A Procedure for Inducing the Leans Illusion in a Hexapod Motion Simulator

Landman, H.M.; van den Hoed, Annemarie; van Baelen, D.; Stroosma, O.; van Paassen, M.M.; Groen, Eric L.; Mulder, Max

DOI
10.2514/6.2021-1137

Publication date
2021

Document Version
Final published version

Published in
AIAA Scitech 2021 Forum

Citation (APA)
Landman, H. M., van den Hoed, A., van Baelen, D., Stroosma, O., van Paassen, M. M., Groen, E. L., & Mulder, M. (2021). A Procedure for Inducing the Leans Illusion in a Hexapod Motion Simulator. In *AIAA Scitech 2021 Forum: 11–15 & 19–21 January 2021Virtual/online event* (pp. 1-7). Article AIAA 2021-1137 (AIAA Scitech 2021 Forum). American Institute of Aeronautics and Astronautics Inc. (AIAA). https://doi.org/10.2514/6.2021-1137

A Procedure for Inducing the Leans Illusion in a Hexapod Motion Simulator

Annemarie Landman*, Annemarie van den Hoed †, Dirk Van Baelen‡, Olaf Stroosma§, M. M. (René) van Paassen¶,
Eric L. Groen‖, and Max Mulder**
Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands
TNO, Kampweg 55, 3769 DE Soesterberg, The Netherlands

Ground-based demonstration of spatial disorientation (SD) has been recommended for military as well as commercial pilot training. Although the leans illusion is the most common form of SD, no data exist yet of an effective ground-based leans procedure for a hexapod simulator. In this paper we describe the development of such a procedure and its tuning with nine subjects. The procedure was then used in an experiment with 18 airline pilots, which is described elsewhere. The final procedure started with a prepositioning phase, during which the simulator platform was slowly tilted to a 3.5° prepositioning roll angle, while the pilot performed a distraction task and the instruments and outside visuals indicated level flight. Next followed an adaptation phase, during which the pilot's vestibular system adapted to the new angle, the outside visibility degraded to zero and the instruments were covered. Then the platform was moved back to level, above the perceptual threshold, after which the instruments were shown again. The pilot was then tasked to roll back to level. The addition of the motion cues caused an increase in roll reversal errors by a factor of 3 in airline pilots. The procedure can be implemented in a scenario for demonstrating the leans in a cost-effective simulator.

I. Introduction

Spatial disorientation (SD) in-flight, which is an erroneous sense of the aircraft attitude and motion due to misleading cues, remains one of the major causes of fatal accidents in aviation. It was estimated that SD has contributed to 12% of loss of control accidents between 1996 and 2010 in civil aviation [1], and it was thought to be the primary cause in 7% of all mishaps [2]. In military operations, SD is a more serious issue, with an estimated contribution of 30% in fatal accidents [3]. The majority of these accidents involved SD of which the pilots were unaware [2]. This suggests that increasing pilot knowledge about SD, and the situations in which SD is likely to occur, may possibly help with recognising the illusions and preventing accidents.

Civilian pilot ground training addresses SD through theoretical training, with the mechanisms and causes of SD being explained in textbooks and the knowledge being examined with written exams (see, e.g., [4–6]). Military pilot ground training and refresher courses often also include SD demonstrations in ground-based devices, which feature a motion platform that is designed to better reproduce certain SD illusions [7, 8]. In contrast, the conventional and more cost-effective hexapod-type motion platform, which is used in commercial pilot training, has limitations that may cause insufficient fidelity for demonstrating certain types of SD correctly. One illusion that is problematic to accurately recreate in both types of ground-based devices is the leans. This is unfortunately also the most frequently occurring illusion in-flight [9]. The leans is a somatogyral illusion caused by the human vestibular system being unable to pick up on slow roll accelerations. For instance, when the aircraft rolls below the perceptual threshold (i.e. supra-threshold) to one side, and then rolls above the perceptual threshold (i.e. super-threshold) back to level, this can give the pilot a strong sensation of being banked to the opposite side. Because the aircraft is also turning during the banked situation, the specific force remains pointed to the floor of the cockpit. In contrast, if the same roll motions are performed with a simulator, one would perceive a change in direction of the gravitational vector. This can possibly prevent the illusion from occurring, or cause behavior that is not truly a response to the leans.

