Spatial Disorientation Impact on the Precise Approach in Simulated Flight

Jan Boril; Vladimir Smrz; Erik Blasch; Mudassir Lone

BACKGROUND: The risks posed by flight illusions impacting pilot spatial orientation have been determined as a safety concern from numerous past aviation accident investigations. Early demonstration of the adverse effects of flight illusions on spatial orientation would be desirable for all pilots, especially at the early training stages to deeply embed good practices for onset detection, flight correction, and response mitigation.

METHOD: Simulated flights on a disorientation demonstrator were performed by 19 pilots for 3 conditions: no illusion, somatogyral illusion, and Coriolis illusion. An objective approach for assessing pilot performance degradation due to flight illusions can be done by using a defined flight profile: instrument landing system (ILS) flight trajectory during final instrument approach. Deviations to the standard ILS profile were recorded to measure and evaluate the influence of the demonstrated flight illusion on pilot performance.

RESULTS: The results show the expectation that the smallest deviations from the ideal trajectory are caused by pilot tracking error (no illusion), and the greatest deviations are caused by the Coriolis illusion. Results demonstrated a statistically significant effect of illusions on performance. According to statements from pilots, training for flight illusion response is essential to complement training in aircraft regulations and aerodynamics.

DISCUSSION: Measuring the influence of vestibular illusions on flight profile with a simulator allows assessment of individual differences and improvement of pilot performance under the conditions of no illusion, the somatogyral illusion, and the Coriolis illusion.

KEYWORDS: Coriolis illusion, somatogyral illusion, disorientation demonstrator, vestibular flight illusions.

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Human spatial orientation emerged as a result of a complex evolutionary process adapting humans specifically for ground movement. In terms of evaluating spatial orientation, each person is unique and no generalized criteria exists which can be universally applied to all people.[5,20] In order to be aware of spatial orientation, pilots need to know primarily where up, down, left, or right is for the aircraft, along with position relative to immediate surroundings (as defined by a relative and absolute coordinate system).[13] Obtaining an accurate knowledge of position is further complicated by the need to perceive the respective speed or velocity for each of the aforementioned directions.[16] In the event of failure of spatial orientation, pilots face a situation known as a flight illusion.[15] Failure to recognize a flight illusion is a major threat to safety. If the pilot does not regain spatial orientation in time, there is a risk of losing aircraft control or possible controlled flight into the terrain.[10,21,22]

The issue of adapting a pilot's spatial orientation system to movement in the air is as old as flying itself. Research conducted in the field of preventing the effects of flight illusions dates back to the period after World War I and intensified significantly during and after World War II, primarily with the development of instrumented flight. Instrument flying procedures are now the basic flight mode for civil aviation. These procedures were developed in the past in order to make air traffic less dependent on the visual reference of the pilot to guide the aircraft in all

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flight phases (which can be limited by cloudiness and low visibility), and so the pilot can navigate according to the information provided by the instrumentation only.

In order to operate under conditions requiring reliance on flight instrument data, instrument flight procedures for all phases of flight have been established at the level of international aviation organizations. The most important are instrument departure procedures, as well as instrument arrival and approach procedures (**Fig. 1**). These procedures allow pilots to safely guide the aircraft at low altitudes due to terrain shape and obstacles without visual control. Without these procedures, it would not be possible to achieve the required air traffic safety, nor to achieve the required air traffic density around large airports under all defined meteorological conditions. These procedures may only be performed by specially licensed pilots and by airplanes with certified avionics systems.

In the final phase of an instrument approach, which is critical to the safety of flight, the Instrument Landing System (ILS) that guides the pilot on an electronic beam to the landing point is still dominant. Most contemporary airliners are able to

