatives remain non-zero which allows for continuous and smoothly coordinated position, velocity and acceleration signals. All other signals were set to zero, such that the simulator would uniquely receive motion inputs in the longitudinal plane.
The physical limitations in extension (neutral position $\pm 55cm$) and actuator velocity ($\pm 0.75m/s$) of the SRS were used to set up boundaries for the signals.

Pitch cue signals

$$\begin{aligned} \theta &= h_0(-20h^7 + 70h^6 - 84h^5 + 35h^4) \\ \dot{\theta} = q &= h_0(-140h^6 + 420h^5 - 420h^4 + 140h^3)(\frac{1}{(h_2 - h_1)}) \\ \ddot{\theta} = \dot{q} &= h_0(-840h^5 + 2100h^4 - 1680h^3 + 420h^2) \cdot (\frac{1}{(h_2 - h_1)})^2 \end{aligned} \tag{4-6}$$

(with h, h_0, h_1, h_2 factors chosen according to the desired motion characteristics and simulator requirements.)

For the pitch rate a maximum of $3deg/s$ was maintained as this is in line with the standard pitch-up procedures of pilots. The pitch cue smooth-step signal was then mirrored and shifted in order to design an identical level-off maneuver.

Heave cue signals

$$\begin{aligned} z &= k_0(-20k^7 + 70k^6 - 84k^5 + 35k^4) \\ \dot{z} = v_z &= k_0(-140k^6 + 420k^5 - 420k^4 + 140k^3)(\frac{1}{(k_2 - k_1)}) \\ \ddot{z} = a_z &= k_0(-840k^5 + 2100k^4 - 1680k^3 + 420k^2)(\frac{1}{(k_2 - k_1)})^2 \end{aligned} \tag{4-7}$$

(with k, k_0, k_1, k_2 factors chosen according to the desired motion characteristics and simulator requirements.)

The heave signal is timed and shifted such that the peak value coincided with the peak value of the pitch-rate or pitch-acceleration (according to desired scenario settings). A mirrored identical heave signal was again triggered such that its peak was again simultaneous with that of the level-off maneuvers' pitch-rate or pitch-acceleration. The final heave intensity values were found by seeking the boundary value of the motion systems limits while also performing the largest chosen pitch cue. This resulted in the choice of a fast climbing and high intensity signal and a second longer lasting but less intense signal. In Section 4-4-4 the exact details of the designed signals can be found.

In Figure 4-19 a motion profile example can be seen of scenario 5. In scenario 5 the heave cues intensity is $0.58m/s^s$, it is timed on $\dot{q}$ and the pitch angle is 15°, the corresponding actuator motions can be seen in Figure 4-20. In Appendix E an overview of all the defined 27 scenarios and their details can be found.

