Eye movement patterns under exposure to spatial disorientation illusions during simulated flight

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Abstract

Objective

To analyze eye-tracking patterns contributing to or mitigating spatial disorientation (SD) during flight, providing insights to reduce its impact.

Background

SD is a significant contributor to aviation mishaps, often resulting from misinterpreted sensory cues, leading to an incorrect understanding of the aircraft's position, attitude, or motion. Understanding eye-scanning behaviors associated with SD can improve training and reduce incidents.

Method

Eye movements of 45 participants (30 aircrew members, 15 cadets) were recorded using Tobii Pro Glasses 2 during SD-inducing flight simulations in the Gyro-IPT SD simulator. Metrics such as fixations, saccades, and visits were compared between SD and non-SD groups, and statistical analyses were performed to identify differences.

Results

Among 284 flight profiles, 136 SD events were recorded across 30 aircrew and 15 cadets. Some illusions targeted navigators, F-15 aircrew, or active aircrew instead of cadets. SD

events during visual illusions were more likely with frequent instrument panel checks. In contrast, vestibular illusions showed the opposite effect and had a higher probability of causing an SD event among participants who examined the HUD in greater frequencies.

Conclusion

Efficient SD mitigation requires task-specific eye-scanning strategies: visual illusions demand greater instrument focus, while vestibular illusions benefit from HUD engagement.

Application

Implementing the knowledge and training based on the current results can improve performance in flight profiles with high SD risk. There is potential to develop a real-time alert system installed on aircraft during real flights, helping to mitigate or entirely eliminate the fatal results of SD events.

Keywords

1. Pilot, crew behavior
2. Situation awareness
3. Simulation and training
4. Eye movements, tracking

5. Flight displays

Precis

This study examined eye-tracking patterns during flight to identify mechanisms underlying spatial disorientation (SD) and strategies for SD avoidance. Findings reveal that to avoid visual illusions instrument focus is required, while HUD engagement is beneficial to avoid vestibular illusions. Results could be applied to training programs to enhance flight safety and reduce SD incidents.

Background

Spatial orientation refers to correctly perceiving one's position or motion relative to the earth, achieved through visual and vestibular cues or intellectually constructed from focal visual, verbal, or other symbolic data (Gillingham, 1992). During flight, spatial orientation pertains to an aircrew member's ability to identify the aircraft's velocity, altitude, heading direction, rotation, and pitch angle. Spatial Disorientation (SD) occurs when these elements are misperceived, leading to errors in interpreting motion, position, or attitude due to lack or misleading cues, primarily from the visual or vestibular systems (B Cheung & Hofer, 2003).

SD in flight is a leading cause of aircraft mishaps attributable to operator error (Gillingham, 1992). It is responsible for 5–10% of all mishaps, 90% of which are fatal (Antunano, 2005). A USAF report found SD was a factor in 30% of mishaps from 1990–1999 and 26% from 1999–2009 (R. Gibb et al., 2011). Similarly, SD contributed to 20% of fatal mishaps in the U.S. Navy between 1990–2000 and 38% between 2000–2017 (Meeks et al., 2024). SD mishaps are frequently caused by undetected illusions, with 80% of incidents occurring without aircrew awareness (Gregg, 1955)

Several visual and vestibular illusions that can occur during flight were identified with the potential risk of developing SD in aircrew members. The main illusions are described as follows:

Somatogravic Illusion (Dark Takeoff, DT)	A false sensation of body tilt resulting from a perception of a nonvertical gravitational force as vertical (Davis et al., 2008). When aircrew members take off in reduced visibility surroundings, they might perceive the pitch to be higher than it is due to the combination of inertia. This sensation can lead the pilot to unneeded lower the pitch angle and even to a crush.
Somatogyral Illusion (SGI)	A straightening movement following a long rotation will initiate movement in the semicircular canal in that direction, creating a sensation of a rotation opposite to the initial rotation. An aircrew member following this feeling will try to straighten their flight while actually entering the original rotation (Boril et al., 2020).
Graveyard Spin (GS)	Similar to the Somatogyral Illusion, after a prolonged spin, a straightening motion can initiate a reaction in the opposite direction in the semi-circular canals, an attempt to Correct this feeling can lead to a spin in the initial direction (Guzy et al., 2008).
Black Hole Approach (BHA)	When approaching a runway with absent ambient cues, estimating the distance from the runway is difficult. The lack of global and local objects fails to produce the perception of the runway as a surface plane on the ground, it allows the runway to “float”. This causes the aircrew member to experience glide path overestimation so that they initiate an inappropriately steep descent. The result is a shallow approach that lies below the correct glide path for obstacle clearance (R. W. Gibb, 2007).

Ground-Light and Stars (GLS)	On a dark night, the ground lights and the stars' lights can appear similar, creating confusion about where the horizon line is. Trying to rely on exterior display in this situation can significantly change the aircraft's altitude (Sánchez-Tena et al., 2018).
Coriolis	Head movements during rotation activate multiple semicircular canals, causing disorientation and nausea (Houben et al., 2022).
False Horizon (FH)	The external view of the horizon can be misleading as the tilted ground line of a mountain or a tilted cloud deck could be misinterpreted as the horizon, and the aircraft is based on the tilted clouds (Zhdan'ko et al., 2012)

Simulators replicating these conditions with high fidelity are recommended for SD training (B Cheung & Wong, 1998).

An SD simulator is a flight simulator that combines: 1) Visual stimuli using screens that stimulate the aircraft's surroundings as the aircrew member would have experienced during a flight, and screens that present the aircraft's instruments, which provide an objective understanding of the aircraft's state; 2) Vestibular stimuli: the simulator has a motion ability in the 3 motion axes: pitch, roll, and yaw. The aircrew member within the simulator controls the motion by operating the throttle lever and flight control stick.

An SD simulator combines visual and vestibular stimuli to replicate flight conditions, enhancing SD training. Simulators allow researchers to study physiological and perceptual changes during SD events. Studies have found that vestibular stimulation can

alter heart and respiration rates (Ilbasmis & Yildiz, 2017). Other studies found that nighttime climbing perception was influenced by optokinetic and cervico-ocular reflexes (Tamura et al., 2016); (Maurice & Gioanni, 2004). Additionally, participants were found to react to the motion and can consistently indicate a roll tilt during a turn, yet they show a slower and inconsistent pitch response during a takeoff (Tribukait et al., 2013). Moreover, a study showed that an attempt to straighten following a long turn when no visual indication is available often results in a return to the original turn direction (Nooij & Groen, 2011).

Eye-tracking (ET) technology provides insights into pilots' visual scanning patterns, revealing attention to critical instruments and external cues. Focus is measured using *fixations* (Valliappan et al., 2020), which usually indicate sustained attention (Unsworth et al., 2020) and perhaps a thorough processing of critical information (Just & Carpenter, 1976), (it can hint at a cognitive overload (Hauland, 2019)). Prolonged fixations on critical instruments were associated with better situational awareness, as pilots spent more time interpreting vital information needed to maintain safe flight operations (Goldberg & Kotval, 1999). In contrast, the *Visit* measure might provide a broader view of how often a pilot re-engages with a particular area, with frequent visits suggesting a high level of monitoring and reassessment of critical information. *Saccades* are rapid eye movements between fixations (Barfield & Furness, 1995). Frequent and large saccades typically indicate active scanning behavior, and reduced saccadic activity may suggest a narrowed focus or cognitive tunneling, where the pilot becomes overly reliant on a single instrument, potentially leading to the neglect of other critical information (Di Stasi et al., 2013). *Pupil*

diameter measurement is linked to higher cognitive load (Filipowicz et al., 2020) effort (Joshi et al., 2016), and surprising sensory outcomes (Yokoi & Weiler, 2021).