---

*Researcher, TNO - Human Performance, annemarie.landman@tno.nl
†Quality Analyst, Cognizant, annemarie.vandenhoed@cognizant.com
‡PhD Candidate, Delft University of Technology - Control & Simulation, d.vanbaelen@tudelft.nl. Student Member AIAA.
§Senior Researcher, Delft University of Technology - Control & Simulation, o.stroosma@tudelft.nl. Senior Member AIAA.
¶Associate Professor, Delft University of Technology - Control & Simulation, m.m.vanpaassen@tudelft.nl.
‖Senior researcher, TNO - Perceptual and Cognitive Systems, eric.groen@tno.nl.
**Professor, Delft University of Technology - Control & Simulation, m.mulder@tudelft.nl. Associate Fellow AIAA.

Leans demonstration procedures for ground-based simulators employ different workarounds for this issue. Documentation was published of two of such procedures [7], which were developed for air force SD training in hexapod simulators that were outfitted with a yaw rotation platform. The first is a procedure developed by AMST (Ranshofen, Austria) for the Airfox simulator. While the pilot slowly rolls the simulated aircraft into a 30° banked turn, the simulator remains upright due to a special (asymmetric) parameter setting of the washout filters. Then, as the pilot rolls the aircraft back to level, the simulator platform rolls quickly to the opposite side, where it stays for a moment due to the filter settings, before it slowly rolls upright again. Thus, both a super-threshold roll motion and a moment of maintaining a roll angle are used to instill a leaning sensation.

A leans demonstration procedure developed by the Environmental Tectonics Corp (Southamption, PA) in the Gyro-IPT makes use of the Coriolis illusion to create a roll sensation [7]. While the pilot rolls the simulated aircraft into a 45° banked turn, the simulator platform is tilted at a subliminal rate to a 10° roll angle and to a 10° nose-up angle, while it accelerates subliminally to a yaw rotation rate of 12°/s. Then, when the pilot rolls out of the turn to level flight, the platform is moved in three seconds back upright (in roll and pitch), while the yaw rotation decelerates to zero in four seconds. Due to the change in pitch while the yaw rotation is still occurring, the Coriolis illusion would cause a roll sensation, which adds to the roll sensation caused by the super-threshold roll motion back to level. Following the leans cues, the pilot is taken out of the loop for a moment (i.e., the attitude displays freeze), and the pilot is tasked to maintain level flight.

These two procedures have different limitations as to their correspondence with actual in-flight leans cues. The first procedure uses, in addition to the roll motions, also the tilt angle of the simulator to make pilots 'lean' to the side. However, this tilting of the specific force does not occur in in-flight leans. The use of the Coriolis effect in the second procedure adds undesired and confusing pitch and yaw cues, while the prepositioning bank angle of 10° is likely to be noticed. No data of either procedure is publicly available on the effectiveness of instilling the leans. However, in an experiment with 10 air force pilots, the motion profile in the first procedure did not cause a significant change in the pilots' roll inputs [10]. The motion profile in the second procedure caused 18 non-pilots to be more likely to counter-steer when flying while the instruments were frozen following the stimuli, but no significant effect was found in another group of 18 pilots [11], nor in a group of 16 air force pilots [12]. There were however significant effects found on control inputs in different experiments with 16 regular pilots [12] and 34 air force pilots [13].

Because of the limitations of existing leans simulation procedures, we designed a new procedure for an experiment in a hexapod simulator without yaw rotation platform. The goal of this experiment was to test the effect of the leans cues on pilot display interpretation and control inputs. To measure a valid response to the leans cues, the platform needed to be steady and upright at the moment of the control inputs. We also wanted to exclude the possibility that different unintended motion cues affected the pilots' response. We first describe the simulator we used in section II. Then, we describe the development and tuning of the procedure in section III. Finally, we give a brief description of the application and the procedure's effectiveness in the leans experiment in section IV. A full description of this experiment can be found in [14].

II. Description of the simulator

The experiment was conducted in the SIMONA Research Simulator (SRS) at the Faculty of Aerospace Engineering of TU Delft (see Ref. [15]). The SRS is a six-degrees-of-freedom full-motion simulator with a hydraulic hexapod motion system which can realize accelerations below human vestibular perception (see Ref. [16]). The subject was seated in the left-hand seat of the cockpit, which featured a collimated 180° horizontal by 40° vertical field of view outside visual. The images were rendered by FlightGear software and projected three high-resolution Digital Light Processing (DLP®) projectors. A control column and yoke, fitted with control loading, was available to the pilot.