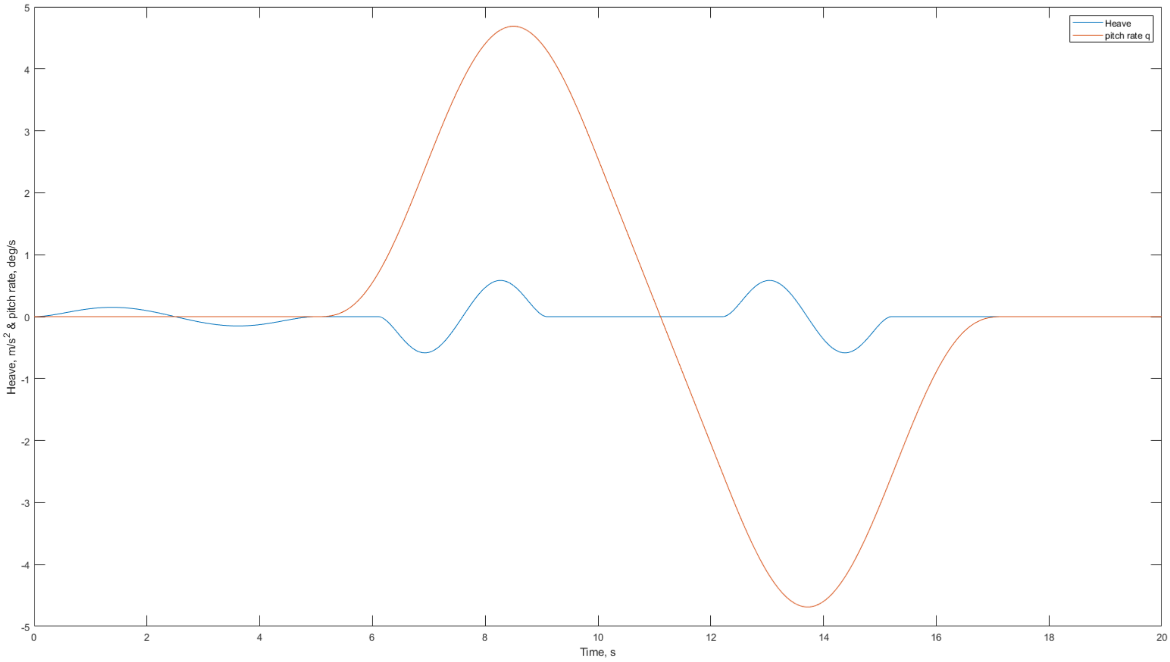


Figure 4-19: Motion profile example of scenario 5

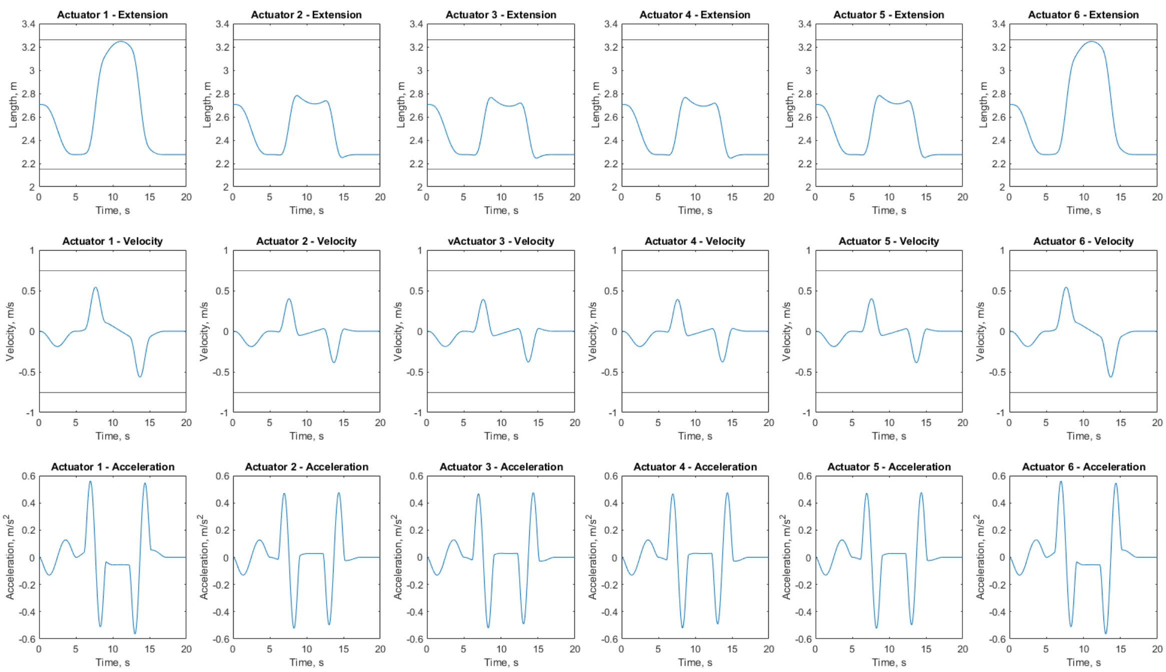


Figure 4-20: Actuator motions within their upper and lower limits

4-4-4 Experiment Procedure

The subjects will be given a briefing of the experiment, a general information sheet to fill in and asked to sign a consent form. The general script of the experimental procedure is given below in Table 4-1. In the appendix the recruitment notice B, participants briefing C and the debriefing D can be found.

Table 4-1: Experiment Timeline

Component	Duration	Description
Participant Welcome	20 min	Experiment Briefing & Fill in information sheets and sign consent form
Seating of participant	10 min	Participants are seated in the SRS and the safety measures are shown
Familiarisation	4 min	Participants are familiarized by providing them with 5 representative practice runs
Experiment, first half	15 min	The first half of the experiment runs are executed.
Break	15 min	The participants can leave the SRS during this break and refresh themselves.
Micro-Familiarisation	1 min	Participants are familiarized by providing them with 1 practice run before the actual experiment continues.
Experiment, second half	15 min	The second half of the experiment runs are executed.
Debrief	15 min	After exiting the SRS, participants fill in a debrief questionnaire, then they get the opportunity to receive a more detailed explanation of the study.
Total Duration	1h 35 min	

Chapter 5

Conclusion

In conclusion it is clear that while the somatogravic illusion is already a well researched topic, there is still place for further investigation. The specific weather situation wherein a wind gust or a heave cue coincides with a pitch cue is chosen as the scope to experimentally further investigate as introduced in the proposed method. The outcome of the future of this study may further help improve training procedures and perceptual models.