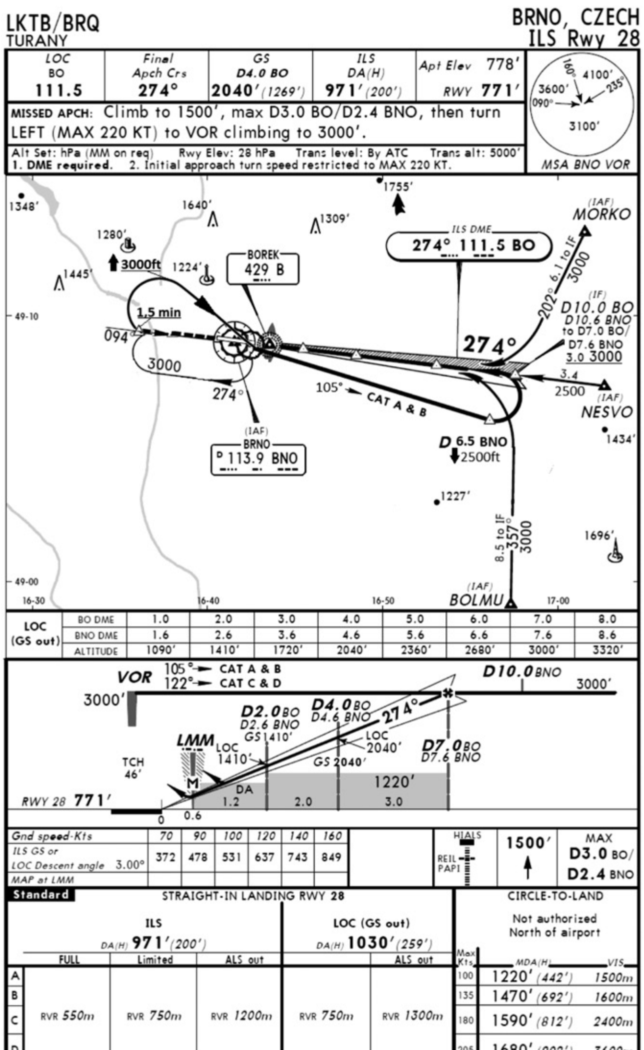

Fig. 1. Flight mission profile map.

guide the aircraft along the landing trajectory in an almost perfect way using autopilot. In the event of a failure of the landing system, the pilot must be able to manually handle procedures in all regulation-defined weather conditions.

While in the case of automatic flight the accuracy (hence safety) of the landing procedure is guaranteed by the certified reliability of the onboard avionics system, in the case of manual control the same must be guaranteed by the reliability of the human factor, i.e., optimal human performance of the pilot. Man, unlike automatic systems, may be subject to various types of flight illusions during flight, which can have a fatal effect on aircraft performance and endanger flight safety. As long as one has to guarantee the safety of the entire flight on board an aircraft (commander), it is necessary to conduct research so that pilots are aware of this danger and do not underestimate it.

Research activities studying human spatial orientation have identified the basic mechanisms and limitations of the human sensory systems while flying. These limitations include time constants for the response of the individual parts of the vestibular system that send information about angular and linear accelerations of the head to the brain.[9] Based on the knowledge of vestibular dynamics, special types of flight simulators, called spatial disorientation demonstrators, have been developed over the last 20 yr that are capable of demonstrating various types of flight illusions to the pilot.[4,7,9] These simulators are currently used to demonstrate the adverse influence of flight illusions on spatial orientation during aeromedical training, primarily for military pilots from most developed countries (e.g., NATO: North Atlantic Treaty Organization). Demonstrating the adverse effects of flight illusions on spatial orientation would be desirable for all pilots, in addition to supporting aircrew such as navigators, air traffic controllers, and unmanned aerial vehicle operators.[11,14,17] However, disorientation requirements are not stipulated in civil aviation regulations as the limited number of specialized training devices is insufficient to satisfy the rising demand for training.[25]

Flight illusions arise when a pilot loses significant visual reference points for determining his position in space. The pilot's basic reference line, when flying at a higher altitude, is the natural horizon line. This line is not available during a flight through clouds, limited visibility flight, or a cloudless night flight if the natural horizon line is not clear enough (e.g., when the lighted points on the ground coincide with the starry sky). It follows that the loss of the pilot's spatial orientation due to flight illusion is largely due to weather conditions (limiting the visibility of the natural horizon) and, therefore, researchers deal only with some illusions occurring without visibility of the natural horizon due to unreliable pilot vestibular system information.

For the purpose of the flight experiment reported in this paper, the two main types of vestibular illusions to which a pilot is exposed during flight without visual references include the somatogyral and Coriolis illusions. Somatogyral illusions are characterized by the inability to perceive a steady rotational movement (over an extended period of time), leading to forming "one's own" natural horizon that is different from reality.[5]

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On the other hand, Coriolis illusions are characterized by the temporary loss of spatial orientation caused by the overloaded vestibular apparatus as a result of exposing the body to rotational acceleration acting in two or more axes.[15,27]

The research presented in this paper was structured in the following three stages:

- Generate a complex flight mission with an integrated illusion applicable to the Environmental Tectonics Corporation Gyro Integrated Physiological Trainer (GYRO IPT II) disorientation demonstrator that is available at the Institute of Aviation Medicine in Prague.
- Integrate the demonstrator with a simulator for training and assessment.
- Test a sample of pilots during flight experiments to determine the degree to which a pilot is influenced by different types of vestibular illusions.
- Record the simulations and analyze the collected experimental data to characterize the effects of the vestibular illusions, determine the usefulness in pilot training, and assess flight profiles for effective pilot experience.