The control inceptors, outside visual characteristics, and motion system performance are all representative of modern full-flight simulator (FFS) training devices. The flight deck mockup is more generic and less detailed than a typical FFS. No special features of the simulator were used in this experiment, making the procedure feasible to be implemented in commercial training simulators.

III. Development and tuning of the leans procedure

A. Method

Nine students from the Control and Simulation track of the Aerospace Engineering faculty of the Delft University of Technology participated in the tuning experiment (mean age = 26.7 years, standard deviation = 1.5). Five students had no flying experience, one had flown once, two had 50-100 hrs experience, and two had 100-200 hrs simulated flight experience.

Participants first received instructions and a safety briefing, after which they were seated in the left-hand seat of the SIMONA Research Simulator. The simulator was outfitted with an A320-like aerodynamic model [17], with an Attitude Indicator (AI) available and the outside visuals generated by FlightGear. To mask any sounds of the simulator, participants wore noise-cancelling headphones while wind sound was played over the speakers in the simulator.

They each performed two sets of eight runs, with a short break in between the sets. In each run, they performed one of four variations of the tested procedure. The procedure always started with the AI visible, the outside visuals showing the horizon during day, and the aircraft flying level at 230 kt in automated flight at 10,000 ft altitude. The full procedure consisted of three phases: a prepositioning phase, an adaptation phase, and a roll cue phase, after which the participant performed a control response task.

In the *prepositioning phase*, the simulator platform would slowly (in 60 seconds) be prepositioned to a roll angle, while the AI and the outside visuals kept indicating level flight. At the beginning of the experiment, this angle was set at 5.2°. This is above the average perception threshold of body tilt of 2°that was found by [18]. However, as humans give precedence to visual information in determining their spatial orientation (i.e., the principle of visual dominance) we expected that the level AI and outside horizon would mask the prepositioning angle. A roll acceleration was used of $9.717 \cdot 10^{-4}$ °/s^2 and a maximum angular velocity of 0.0573 °/s, both of which are under the human perception thresholds of 2.00 °/s^2 and 0.115 °/s, respectively [16, 19]. The roll motion was achieved by gradually increasing the specific force f_y driving the motion cueing algorithm (MCA). The MCA's tilt-coordination mechanism then smoothly commanded the desired simulator roll angle. To distract the participants from the prepositioning angle, they performed a secondary task. This consisted of a set of pen-and-paper flight-related tasks: filling out a flight plan and answering a questionnaire about notices to airmen (NOTAMs) and meteorological aerodrome reports (METARs).

The AI was then covered (turned to black) and the outside visibility degraded to zero. The latter was achieved by increasing the load factor within the FlightGear visuals only, which will fade the outside scene to black to simulate pilot blackout. Next followed a 30-seconds *adaptation phase*, during which the prepositioning roll angle was maintained. It was shown previously that maintaining a full-body sideways tilt angle causes an after-effect, where a new tilt angle of the body back to level is overestimated towards the opposite direction [20]. The duration of 30 seconds with the instruments covered and no visible outside cues was also important to create a realistic leans procedure for the later experiment. In 30 seconds, the simulated aircraft can potentially roll sub-threshold to the bank angle for which we would require a response (see, IV).

Next, in the *roll cue phase*, the simulator platform was moved super-threshold upright again in two seconds, with a maximum roll acceleration of 3.2°/s^2 and roll rate of 1.8°/s. Immediately after it was upright, the "autopilot off" alert sounded. This was the signal for the participant to move *the simulator platform* upright in one fluent motion, without referring to any visual cues, which were kept covered. They controlled the roll angle of the simulator (*instead of that of the simulated aircraft*) with the yoke, where the yoke deflection directly translated to a roll rate of the simulator. This was explained to them previously. In each run, one of the following four versions of the procedure was presented:

- **Full motion** In this version all procedure phases were presented as described above. The fast roll cue following the adaptation phase was expected to cause the participant to assume that the simulator was tilted towards the opposite direction of the prepositioning angle, while it was actually upright. Thus, if the procedure succeeded in inducing the the leans illusion, a roll input towards the opposite direction of the roll cue would be made.
- **Prepositioning only** In this version, the procedure was presented without the fast roll cue at the end. Thus, the simulator platform remained in the prepositioning angle. If the participant was unaware of the prepositioning angle, no roll input would be given. Otherwise, the participant would move the platform upright.
- **No motion** In this version the simulator was not moved at all during the procedure. We used this as a filler run, to let the participants experience that the simulator could also potentially be upright at the "autopilot off"-alert.
- **No prepositioning** In this version, the motion in the prepositioning phase was skipped. The simulator remained upright until the roll cue phase, where the fast roll cue resulted in a 5.2° tilt angle when the "autopilot off"-alert sounded. The participant was expected to make a roll input back to level. This was used as a filler run to let the

participants experience that the simulator could be tilted at the “autopilot off"-alert.