Appendix A

Simulink adaptation of perceptual model 3-3

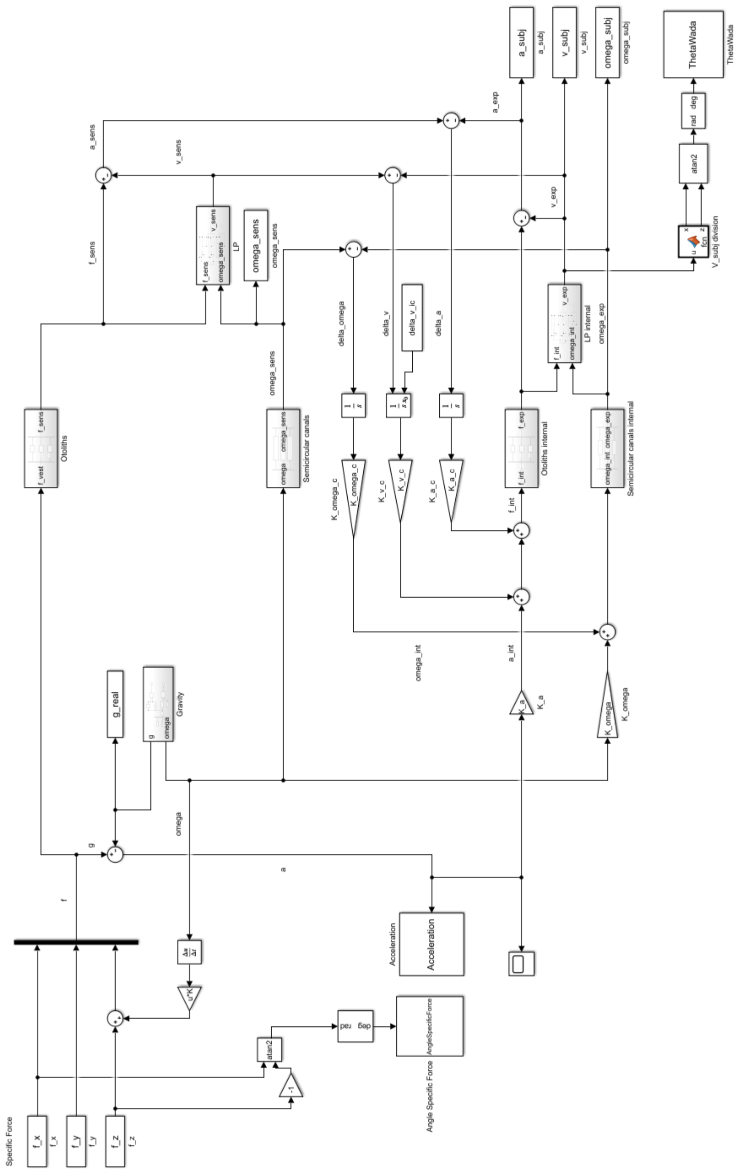


Figure A-1: The perceptual model as used in this analysis

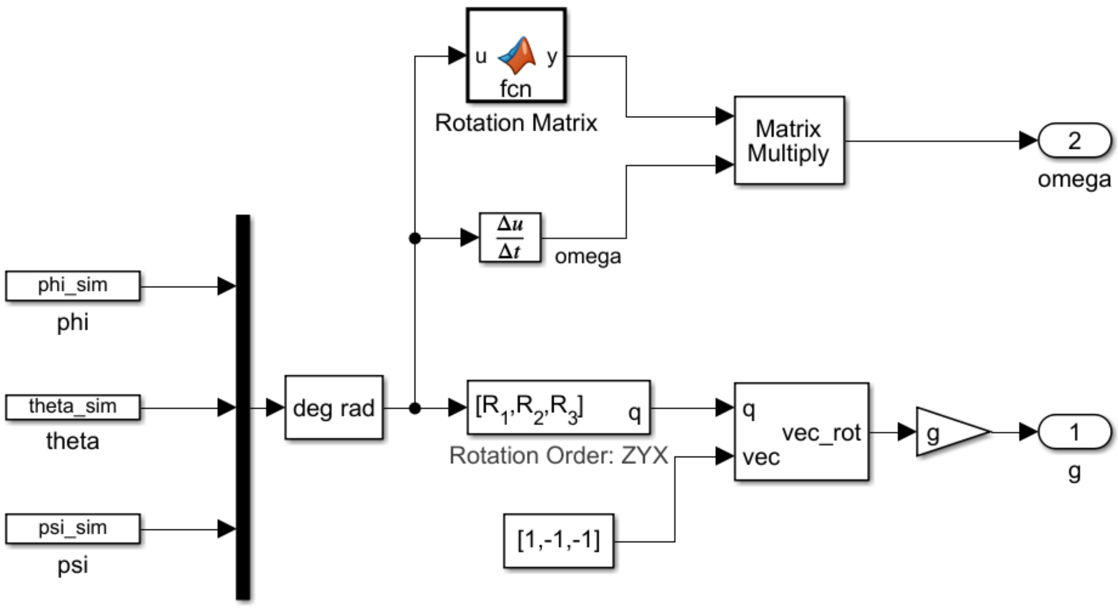


Figure A-2: The content of the gravity block as used in the perceptual modelA

Appendix B

Participant recruitment notice

Beste ,

Voor mijn afstudeeropdracht bij de faculteit Lucht- en Ruimtevaarttechniek aan de TU Delft onderzoek ik de waarneming van pitch in grote verkeersvliegtuigen. Hiervoor heb ik een experiment gepland dat binnenkort plaats zal vinden in de Simona hexapod simulator, hier op de faculteit. Ik ben op zoek naar deelnemers die als commerciele piloot ervaring hebben met grote verkeersvliegtuigen (bv: een twinjet zoals een 737). Ik verwacht dat dit rond februari gaat plaatsvinden.

De deelnemers zullen tijdens een reeks van runs in de simulator steeds een pitch up en level off beweging voelen. Na iedere run zullen zij aangeven wat voor hun de gevoelde pitch hoek was. Deelname duurt 2 tot 2,5 uur.

Met dit onderzoek willen wij een publicatie uitbrengen die bijdraagt aan het begrijpen van motion perceptie en het ontwikkelen van betere simulatoren.
Jouw deelname zou mij heel erg helpen om een goed onderzoek neer te zetten en zo een steentje bij te dragen aan de veiligheid van grote verkeersvliegtuigen.

Als je mee wilt doen, geef mij dan even een seintje. Dan stuur ik je tegen die tijd een voorstel voor een datum en tijd.

Vriendelijke groeten,

Berna Gungen
Mail: b.n.gungen@student.tudelft.nl
Tel : 0614055827 (whatsapp contact ook mogelijk)

Figure B-1: Recruitment notice which was forwarded to recruit participants for the experiment

Appendix C

Participant Briefing

Briefing

Dear participant,

How nice that you are going to participate in my experiment in which we are investigating the perception of pitch changes in large commercial aircraft.

With this 'briefing' I would like to send you some information prior to our experiment.

The experiment will take place in the Simona Research Simulator at the Faculty of Aerospace Engineering at TU Delft. The faculty is easily accessible both by public transport and by car, below you will find some further details.

Address:
TU Delft, Faculteit Luchtvaart- en Ruimtevaarttechniek
Kluyverweg 1,
2629 HS Delft

Car:
The faculty is easily accessible by car and has its own free parking space that you can use.

OV:
• Buses go from Delft Central Station to the Kluyverpark bus stop.
• From Delft Campus Station (formerly South) the faculty can be reached in a 13-minute walk.