The available literature does not clarify the extent to which flight simulators (especially those installed in military aviation institutes) are being used for research tasks that focus on increasing the awareness of the effects of flight illusions.[21,22] Hence, there is a need to conduct research aiming to objectively investigate the effects of a demonstrated flight illusion on pilots to support training and safety.

Despite benefiting from years of human factors and man-machine interface research for modern flight displays, aircraft pilots still question the presented data that define the aircraft's position and attitude because of his/her proprioceptive and vestibular systems' responses. In many cases, both sensory systems and displays result in perceived conflicting information. Conducting regular and knowledge refreshment training in spatial disorientation, especially how and why it happens along with techniques for identification and mitigation, are essential to maintain or enhance flight safety.

The research team, upon agreement with the Institute of Aviation Medicine in Prague, set the main research objectives as: 1) draw up the methodology for the objective assessment of the effects of the demonstrated flight illusion on a pilot's spatial orientation; 2) improve the aeromedical training of military pilots; and 3) present a methodology for incorporation of illusion awareness into standard aeromedical training. The objectives fostered a series of experiments by:

- Using a standard spatial disorientation (SD) demonstrator to present an unexpected flight illusion during a complex flight mission.
- Determining an objective measure (or calculation) based on the deviation caused by a flight illusion to compare the results (i.e., between no illusion flights and illusion flights, or between different illusions flights).
- Quantifying the intersample differences between the subject pilots who have the same flight experience and are exposed to the same flight illusion demonstration (variable human performance is known to the authors, but it could not be taken into account through such experiments) to assess whether an individualistic and subject tailored approach is needed for pilot SD training.

METHODS

Subjects

Participating in the study were 19 student pilots in their final year in military pilot training at the University of Defense in Brno. All subjects were flying Zlin Z-142 aircraft, which is used for initial flight training in the Czech Air Force. All participants were men, reflecting the gender distribution of pilots in the Czech Air Force. The study protocol and experiment was approved by the Ethical Review Board of the University of Defense in Brno. Each participant provided written informed agreement with participating in the experiment and the experimental results were anonymized by allocation of each pilot to a code number.

Equipment

The flight experiment equipment used the GYRO IPT II.[26] The GYRO IPT II is an interactive, multifunctional training system with built-in flexibility to accommodate the training needs of all flight students from first time trainees to experienced pilots. It consists of a single occupant cockpit assembly mounted upon a sophisticated motion base. The cockpit is configured as a generic training aircraft with a single turboprop engine. The system includes a pilot seat, closed-loop interactive flight controls, forward out-the-window visual display, front panel instrumentation gauges, and realistic aircraft audio cueing.

A unique motion base featuring 4 + 2 degrees of freedom delivers pitch, roll, yaw, heave, and surge (pitch with heave) and sway (roll with heave) movements to the underside of the cockpit assembly. These compound motion base actions are directed by an advanced motion control system capable of producing precise multiaxis movements that create both linear and angular accelerations. Such accelerations can be produced at detectable rates, as well as at undetectable (subthreshold) rates, to support high fidelity flight simulations through a variety of vestibular illusions.

The motion base and cockpit assembly are controlled from an instructor's station that stands adjacent to and is electrically connected with the flight simulator. The instructor's station is equipped with all the necessary computers, instructor flight controls, mission recording, playback equipment, and an intercom with audio system to direct and monitor all simulator operations.

Procedure

In order to compare the pilot's response to the same type of load (demonstrated vestibular illusion), under the same simulated conditions (flight in clouds without natural horizon visibility), it was necessary for all pilots to fly the same trajectory and

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experience the illusion at the same location. This could be achieved by selecting the modified instrument flight procedure. Fig. 1 is a standard instrument departure and approach for the Brno international airport made according to the instrument chart for the ILS for runway 28 (RWY28) of the Jeppesen Company.

The Brno airport was chosen because it is equipped with the necessary ground navigation equipment and has an appropriately situated runway. The modified instrumentation procedure was in the form of an instrument map that pilots carried in the cockpit. The airport navigation equipment and the type of aircraft allowed the pilot to follow the specified trajectory throughout the entire simulated flight only according to the onboard instrument information.

In the horizontal plane, the flight profile consisted of the following segments:

- an artificial instrument departure followed by a right turn with an active flight to the VHF Omni Directional Radio Range device (VOR) BNO (equipment designator—see Fig. 1);
- active instrument flight from the VOR BNO (magnetic radial 105°) followed by a left turn to intercept the Localizer (LLZ) ILS BO (equipment designator); and
- standard instrument approach ILS RWY28 (procedure designator).