Each version was presented four times, two times in each set. Left and right variations were presented an equal number of times. The order of the procedures was randomized by using a Latin Square method for nine participants. Turbulence on the z-axis of the simulator was used for half the runs of each variation. This turbulence followed a Dryden model with turbulence intensity gain (σ) = 0.8, turbulence scale length (L) = 2000, and relative speed (V) = 200; [21]. The turbulence gain was later increased to (σ) = 1.0.

B. Dependent measures

The first control input and its direction were registered if there was any deflection of the column following the “autopilot off" alert. After the experiment, participants were asked whether they noticed the prepositioning, and whether they had any suggestions for improvement of the procedure.

C. Results and iterative tuning

As expected, none of the nine participants made an error in the No prepositioning filler procedure. Five errors were made in the No motion filler procedure, when the simulator was not moved at all. Four of these were under high turbulence and one under low turbulence conditions. The outcomes of the other two procedures, as well as the different settings tested are shown in Table 1 and 2. The number of runs was sometimes lower due to measurement errors.

Table 1 Errors in the Full motion procedure and iterative tuning steps

PP	Propositioning angles used (°)	Turbulence gains used	N runs	Turbulence gain at errors (n errors)	Propositioning angles at errors, (n errors)
1	5.2	0.0, 0.8	4	-	-
2	5.2	0.0, 0.8	4	-	-
3	4.5	0.0, 0.8	3	0.00 (1)	4.5 (1)
4	4.5	0.0, 0.8	4	-	-
5	4.5, 3.5	0.0, 1.0	4	0.00 (2), 1.25 (2)	4.5 (2), 3.5 (2)
6	4.5, 3.5	0.8, 1.0	4	1.00 (2), 1.25 (2)	4.5 (2), 3.5 (2)
7	4.5, 3.5	0.8, 1.0	4	1.00 (2), 1.25 (2)	4.5 (2), 3.5 (2)
8	4.5, 3.5	0.0, 0.8	4	-	-
9	4.5, 3.5	0.0, 0.8	4	1.00 (2)	4.5 (1), 3.5 (1)

Table 2 Errors in the Prepositioning only procedures and iterative tuning steps.

PP	Propositioning angles used (°)	Turbulence gain gains used	N runs	Turbulence at errors (n errors)	Propositioning angles at errors (n errors)
1	5.2	0.0, 0.8	4	-	-
2	5.2	0.0, 0.8	4	-	-
3	4.5	0.0, 0.8	4	-	-
4	4.5	0.0, 0.8	3	-	-
5	3.5, 3.0	0.0, 1.0	4	-	-
6	3.5, 3.0	0.8, 1.0	3	1.25 (1)	3.5 (1)
7	3.5, 3.0	0.8, 1.0	2	-	-
8	3.5, 3.0	0.0, 0.8	4	-	-
9	3.5, 3.0	0.0, 0.8	2	-	-

For participant 1 and 2, the used prepositioning angle was set at 5.2°. No erroneous inputs were made in the Full motion runs, and both participants made correct inputs in the Prepositioning only runs, indicating that the prepositioning was noticed. It was therefore decided to reduce the prepositioning angle to 4.5° for participant 3 and 4. Here we observed one error in Full motion. Thus, for participants 5-9 we further reduced the prepositioning angle and tested 4.5°

as well as 3.5° in Full motion, and 3.5° as well as 3.0° in Prepositioning only. These smaller angles appeared to yield better results. Participants 5-7 each made an error in each of the Full motion runs, and one participant did not notice a tilt angle of 3.5° angle in one run. Participant 8 and 9 made fewer errors. However, from our observations they appeared to be very focused on the motions and less on the distraction task.