Eye tracking can help us understand the way aircrew members respond to physiological effects, it is at once an objective physiological response indicator - as it gives us information about saccades and pupil diameter - as we can measure the scanning patterns of the visual stimuli in the surroundings, and a subjective indicator of experience - as it provides fixation areas that indicate to which areas of interest the subject gave attention.

When examining visual scanning patterns in pilots using imagery that stimulates the external visual environment of the cockpit, it was found that efficient scanning across multiple AOIs, supported by well-timed saccades, is crucial for maintaining situational awareness and preventing SD (Thomas & Wickens, 2016). Similarly, prolonged fixations and visits on critical instruments were associated with better situational awareness, as pilots spent more time interpreting vital information needed to maintain safe flight operations (Goldberg & Kotval, 1999).

Research conducted in the Korean Air Force examined differences between scanning patterns across flight instruments between a group where a verbal report was required and one that wasn’t (Kang et al., 2021). That study found that the verbal report group focused more on areas of interest (AOI) and had higher fixation frequency in the altitude measure in the Head-Up Display (HUD) in Coriolis, FH, and GS illusions. A Japanese Air Force study examining eye movements during DT illusions found an automatic downward motion during the pitch-up motion, a reflexive response meant to stabilize the visual input

(Tamura et al., 2016). When comparing experienced pilots and non-pilot participants in FH, SGI, and Coriolis illusions, the research found that experienced pilots were as susceptible to SD as non-pilots (Bałaj et al., 2018). It also found that the pilots had a shorter fixation on aircraft instruments, except during landing.

Previous studies have focused on a limited range of AOIs and illusions although a broader range of scenarios is required to perceive a more comprehensive understanding of SD mechanisms. As Cheung claims, there is a need for improved training that will improve pilots' physical and mental performance during sensory conflict. Special attention should be drawn to the properties of various flight displays that may contribute to SD (Bob Cheung, 2013).

Previous studies have also focused only on one aircrew member population – experienced pilots, comparing those to navigators and flying cadets can help us create better learning paradigms to help prevent SD events. A predictive model including different populations can add a data-driven angle to identify underlying mechanisms.

Therefore, in this study, we aimed to use ET to understand the mechanisms leading to SD events and to understand what separates those who experience SD events and those who do not.

Based on the above literature in the current study we aimed to examine the eye-scanning patterns of aircrew members in scenarios that have the potential to create an SD event will help us identify the mechanisms underlying their occurrences and create more targeted training against their effects. The current research is exploratory and aims to

identify significant differences in eye-scanning parameters as they relate to flight measurements within scenarios with SD events potential. It also analyzes interpersonal factors such as flight experience and role that can affect eye-scanning parameters. It is aimed to identify what separates aircrew members who experience the SD effect and react incorrectly to the illusion versus those who do not identify the desired action to help avoid SD events.

Methods

Study Design

We collected participants as part of their pre-existing training program. The participants were from two groups: flying cadets and experienced pilots. The study was approved by the Ethics Committee of the Israeli Defense Forces based on the ICH-GCP principles. This is an exploratory pilot and was not pre-registered, yet the procedure and sample size were predetermined by the ethics protocol.

Apparatus and measurement

Eye tracking glasses: The Tobii Pro Glasses 2 Live View Wireless 100 were used to collect data, the parameters extracted from the glasses are elaborated Table 1 – Eye-tracking and SD trainer parameters in the variables section.

SD trainer: The Gyro-IPT simulator (Environmental Tectonics Corporation, Inc., Southampton, US), located at the Israeli Air Force Aeromedical Center was used. This dynamic motion-based simulator has 3 degrees of freedom (roll ±25°, pitch ±25°, yaw 360°, and Heave =/- 25cm) has a one-channel, non-collimated out-the-window visual display (120*40 3 windows wide field of view, real image). The flight instruments panel displayed in the cabin represents typical indicators that are applied in the pilots' aircraft (Military Institute of Aviation Medicine, Warsaw, Poland et al., 2023).