In the vertical plane, the flight profile consists of the following segments:

- after takeoff, a continual climb to an altitude of 3000 ft (914.4 m);
- continue at 3000 ft altitude from the top of climb to the top of descent (by starting a left turn to intercept LLZ);
- descend to an altitude of 2500 ft (762 m) by intercepting the ILS LLZ R28 (magnetic heading 274°) during the left turn; and
- after intercepting the ILS glide slope, continue the descending profile of the ILS R28.

A somatogyral or Coriolis illusion was evoked while finishing the turn to intercept the LLZ of the ILS RWY28 approach.

In the cockpit, the pilot is required to set all needed frequencies on the panel designed for navigational and communication adjustment, and sets the indicators on the horizontal situation indicator to the position as needed for his/her flight. As soon as the profile is activated, the pilot starts the takeoff and continues the initial climb. Then he retracts the flaps, adjusts the power setting, and keeps the aircraft on course to the moment when the stopwatch shows 1 min and 30 s. When the aircraft reaches the height of 300 ft (91.4 m) above the airport, the visual meteorological conditions generated by the simulator changes to instrument meteorological conditions, resulting in the loss of any out-the-window visual cues and forcing the pilot to use the instruments.

After reaching the time 1 min and 30 s in the continuous climb, the pilot starts a right turn with 15° bank until approximately 140° magnetic heading is reached. Subsequently, the pilot starts the procedure of active instrument flight to the VOR BNO. After overflying the VOR BNO, the pilot starts the procedure for active instrument flight from the VOR BNO on the magnetic radial of 105°. On this radial, the pilot continues to a distance of 6.5 nmi from the distance measuring equipment BNO when the pilot starts a left turn to intercept the LLZ ILS RWY28 and descends to the altitude of 2500 ft. The descent in the turn increases the pilot's workload, making him/her more susceptible to spatial disorientation.

In a left descending turn, the demonstration of the somatogyral or Coriolis illusions (the simulator creates the illusion demonstration procedure) occur, which culminates at the end of the turn. At the same time, when the pilot tries to intercept the LLZ, he/she experiences the original personal influence of the illusion, which disturbs his/her concentration and affects spatial orientation. The Coriolis illusion is evoked right after the pilot obtains an automatic command to check the transponder code where he/she has to visually focus in the down left corner of the cabin. According to the pilot's individual level of sensitivity to the illusion influence, he/she will temporary (approximately 3 min) deviate from the ideal instrument trajectory, which can be objectively assessed according to the aforementioned procedure. The reader should note that the flight instruments show valid data throughout the duration of the test. After the illusion influence subsides and spatial orientation is restored, the pilot continues with the ILS approach for landing. The visual meteorological conditions are restored at the height of 300 ft above ground and the simulation is complete when the aircraft lands.

An ILS approach for the flight experiment was selected intentionally because of the need to compare the potentially deviated flight trajectory (induced by the illusion) with some predefined trajectory in space, which at this time can only be the ILS trajectory (Required Navigation Performance approach trajectory was not available on the simulator equipment). Hence, the illusion influence was placed just before the start of intercepting the ILS trajectory, which allowed the possibility of objectively assessing the expected trajectory deviations.

Statistical Analysis

Firstly, the authors used analysis of variance (ANOVA) and also *t*-tests for statistical analysis. The outcomes from the tests are discussed in the Results section. Secondly, the authors realize that the approach used to analyze the data is limited in this study. For that reason the basic statistical metrics such as median values in the data and the overall statistical distribution of the observed deviations from the ideal flight profile were added to complete an overall picture.

RESULTS

Table I shows the overview of the simulation results obtained from the flight experiments in terms of deviations as follows:

- Columns form three result segments in the order: no illusion, somatogyral illusion, and Coriolis illusion.

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- In each segment, there is a pilot code, a deviation from the ideal trajectory in the horizontal and vertical plane (dimensionless values), and their mathematical product which demonstrates the relative ratio of the horizontal and vertical deviations. The assessment methodology does not enable to define horizontal deviation in units of length and, as a consequence, the total deviation is a dimensionless value.[2]
- The 30 trial flights and 76 simulated flights (measurements) are divided into 20 d between 2017–2019 that were performed depending on pilot availability, pilot level of training, disorientation demonstrator accessibility, and the measurement procedure (time interval: 6 mo to 1 yr to limit the impact of the experience gained in demonstrating the somatogyral illusion). Due to these factors, the authors were not always able to have and evaluate all flights, which are the missing values in Table I.