D. Conclusions from the tuning experiment

The prepositioning angle of 5.2° seemed to be too large, and the best results were obtained with an angle of 3.5°. This corresponded with an added specific force f_y to the aircraft model output that increased gradually to 0.6 m/s^2. Participants also indicated that this prepositioning angle allowed for a clearly sensed super-threshold roll cue. Therefore we decided to use this angle for the main experiment. Although a prepositioning angle of 3.0° was still noticed by the participants in the tuning experiment, there were reasons to expect that the motion profile would be more successful in the main experiment. First, participants in the tuning experiment were performing a response task based on the motions, which likely made them more focused on the motion and the prepositioning, whereas participants in the main experiment were not. Second, participants were sometimes observed to be doubting for some time whether the platform was tilted or not, especially at the smaller prepositioning angles, indicating that these angles were difficult to notice without considerable effort and some time. Third, even though participants noticed the preposition angle, this did not prevent them from making errors in the Full motion protocol.

We also decided to include turbulence with a 1.0 gain in the main experiment. Although no clear differences in performance were observed, slightly better results were obtained when participants were exposed to higher levels of turbulence in the tuning experiment.

IV. Application of the procedure in a leans experiment

In the leans experiment, the developed procedure was used to test whether pilots were more likely to make an interpretation error when responding to the AI. A full description of this experiment can be found in [14], but here we give a brief overview of the results. Airline pilots (n = 20) performed a number of runs that were similar to the Full motion procedure in the tuning experiment. No motion runs were also included as baseline. The response task now consisted of rolling *the aircraft* level (instead of the simulator platform), based on the AI which appeared after the "autopilot off" alert sounded. Pilots were told that the goal of the experiment was to test how pilots would respond to the AI following a period of distraction, and they were instructed to respond immediately upon seeing the AI. Unbeknownst to the pilots, the AI could show a banked situation in the same direction as the super-threshold roll cue (most runs), a banked situation in the opposite direction of the roll cue (4 runs), or level flight (4 runs). This opposite AI presentation is possible in real flight, if the aircraft first rolls sub-threshold to a certain bank angle, and then briefly rolls super-threshold into the opposite direction, but it does not roll back to level. As a distraction task, the participants were performed a version of the Multi Attribute Task Battery (MATB-II [22]) from the start of the procedure until the "autopilot off"-alert sounded.

The hypothesis was that the super-threshold roll cue would cause the pilots to make a roll input away from level (i.e. a roll reversal error), but only when the AI showed a banked situation in the opposite direction of the roll cue, and not when it indicated level flight, or when it was banked in the same direction as the cue. This is because a banked AI can erroneously be interpreted as showing a bank angle to the opposite direction. If the leans procedure instilled the sensation of being banked, this was expected to facilitate the incorrect interpretation and thereby cause roll reversal errors.

However, the first two pilots we tested made no errors. We decided to make a final change to the procedure and discarded their data. We timed the "autopilot off" alert two-seconds earlier, to signal to the pilots that they were to stop performing the MATB-II, sit up straight and take the controls before the roll cue was presented. This prevented them from potentially "quarantining" the motion sensations as they were being preoccupied by the MATB-II [23]. Figure 1 shows a timeline of the stimuli in the final version of the protocol.

For the remaining 18 pilots, we found that the motion cues were highly effective in causing AI interpretations errors. The first time a run with the opposite AI was encountered, 7 of the 18 pilots (38.9%) made a roll reversal error. Over the total four opposite test runs, the average error rate was 19.4%. In contrast to the non-pilots, here we found a clear learning effect, as the proportion of pilots making an error dropped steadily to 0% in the fourth run.

Compared to the error rate in runs with no motion cues (i.e., 6.9%), the error rate in the opposite runs was higher by a factor of almost 3. We found no effect of pilot experience on error rates (< 5000 flight hours vs. > 10,000 flight hours). There were no errors in the runs in which the AI indicated level flight. Although pilots were instructed to respond