On the day of your experiment, I will welcome you at the entrance of the faculty at the agreed time. At that moment we will also do a QR code check with the 'CoronaCheck' app. The faculty is currently enforcing the following corona measures:

- Current RIVM measures are followed at all times
- Within the faculty, everyone is requested to wear a mask
- Participants should have no symptoms associated with COVID-19
- Participants must have a valid 'CoronaCheck QR code'
- All parties involved in the experiment from TU Delft must have completed a self-test within 24 hours in advance.

Then we will walk to the department where the simulator is located. Before we start with the experiment, I will inform you in detail about the safety instructions of the simulator and how the experiment will take place. In this video you can find some more information about the safety instructions: https://www.youtube.com/watch?v=PXijsyJ3hro

You will also receive these three documents in advance:

- experiment description (page: 3)
- a participant information form (page: 4)
- and a so-called 'informed consent' form (page: 5)
- ADI's that you get to see during the ecperiment (page: 7)

These forms have also been added to this document so that you can read them to better understand the contents of this experiment, but you don't need to do anything with them. If you have no further questions, we will begin the experiment next. The expected duration of the experiment in the simulator is 90 minutes. Halfway through the experiment there is a long break, during which you can step out of the simulator. Between the runs there is always the option of a (long) break if you indicate that you need it.

After the experiment we will do another debriefing, in which we will ask some more questions about your perception of pitch. There is also the opportunity to provide some more detail about our research.

I expect that we will be ready with everything 2 to 2.5 hours after your arrival.

Risk

Because the experiment takes place in the simulator, there is a small chance of motion sickness. If you feel any discomfort during the experiment, please let us know. We can then take a break or, if desired, stop the experiment.

Data

During this experiment we will note your pitch angle choices after each run as described in the *experiment description (page 3)*. Furthermore, we will collect the information from the *participant information form (page 4)*, *the informed consent form (page 5)* and your answers from the debriefing. We will handle this information very carefully and anonymize it for use in data analysis, publication and storage for future reference.

If you have any questions, please do not hesitate to ask, you can reach me by email or by phone!