Fig. 2 shows the 2D scattering of the horizontal and vertical deviations for each pilot during all three types of flight experiment (no illusion, somatogyral illusion, and Coriolis illusion). It can be observed that the scattering values define symmetrical dispersion patterns (by suitably choosing a logarithmic scale for the two axes) and clearly show differences and ratios in the variance for the separate types of simulated flights. To a certain extent, Fig. 2 represents the normalized deviations of area along the ideal path in a plane perpendicular to the flight trajectory. The graphical results correspond to the expectation that the smallest scattering should be caused by the pilot tracking error with no illusion, and the greatest scattering should be caused by the Coriolis illusion. An interesting result is to compare the size of the three scatter patterns.

Fig. 3 shows the results obtained using a box plot chart, which highlights the median and quartile values along with deviations in the results of the three types of simulated flights for the no illusion, somatogyral illusion, and Coriolis illusions, respectively, in the horizontal plane, vertical plane, and their mathematical product (total deviation). The data in Fig. 3 clearly shows that the observed deviations in cases with no illusion have the expected Gaussian distributions due to the variability in pilot control behavior.[18] These results can be interpreted as follows:

- The results in the horizontal plane correspond to the expectation that the median values and associated standard deviations interval will be higher for the somatogyral illusion and Coriolis illusion relative to cases with no illusion. Moreover, it is also evident that the Coriolis illusion leads biased Gaussian distribution in horizontal deviations. The results reflect the fact that there are significant differences in the way the Coriolis illusion affects individual pilots and some pilots are more strongly affected.
- The median results for deviations in the vertical plane show the somatogyral illusion having a higher impact on pilot performance. However, the Coriolis effect was again found to have large interpilot variations. It should be noted that tests with far more subjects are needed to reach definitive conclusions.
- When considering the total deviation, there is a clear difference between the influence of the somatogyral and the Coriolis illusions on pilots' spatial orientation. Results for total deviations clearly show that while the somatogyral illusion effects are roughly Gaussian for the subjects (and, therefore, pilots have similar susceptibility), the effects of the Coriolis illusion significantly vary for each pilot. Although the median is low, a significant amount of the deviations are large enough to bias the observed deviations.

From the pilot's perspective, it was observed that the vestibular illusions primarily cause deviations in the horizontal plane. The deviations in the vertical plane are mostly the consequence of partial loss of spatial orientation. However, in such a limited sample of results, observations could not determine a direct relationship between horizontal (primary) and vertical (secondary) deviation; however, the directional results represent a similar trend.

Fig. 4 shows the following, respectively:

- the portion of the flight path (intermediate and final approach) in the coordinate system;
- the vertical profile of the final approach; and
- the magnitude of the aircraft final heading change by the final approach, which is directly related to adherence to the prescribed flight trajectory.

From the total flight trajectory of the flight experiment in Fig. 1, only those parts of the trajectory are shown and mathematically evaluated where the vestibular flight illusions were demonstrated as shown in Fig. 4. Data from the final approach segment defined by the ILS is also shown. All simulated flights demonstrate the influence of vestibular flight illusions.

Deviation from Ideal Trajectory Caused by Pilot Tracking Error

Fig. 4A represents a demonstration of flight trajectory deviations (dashed lines) from the ideal trajectory (bold line) caused only by pilot tracking error. Pilot tracking error is defined as a pilot inaccuracy while controlling an aircraft in the final phase of approach. In the final approach, pilots were not influenced by any flight illusion. Most of the deviations from the ideal trajectory correspond with the average deviations while controlling an aircraft in the final phase of approach without using an autopilot.

Deviation from Ideal Trajectory Caused by Somatogyral Illusion

Fig. 4B represents a demonstration of flight trajectory deviations (dashed lines) from the ideal trajectory (bold line) caused by the somatogyral illusion. The real trajectory (dotted bold line) represents an extreme case where the demonstrated illusion has strongly influenced the pilot. The deviations in the horizontal and vertical plane could cause a serious threat to flight safety; for example, an increased risk of hitting the hilly terrain in the vicinity of the final approach track. The impact of the demonstrated flight illusion is clearly evident when comparing the variations in flight trajectories with the illusion effect to the variations observed in flight trajectories without the illusion effect.

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Table I. Deviations from the Ideal Trajectory: No Illusion/Somatogyral Illusion/Coriolis Illusion.