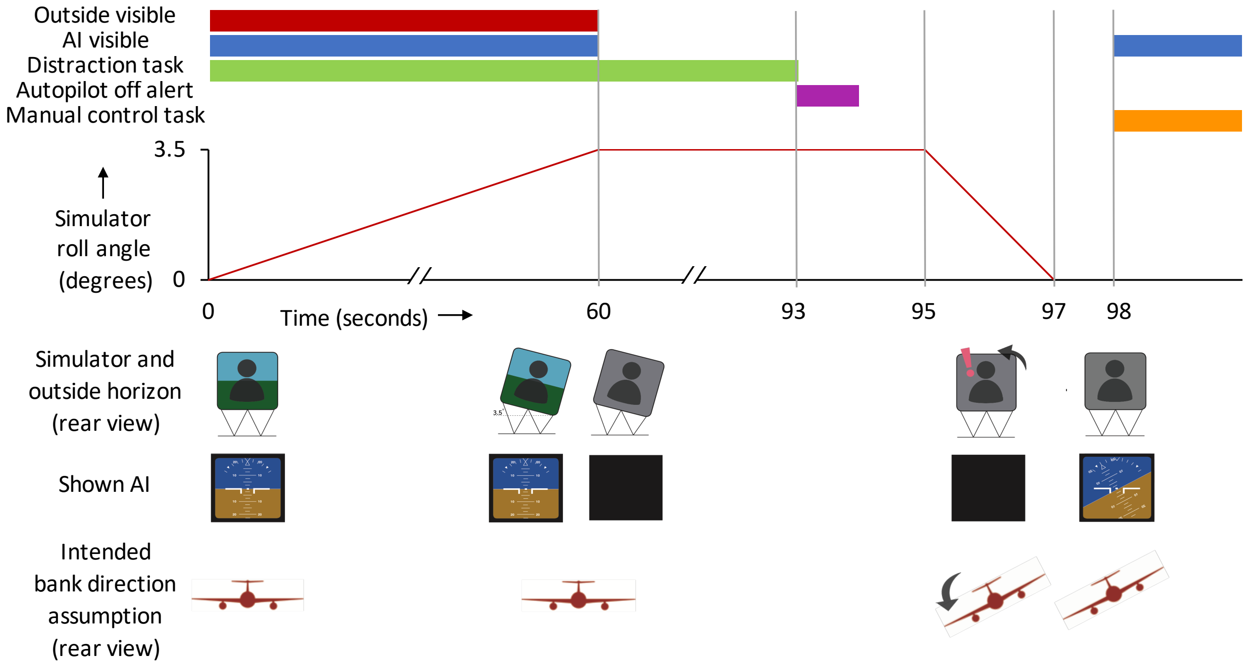

Fig. 1 A timeline of the procedure. This example shows the procedure with the AI presented in the opposite direction as the intended sensation. The figure is taken with permission from [14].

immediately, the average response time was around 2.0 seconds. One pilot remarked that he had experienced the leans not too long ago in-flight, and that the sensation was very similar.

V. Conclusions

The developed and tuned procedure was highly effective in inducing the leans in non-pilots as well as in pilots. The leans experiment with pilots was focused on display interpretation rather than leans sensation. The outcomes indicated that many pilots had an incorrect assumption about the bank angle which caused them to make an erroneous input *despite* having the AI presented to them. The number of pilots who experienced the leans sensation due to this protocol is likely even higher than the number who made an erroneous input. The motion cues stayed close to the motion cues that would be present in an actual in-flight leans situation. The procedure can be easily implemented in a hexapod simulator for leans demonstrations or for research. When used for leans demonstrations, the procedure could be further improved by integrating it into a more complex and realistic flying task.

Acknowledgments

We would like to thank all participants for helping us perform the experiments.

References

[1] Belcastro, C. M., Foster, J. V., Shah, G. H., Gregory, I. M., Cox, D. E., Crider, D. A., Groff, L., Newman, R. L., and Klyde, D. H., "Aircraft loss of control problem analysis and research toward a holistic solution," *Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 4, 2017, pp. 733–775.

[2] Newman, R. L., and Rupert, A. H., "The magnitude of the spatial disorientation problem in transport airplanes," *Aerospace medicine and human performance*, Vol. 91, No. 2, 2020, pp. 65–70.

[3] Gibb, R., Ercoline, B., and Scharff, L., "Spatial disorientation: decades of pilot fatalities," *Aviation, space, and environmental medicine*, Vol. 82, No. 7, 2011, pp. 717–724.

[4] *Human Performance and Limitations*, Bristol Ground School, Bristol, UK, 2016.

[5] *Human Performance and Limitations – Spatial Disorientation and Sensory Illusions*, Nordian Aviation Training Solutions, Sandefjord , Norway, 2016.

[6] *Human Performance and Limitations*, CAE Oxford Aviation Academy, Oxford, UK, 2009.