Figure 1 - SD simulator

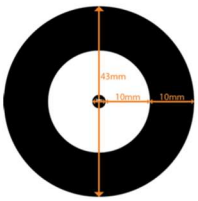
(1) Left: the SD simulator from the outside, has a motion ability in 3 axes. (2) Right: internal view of the SD simulator containing a visual external display and the cockpit instruments panel.

Procedure

Forty-five participants were recruited. Thirty active aircrew members and fifteen flying cadets. They were approached when they arrived to train in the SD simulator according to the Israeli Air Force training regulations. Before the beginning of the training session, they were presented with the study's aims and the procedure. They were explained the study would not change the course of the mandatory training they arrived for and would

only add the eye-tracking glasses. Those who agreed to participate signed the consent form. Then, a briefing session was provided for each participant about the simulator and the training procedure. The participants were equipped with the Tobii glasses, and a calibration process was conducted using the internal calibration algorithm of Tobii Glasses 2. During the calibration process, the participant had to wear the Head Unit while focusing on the center of the calibration target (Figure 2 - calibration target) located about one meter from the participant

Figure 2 - calibration target



Then the participants entered the SD trainer and underwent the training procedure, which contained up to 8 flight profiles:

a. Free flight
b. Dark takeoff (DT) – a takeoff simulation during a dark night. 4 seconds after takeoff the Head-Up Display (HUD) is shut down.
c. Somatogyral illusion (SGI) – a prolonged turn during a dark night for 40 seconds, followed by a straightening instruction.
d. Black hole approach (BHA) – an approach to landing during a dark night with no ground light around the landing strip except for the landing lights.
e. Ground-lights and stars (GLS) – during a prolonged turn on a dark night, all the instruments (HUD and regular flight instruments panel) are shut down. The external view consists of starlight and its reflection in the sea.
f. Coriolis – during a prolonged turn an instruction to look backward is played.

g. Graveyard spin (GS) – within a cloudy environment an instruction to enter a downward spin is given, and after a prolonged spin a straightening instruction is given.
h. False horizon (FH) – the subject is requested to climb and enter a turn simultaneously. During the climb, the aircraft enters a heavy cloud area. While the aircraft exits the cloud line the Artificial Horizon display on the HUD is shut down. The cloud line is at an angle of 7 degrees compared to a straight horizon, creating a false horizon. Instructions to straighten are given.

Participants

Aircrew members (n=30): operational experienced high-performance aircrew members: pilots and navigators, 30-50 years old (average 37.74±5.46 years 1 SD), with 12-22 years of experience.

Flying cadets (n=15): pilot cadets and navigator cadets, during the second year of the flying academy (average 19.84±0.01 years 1 SD). The training profile for cadets included only 4 out of the 7 illusions (SGI, BHA, GLS, and Coriolis) in the aircrew member training profile, as elaborated below.

Variables

The demographic parameters: Aircraft type (F-15, F16, or T-6), Aircrew member role (navigator or pilot), and age were collected and are reported in the results.

Eye-tracking parameters were extracted from the eye-tracking glasses using the Tobii Pro lab program. Flight parameters were extracted from the Gyro IPT program per flight profile. The data consisted of the aeromodel parameters (Table 1).

Table 1 – Eye-tracking and SD trainer parameters

Apparatus	*Key indicator*	*Unit*
Eye-tracker	The total duration of fixation and visits in AOIs and the total	ms
Eye-tracker	Time to first visit in AOI	ms
Eye-tracker	Number of fixations in AOIs and total.	
Eye-tracker	Number of visits in AOIs and total.	
Eye-tracker	Number of saccades in AOIs and total.	
Eye-tracker	Maximum peak velocity of saccades	(°)/s
Eye-tracker	The average amplitude of saccades	(°)
SD trainer	Altitude	m
SD trainer	Velocity – ground speed, airspeed, North velocity, east velocity	m/s
SD trainer	Heading Position	(°)
SD trainer	Pitch, Roll, and Yaw positions	(°)
SD trainer	Pitch, Roll, and Yaw velocity	(°)/s

Each sortie timeline was marked with TOIs as described in Table 2 (pre-SD window, SD window, and SD events if occurred). For each illusion SD events and SD windows were marked based on criteria appearing in Table 3 using the flight measures mentioned above

from the SD trainer produces (altitude, velocity, heading position and pitch, roll and yaw position, and velocity).