NO ILLUSION - PILOT TRACKING ERROR				SOMATOGYRAL ILLUSION				CORIOLIS ILLUSION			
PILOT (CODE)	HORIZONTAL DEVIATION	VERTICAL DEVIATION	TOTAL DEVIATION	PILOT (CODE)	HORIZONTAL DEVIATION	VERTICAL DEVIATION	TOTAL DEVIATION	PILOT (CODE)	HORIZONTAL DEVIATION	VERTICAL DEVIATION	TOTAL DEVIATION
A2	X	X	X	A2	1452	10,148	14,735	A2	1626	17,705	28,788
A3	561	10,410	5840	A3	983	19,544	19,212	A3	733	15,788	11,573
A4	X	X	X	A4				A4	1479	25,525	37,751
A5	515	15,218	7837	A5	1054	18,207	19,190	A5	4430	29,079	128,820
A6	1068	12,377	13,219	A6	680	20,810	14,151	A6	1364	19,513	26,616
A7	735	10,718	7878	A7	974	19,633	19,123	A7	1133	47,672	54,012
A8	581	17,115	9944	A8	756	19,103	14,442	A8	959	17,457	16,741
B1	X	X	X	B1	780	10,869	8478	B1	702	15,433	10,834
B2	895	16,989	15,205	B2	1072	21,278	22,810	B2	1045	10,942	11,434
B3	809	12,575	10,173	B3	X	X	X	B3	675	11,830	7985
B4	756	15,426	11,662	B4	1117	19,226	21,475	B4	X	X	X
B5	693	12,894	8936	B5	785	32,439	25,465	B5	1155	45,773	52,868
B6	835	13,673	11,417	B6	1777	31,135	55,327	B6	X	X	X
C1	554	10,843	6007	C1	1127	8503	9583	C1	1588	12,370	19,644
C2	1003	11,285	11,319	C2	778	13,928	10,836	C2	X	X	X
C3	604	14,562	8795	C3	X	X	X	C3	X	X	X
C4	681	16,133	10,987	C4	944	23,063	21,771	C4	2250	49,029	110,315
C5	515	13,498	6951	C5	895	18,367	16,438	C5	X	X	X
C6	422	13,840	5840	C6	543	17,013	9238	C6	717	15,505	11,117
Avg	702	13,597	9501	Avg	995	18,055	18,454	Avg	1418	23,830	37,750

X = missing values; not all pilots/flights were able to be evaluated.

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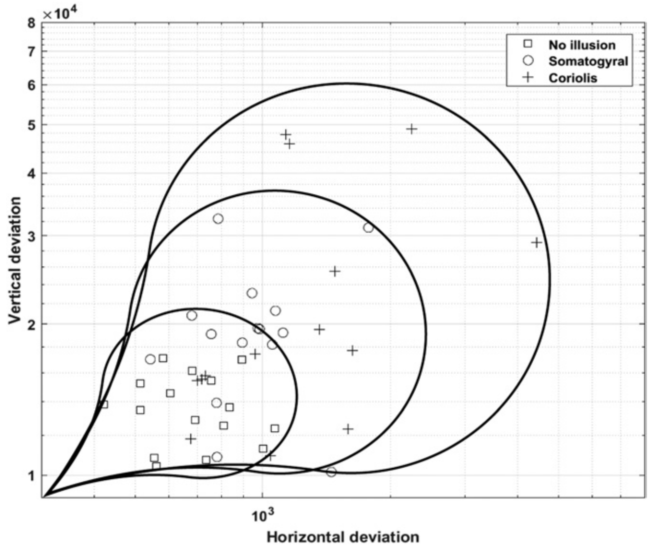

Fig. 2. Scatter chart of horizontal and vertical deviations from the flight path.

Deviation from Ideal Trajectory Caused by Coriolis Illusion

Fig. 4C represents a demonstration of flight trajectory deviations (dashed lines) from the ideal trajectory (bold line) caused by the Coriolis illusion. Flight trajectories (dotted bold line) represent extreme cases where the pilot is strongly influenced by the demonstrated illusion. Large variations in horizontal and vertical deviations could result in a serious flight safety hazard. For most of these trajectories, there is an evident dynamic oscillation which is characteristic of a man-machine system, which could lead to an aircraft crash, i.e., the greater influence of the Coriolis flight illusion relative to the somatogyral flight illusion is clearly evident when comparing differences in trajectory deviations from the ideal for both types of illusions.