Kind regards,

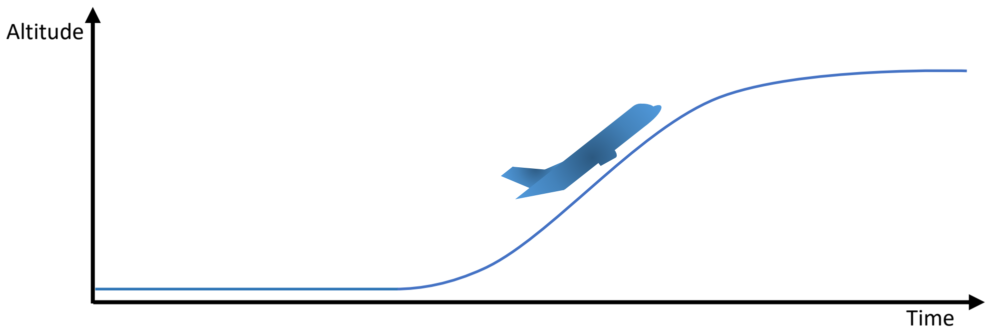
Berna Gungen

Tel: +31614055827

Mail: b.n.gungen@student.tudelft.nl

Experiment Description

- We are interested in the observation of pitch changes in a large commercial aircraft where the pilot is far in front of the center of gravity.
- You will receive a number of runs in the simulator.
- Imagine flying on autothrottle, in a twinjet like a 737 during level changes after a takeoff at about 5000 to 10000ft.
- Each run lasts 20 seconds.
- During each run you will feel a pitch up and level off movement like the one below, but sometimes you can feel something else where there is no pitch (0°) change:



- Try to imagine that you are actually flying.
- The display will be switched off during the runs. Instead, you'll see 8 attitude indicators that indicate options for pitch angles.
- Focus on the maximum pitch angle during each run.
- Look at the attitude indicators while you look for the attitude indicator that best represents the maximum pitch angle that you have felt.
- At the end of the run, indicate the letter of that attitude indicator.
- If you have not felt it clearly or are in doubt, that is no problem. During this experiment your first feeling is most important, so just report that.
- The expected duration of the experiment is: 90 minutes, halfway through the experiment there is a long break, during which you can step out of the sim.
- Between the runs there is always the option of a (long) break if you indicate that you need it.
- If you feel any first signs of motionsicknes, let us know.
- At the end we will do a debrief with some more questions.
- If you still have questions now, don't hesitate to ask ☺!

Participant Information

Before we start with the experiment, we would like to ask you to fill in some information. Of course, all provided information will be kept confidential.

Age: ………

Gender: ……

Experience as a pilot, in number of years: ………………………………………………………………………………..

Rank: ………

Large Aircraft types & hours flown: …………………………………………………………………………………………

Medium Aircraft types & hours flown: ………………………………………………………………………………………

Current aircraft types: ……..

Date of last flight: ………

Consent Form for Participation in Pilot Pitch Perception Study

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the experiment information dated [/ /], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, during or after the experiment, without having to give a reason.	○	○
I confirm that I currently do not have any symptoms associated with COVID-19.	○	○
I confirm that the researcher has provided me with detailed safety instructions to ensure my experiment session can be performed in line with current RIVM COVID-19 regulations at all times and that these instructions are fully clear to me.	○	○
I confirm that (tick the appropriate box): – I am a student or staff member at TU Delft and have performed a COVID-19 self-test no more than 24 hours prior to my arrival for the experiment or – I am not a student or employee at TU Delft and have presented the researcher with a valid 'CoronaCheck' QR code upon my arrival for the experiment	○	○
Risks associated with participating in the study		
I understand that taking part in this study involves the risk of motion sickness.	○	○
Use of the information in the study		
I understand that information I provide will be anonymised before data analysis, publication and storage for future use.	○	○
I understand that contact information collected about me, will not be shared beyond the study team and any record of this information will be deleted after the conclusion of this study.	○	○
I understand that there are no professional risks associated with the experiment with respect to work assessment by my employer.	○	○