[7] Bles, W., "Spatial Disorientation Training-Demonstration and Avoidance (entrainement a la desorientation spatiale-Demonstration et reponse)," Tech. rep., NATO RESEARCH AND TECHNOLOGY ORGANIZATION NEUILLY-SUR-SEINE (FRANCE), 2008.

[8] Ludlow, S., "Reducing the Threat of the Somatogravic Illusion," *Flight Safety Foundation International Air Safety Summit (IASS)*, Dubai, UAE, 2016.

[9] Pennings, H. J., Oprins, E. A., Wittenberg, H., Houben, M. M., and Groen, E. L., "Spatial Disorientation Survey Among Military Pilots," *Aerospace medicine and human performance*, Vol. 91, No. 1, 2020, pp. 4–10.

[10] Ledegang, W. D., and Groen, E. L., "Spatial disorientation influences on pilots' visual scanning and flight performance," *Aerospace medicine and human performance*, Vol. 89, No. 10, 2018, pp. 873–882.

[11] Lewkowicz, R., Bałaj, B., and Francuz, P., "Susceptibility to Flight Simulator-Induced Spatial Disorientation in Pilots and Non-Pilots," *The International Journal of Aerospace Psychology*, 2019, pp. 1–13.

[12] Stróżak, P., Francuz, P., Lewkowicz, R., Augustynowicz, P., Fudali-Czyż, A., Bałaj, B., and Truszczyński, O., "Selective attention and working memory under spatial disorientation in a flight simulator," *The International Journal of Aerospace Psychology*, Vol. 28, No. 1-2, 2018, pp. 31–45.

[13] Lewkowicz, R., Stróżak, P., Bałaj, B., and Francuz, P., "Auditory verbal working memory load effects on a simulator-induced spatial disorientation event," *Aerospace medicine and human performance*, Vol. 90, No. 6, 2019, pp. 531–539.

[14] Van den Hoed, A., Landman, A., Van Baelen, D., Stroosma, O., Van Paassen, M., Groen, E., and Mulder, M., "Leans Illusion in Hexapod Simulator Facilitates Erroneous Responses to Artificial Horizon in Airline Pilots," *Human Factors: The Journal of the Human Factors and Ergonomics Society*, in press.

[15] Stroosma, O., Van Paassen, M., and Mulder, M., "Using the SIMONA research simulator for human-machine interaction research," *AIAA modeling and simulation technologies conference and exhibit*, 2003, p. 5525.

[16] Heerspink, H., Berkouwer, W., Stroosma, O., van Paassen, R., Mulder, M., and Mulder, B., "Evaluation of vestibular thresholds for motion detection in the SIMONA research simulator," *AIAA modeling and simulation technologies conference and exhibit*, 2005, p. 6502.

[17] Lombaerts, T. J. J., Looye, G., Seefried, A., Neves, M., and Bellmann, T., "Development and Concept Demonstration of a Physics Based Adaptive Flight Envelope Protection Algorithm," *International Federation of Automatic Control*, Vol. 49, No. 5, 2016, pp. 248 – 253. https://doi.org/10.1016/j.ifacol.2016.07.121.

[18] Janssen, M., Lauvenberg, M., van der Ven, W., Bloebaum, T., and Kingma, H., "Perception threshold for tilt," *Otology & Neurotology*, Vol. 32, No. 5, 2011, pp. 818–825.

[19] Gundry, A., "Thresholds to roll motion in a flight simulator," *Journal of Aircraft*, Vol. 14, No. 7, 1977, pp. 624–631.

[20] Crane, B. T., "Roll aftereffects: influence of tilt and inter-stimulus interval," *Experimental brain research*, Vol. 223, No. 1, 2012, pp. 89–98.

[21] Liepmann, H. W., "On the application of statistical concepts to the buffeting problem," *Journal of the Aeronautical Sciences*, Vol. 19, No. 12, 1952, pp. 793–800.

[22] Santiago-Espada, Y., Myer, R. R., Latorella, K. A., and Comstock Jr, J. R., "The multi-attribute task battery ii (matb-ii) software for human performance and workload research: A user's guide," 2011.

[23] Gresty, M. A., Waters, S., Bray, A., Bunday, K., and Golding, J. F., "Impairment of spatial cognitive function with preservation of verbal performance during spatial disorientation," *Current Biology*, Vol. 13, No. 21, 2003, pp. R829–R830.