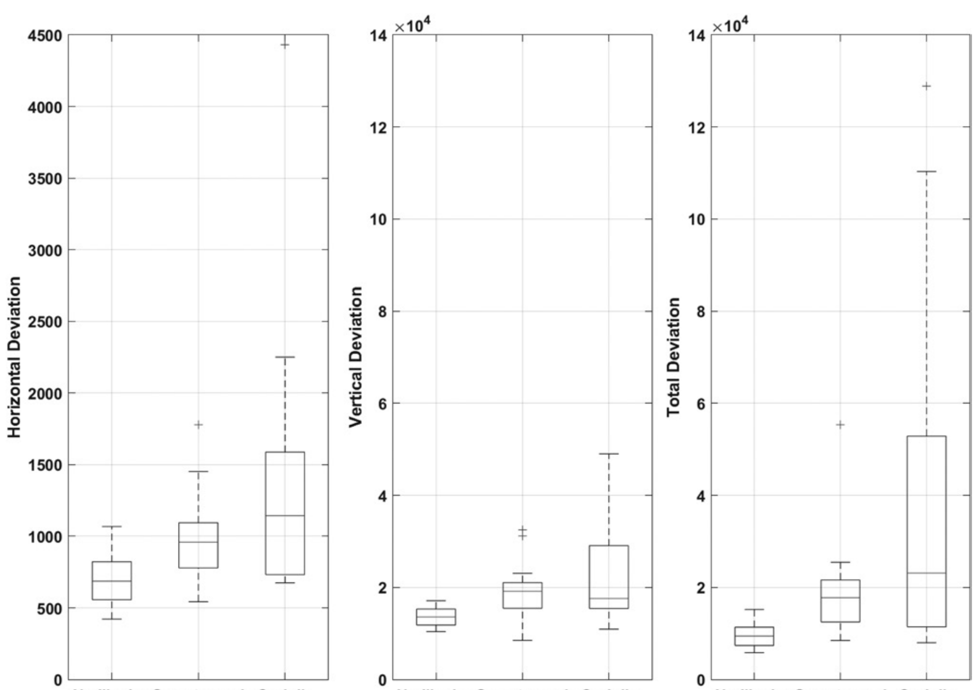

Fig. 3. Box plot chart of deviations in the three simulated flights.

Statistical Significance Test

For the test, there were 19 subjects, with valid tests of 16 no-illusion, 16 somatogyral illusions, and 14 Coriolis illusions as shown in Table I. Since all subjects had at least two tests, the average score for the illusion test was used to augment the trails in which data was not deemed adequate. The ANOVA showed a significant effect [$F(1, 19) = 10.25, P < 0.0002$], similar to previous spatial disorientation studies looking at training[6] and display[12] effects. To assess the differences between the illusion tests, t-test results were significant with comparison of Somatogyral to No Illusion [$t(19) = -3.92, P = 0.002$], Coriolis to No Illusion [$t(19) = -3.80, P = 0.003$], and Coriolis to Somatogyral illusion [$t(19) = -2.44, P = 0.01$].

DISCUSSION

The authors observed pilot performance during simulated flight at the final approach phase where the pilot was subjected to vestibular flight illusions. It has been shown that the standard SD demonstrator GYRO IPT II can be used for simulating unexpected flight illusion during a complex flight mission and not only for predefined (known and expected) flight missions created by the producer. No instructions and commands were given from outside (instructor station) during the simulated flight. Moreover, the authors suggest a way to objectively measure and calculate the deviation caused by a flight illusion to assess the different levels of risk between cases where there is no illusion and scenarios where the pilots are subjected to somatogyral and Coriolis illusions. This work also provides information on the differences in the pilot's behavior when exposed to the same flight illusion demonstrations. The differences are significant for the no illusion, somatogyral illusion, and Coriolis illusion, respectively. Further clarification inherently shows the variation in pilots' vestibular system sensitivity, demonstrating the probable need for individual disorientation training.[19,23]

The observed effects of flight illusion during simulated flights were found to be consistent with earlier research,[1,8,12] such as commercial pilot training by authors Klyde, Lampton, and Schulze.[14,17] The results from this study also hint toward a point where pilots who practice in the SD demonstrator can adopt certain habits to counter the risks posed by such flight illusions. Since pilots have a high probability of these occurrences in their career, such adaptation can be useful.