Signatures

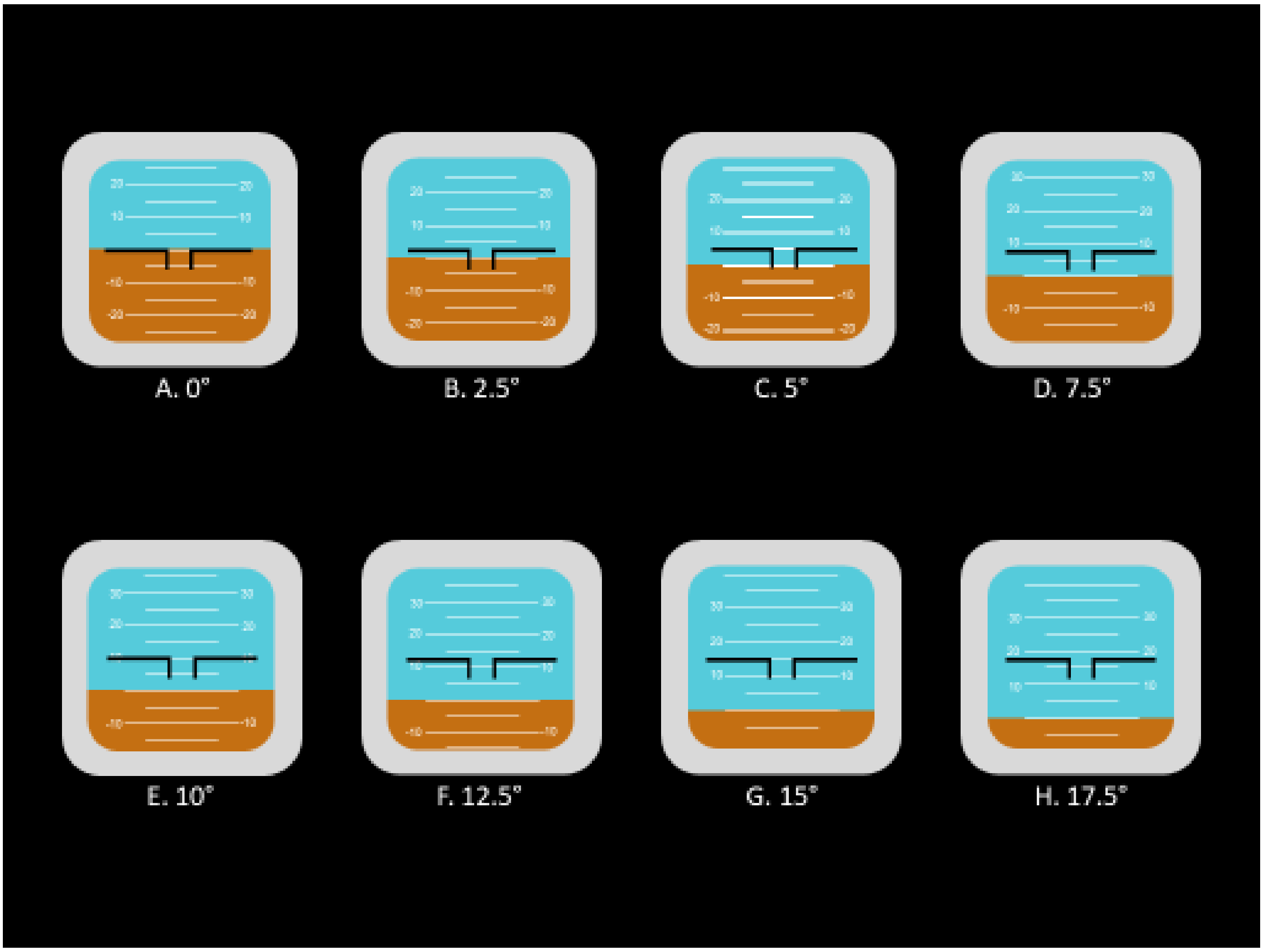
______________________ ______________________ ________
Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

______________________ ______________________ ________
Berna Gungen Signature Date

Study contact details for further information:
[*Berna Gungen, +31614055827, bernagungen@gmail.com*]

Experiment ADI's



Appendix D

Participant Debriefing

Participant Number:

Debriefing

With this experiment we want to see whether heave cues (vertical movements) can influence pitch perception. We are also investigating whether heave cues can be confused with a pitch movement by themselves. We would like to ask you a few questions about this.

1. **Did you use one (or multiple) strategy(s) to estimate the angle? If yes which one?**

   ....

   ....

   ....

   ....

   ....

   ....

   ....

   ....

   ....

2. **During this experiment, heave cues (vertical movements) took place.**
   What do you think the effect is of such heave cues on estimating the pitch angle?

1	2	3	4	5
Strong underestimation	**underestiomation**	**unchanged**	**Overestimation**	**Strong overestimation**

Further remarks:

....

....

....

....

....

....

....

Participant Number:

3. Have you had any kind of training on the somatogravic illusion*?

Yes ☐ **No** ☐

Further remarks:

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4. Do you have any further (general) remarks?

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**** Somatographic illusion: A form of spatial disorientation in which the pilot mistakenly perceives an acceleration force as the rotation of the gravitational vector, resulting in a convincing sensation as if the aircraft is making a strong pitch up movement.***

Appendix E

Overview of scenarios and their details

Table E-1: Overview of scenarios and their details

Scenario No.	Pitch Angle [°]	Heave Intensity $[m/s^2]$	Heave duration [s]	Timing of heave (at peak value)	Description
1	5	0.58	1.5	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
2	7.5	0.58	1.5	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
3	10	0.58	1.5	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
4	12.5	0.58	1.5	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
5	15	0.58	1.5	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
6	5	0.84	1.25	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
7	7.5	0.84	1.25	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
8	10	0.84	1.25	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
9	12.5	0.84	1.25	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
10	15	0.84	1.25	Pitch acceleration $\dot{q}$	Heave at max $\dot{q}$
11	5	0.58	1.5	Pitch rate q	Heave at max q
12	7.5	0.58	1.5	Pitch rate q	Heave at max q
13	10	0.58	1.5	Pitch rate q	Heave at max q
14	12.5	0.58	1.5	Pitch rate q	Heave at max q
15	15	0.58	1.5	Pitch rate q	Heave at max q
16	5	0.84	1.25	Pitch rate q	Heave at max q
17	7.5	0.84	1.25	Pitch rate q	Heave at max q
18	10	0.84	1.25	Pitch rate q	Heave at max q
19	12.5	0.84	1.25	Pitch rate q	Heave at max q
20	15	0.84	1.25	Pitch rate q	Heave at max q
21	0	0.58	1.5	-	Heave, no pitch
22	0	0.84	1.25	-	Heave, no pitch
23	5	0	0	-	No heave, only pitch
24	7.5	0	0	-	No heave, only pitch
25	10	0	0	-	No heave, only pitch
26	12.5	0	0	–	No heave, only pitch
27	15	0	0		No heave, only pitch

Bibliography

[1] Randall J Mumaw, Eric Groen, Lars Fucke, Richard Anderson, Jelte Bos, and Mark Houben. A new tool for analyzing the potential influence of vestibular illusions. In *ISASI Forum*, volume 49, pages 6–12, 2016.

[2] Paul R. MacNeilage, Martin S. Banks, Daniel R. Berger, and Heinrich H. Bülthoff. A Bayesian model of the disambiguation of gravitoinertial force by visual cues. *Experimental Brain Research*, 179(2):263–290, 2007.

[3] David H Klyde, Amanda K Lampton, and Philip C Schulze. Development of spatial disorientation demonstration scenarios for commercial pilot training. In *AIAA Modeling and Simulation Technologies Conference*, page 1180, 2016.

[4] David Owens. The Go Around Procedure. *Safety First - The Airbus Safety Magazine*, 12(July):1–8, 2011.

[5] Fred H Previc and William R Ercoline. *Spatial disorientation in aviation*, volume 203. American Institute of Aeronautics and Astronautic, 2004.

[6] Annemarie Landman, Eric L. Groen, M. M.(René) van Paassen, Adelbert W. Bronkhorst, and M. Mulder. Dealing With Unexpected Events on the Flight Deck: A Conceptual Model of Startle and Surprise. *Human Factors*, 59(8):1161–1172, 2017.

[7] David H Klyde, Amanda K Lampton, and Philip C Schulze. Evaluation of a steep turn spatial disorientation demonstration scenario for commercial pilot training. In *AIAA Modeling and Simulation Technologies Conference*, page 1079, 2017.

[8] Gilles Clément, Steven T. Moore, Theodore Raphan, and Bernard Cohen. Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight. *Experimental Brain Research*, 138(4):410–418, 2001.

[9] B. J. Correia Grácio, K. N. De Winkel, Eric L. Groen, M. Wentink, and J. E. Bos. The time constant of the somatogravic illusion. *Experimental Brain Research*, 224(3):313–321, 2013.

[10] Yuvi Kahana and Philip A Nelson. Boundary element simulations of the transfer function of human heads and baffled pinnae using accurate geometric models. *Journal of sound and vibration*, 300(3-5):552–579, 2007.

[11] T. Wada, S. Fujisawa, and S. Doi. Analysis of driver's head tilt using a mathematical model of motion sickness. *International Journal of Industrial Ergonomics*, 63(January):89–97, 2018.

[12] Norimasa Kamiji, Yoshinori Kurata, Takahiro Wada, and Shun'ichi Doi. Modeling and validation of carsickness mechanism. *Proceedings of the SICE Annual Conference*, pages 1138–1143, 2007.

[13] Henry Gray. *Anatomy of the human body*, volume 8. Lea & Febiger, 1878.

[14] P. Lawrence, B. Bramble, B. Aaron, L. Ward, D. Runyon, and D. Howard. Factual report. Technical report, NTSB, November 19, 2019.

[15] Charles Cates. Flight data recorder - specialist's factual report. Report NTSB DCA19MA086, NTSB, Vehicle Recorder Division Washington, Washington, D.C. 20594, 2019.

[16] First Officer John Jester. Party submission of the international brotherhood of teamsters local 2750 to the national transportation safety board, atlas air flight 3591. Report NTSB DCA19MA086, International Brotherhood of Teamsters Local 2750, Accident Investigation Department, 35 East 7th St., Suite 202 Cincinnati, OH 45202, 2019.