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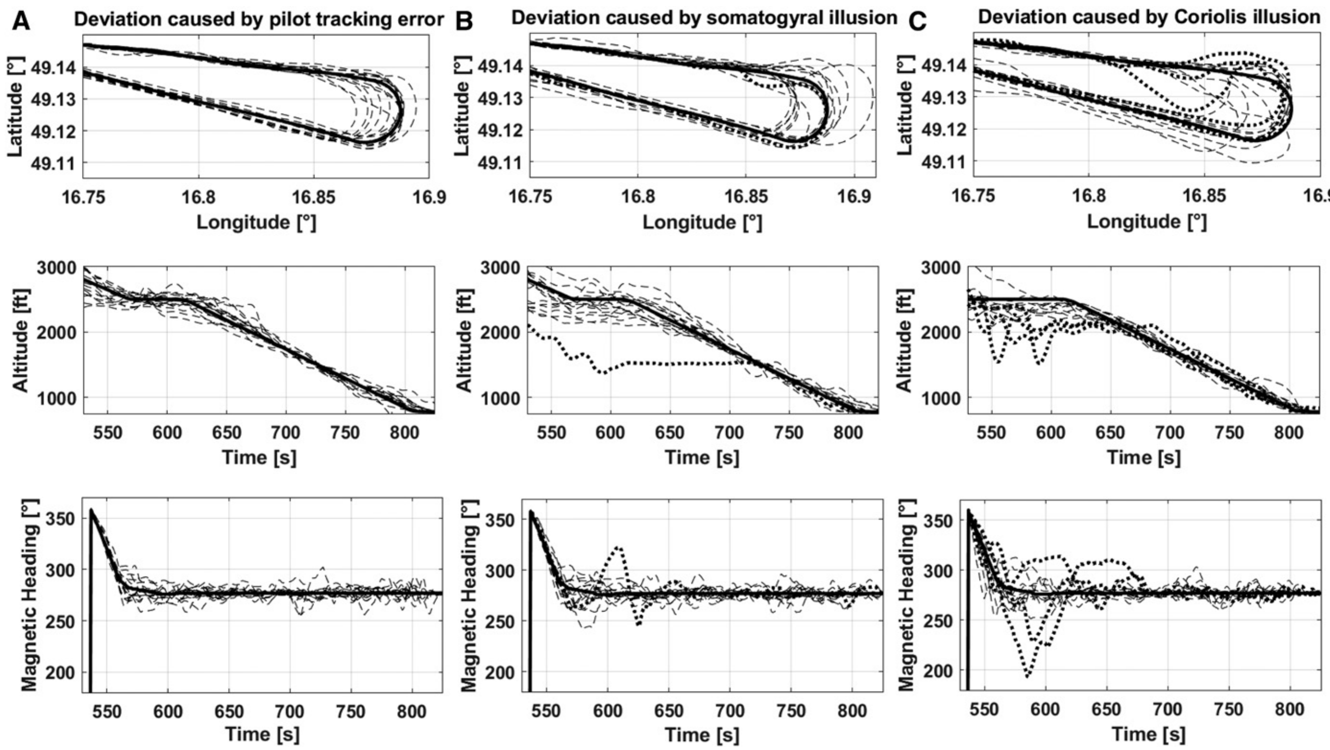

Fig. 4. A) Deviation caused by pilot tracking error. B) Deviation caused by the somatogyral illusion. C) Deviation caused by the Coriolis illusion.

There is a limitation associated with the present findings due to the simulator GYRO IPT II which was used. Unfortunately, there is only one chance of exposing a pilot to the unexpected flight illusion because the pilot's ability to adapt based on his/her experience does not allow repeated exposure. Finally, the utilization of the SD demonstrator for the "unexpected" flight illusion training is limited because of the pilot's knowledge before flight. Pilots have been tested at the Institute of Aviation Medicine and they knew about using an SD demonstrator, which means their expectations influenced subsequent performance. Hence, once the scenarios are used for testing, the pilot adapts to the illusory effect and the flight mission has been revealed.

In conclusion, the current research developed, measured, and quantified the effects of two of the main types of vestibular illusions experienced during simulated flight: somatogyral and Coriolis. The average total deviation from the ideal trajectory influenced by the somatogyral illusion is roughly twice as large as pilot tracking error. The average total deviation from the ideal trajectory influenced by the Coriolis illusion, on the other hand, is roughly four times larger than pilot tracking error. This observation can lead to a conclusion that the risk due to the Coriolis illusion is roughly twice that due to the somatogyral illusion. It was shown by the flight experiment that the Coriolis illusion is more dangerous to flight safety than the somatogyral illusion, and can result in drops of altitude during the final approach, which could have fatal consequences.[15,24,27]

The findings highlight that some pilots are more sensitive to spatial position assessment (differing in visual, perceptual, and vestibular receptors), which influences flight illusion perception. This fact could play an important role in flight safety which should be addressed through additional SD protection training. Recent research by the authors has found that 75% of pilots who answered the survey are interested in being more informed and trained about the causes and effects of illusions in flight.[3] The formalization of routine SD testing helps to recognize which pilots are more sensitive so as to tailor SD training directly and precisely to each pilot.

Future research should also investigate the influence of the pilot's psychological assumptions on handling demonstrated vestibular flight illusions. Moreover, it is not clear whether an objective assessment of pilots' psychophysiological resistance against loss of spatial orientation due to a flight illusion can play a significant role in controlling an aircraft during the final approach phase.

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