[17] Randy Gibb, Bill Ercoline, and Lauren Scharff. Spatial disorientation: Decades of pilot fatalities. *Aviation Space and Environmental Medicine*, 82(7):717–724, 2011.

[18] Jacob L Meiry. *The Vestibular Dynamic System and Human Dynamic Space Orientation*. PhD thesis, Massachusetts Institute of Technology, 1966.

[19] JE Bos and W Bles. Modelling motion sickness and subjective vertical mismatch detailed for vertical motions. *Brain Research Bulletin*, 47(5):537–542, 1998.

[20] C.S. Lessard, R. Matthews, and D. Yauch. Effects of rotation on somatogravic illusions. *IEEE Engineering in Medicine and Biology Magazine*, 19(2):59–65, 2000.

[21] Terence J Lyons, William Ercoline, Kevin O'Toole, and Kevin Grayson. Aircraft and related factors in crashes involving spatial disorientation: 15 years of us air force data. *Aviation, space, and environmental medicine*, 77(7):720–723, 2006.

[22] Bureau d'enquêtes et d'Analyses pour la sécurité de l'aviation civile. Study on aeroplane state awareness during go-around. Report 1, BEA, Le Bourget, France, 2013.

[23] S Ludlow. Reducing the threat of the somatogravic illusion. *Flight Safety Foundation International Air Safety Summit (IASS)*, 2016.

[24] A. H. Rupert, B. McGrath, and F. Guedry. Tgulf air flight gf-072 perceptual study. Report Appendix E, Naval Aerospace Medical Research Laboratory, 280 Fred Bauer St. Building 1811 Pensacola, FL 32508-1046 United States, 2000.

[25] Afriqiyah airways flight 771. `https://aviation-safety.net/database/record.php?id=20100512-0`. Accessed: 2020.11.30.

[26] The Boeing Company Robert J. McIntosh, Director Product Safety. Boeing submission to the national transportation safety board for atlas air 767-300bcf n1217a accident trinity bay, tx,23 february 2019. *NTSB*, 1(DCA19MA086), February 07,2020.

[27] Braden McGrath, Ben Lawson, Michael Newman, and Angus H Rupert. An algorithm to improve ground-based spatial disorientation training. In *AIAA Modeling and Simulation Technologies Conference*, page 0656, 2015.

[28] David G Newman and AFAIM FAICD. *An overview of spatial disorientation as a factor in aviation accidents and incidents*. Number B2007/0063 in 1. Australian Transport Safety Bureau Canberra City,, Australia, 2007.

[29] AD Van Beuzekom and JAM Van Gisbergen. Properties of the internal representation of gravity inferred from spatial-direction and body-tilt estimates. *Journal of Neurophysiology*, 84(1):11–27, 2000.

[30] Brant Clark and Ashton Graybiel. Perception of the visual horizontal in normal and labyrinthine defective observers during prolonged rotation. *The American Journal of Psychology*, 79(4):608–612, 1966.

[31] N. Kamiji, Y. Kurata, T. Wada, and S. Doi. Modeling and validation of carsickness mechanism. *Proceedings of the SICE Annual Conference*, pages 1138–1143, 2007.

[32] Daniel M Merfeld. Modeling the vestibulo-ocular reflex of the squirrel monkey during eccentric rotation and roll tilt. *Experimental Brain Research*, 106(1):123–134, 1995.

[33] Jelte E Bos and Willem Bles. Theoretical considerations on canal–otolith interaction and an observer model. *Biological cybernetics*, 86(3):191–207, 2002.

[34] Tomoya Uefune, Takahiro Wada, and Kohei Sonoda. Computation of the vestibulo-ocular reflex for eye closure based on the 6dof-svc model. In *2016 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 001285–001290. IEEE, 2016.

[35] J Corvera, CS Hallpike, and EHJ Schuster. A new method for the anatomical reconstruction of the human macular planes. *Acta oto-laryngologica*, 49(1):4–16, 1958.

[36] Arne Tribukait and Ola Eiken. Flight experience and the perception of pitch angular displacements in a gondola centrifuge. *Aviation Space and Environmental Medicine*, 83(5):496–503, 2012.

[37] Arne Tribukait and Ola Eiken. Semicircular canal influence on the visually perceived eye level during gondola centrifugation. *Aviation Space and Environmental Medicine*, 77(5):500–508, 2006.

[38] Wietse D Ledegang and Eric L Groen. Spatial disorientation influences on pilots' visual scanning and flight performance. *Aerospace medicine and human performance*, 89(10):873–882, 2018.

[39] J. A. Stoop and J. P. Kahan. Party submission of atlas air, inc. *Investigation of Atlas Air Flight 3591 trinity Bay, Houston Texas*, 1(NTSB DCA19MA086), February 07, 2020.

[40] Max Mulder. *Cybernetics of Tunnel-in-the-Sky Displays*. PhD thesis, TU Delft, 11 1999.