Table 2 - TOI categories

Key indicator	*Explanation*
Pre SD window	5 seconds before the onset of the illusion (SD event)
SD window	The time when the illusion is active
SD event	The aircrew members reacted as expected from the illusion.

Table 3 - Flight profiles TOI marking

Illusion	*SD window*	*SD events*	*Explanation*
*Dark takeoff (DT)**	4 sec from takeoff, for 20 sec	Altitude <=1000 m Pitch Position <= 0°	A descent when the aircraft is still too low
Somatogyral illusion (SGI)	40 sec from roll start, for 20 sec	Roll Position > 0° and Roll Velocity >= 3 °/s	A motion toward the original roll
Black hole approach (BHA)	No SD window	Y position > 4000m and Altitude < 60 m or a crash	The aircraft lowers below 60 m when its steel is 4 km from the landing strip or a crash.
Ground-light and stars (GLS)	4 sec from the second the heading position is 359, for 15 sec	Altitude changes of 152 m, or Speed changes of 26 m/s	Drastic changes in the aircraft's status – 152 m in altitude or 26 m/s in velocity

Coriolis	Head movement (taken manually from recording), for 10 sec	Roll Velocity < -7	A drastic stick movement due to the roll sensation
*Graveyard spin (GS)**	No SD window	Roll Position > 0° and Roll Velocity >= 3 °/s	A motion towards the original spin
*False horizon (FH)**	Altitude > 2590 m, for 12 sec	Roll position <= -5 and Roll Velocity <=0	A straightening according to the object's slope

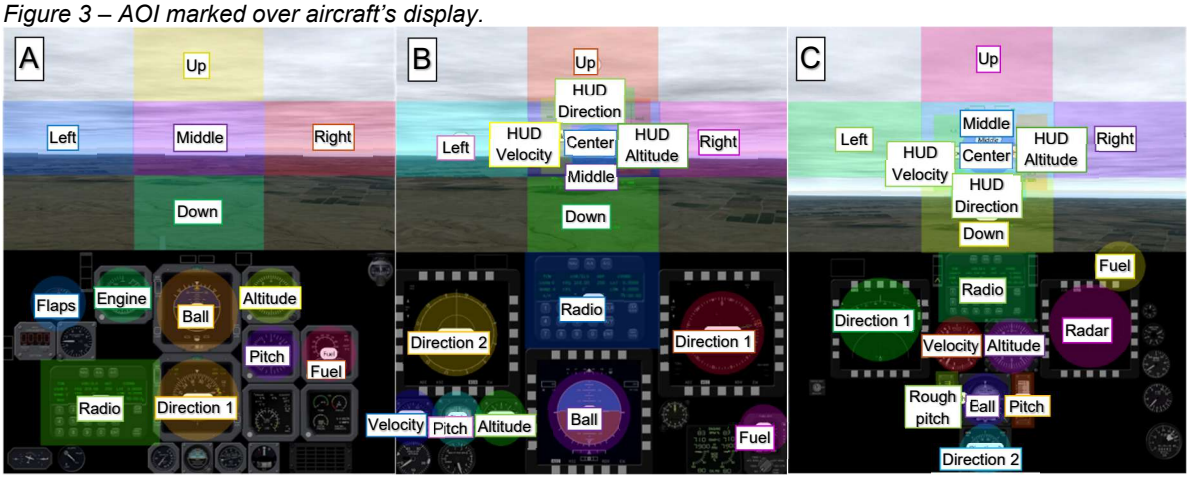
**Illusions not included in the SD training of cadets*

AOIs

AOI was marked for each instrument, HUD element, and external aircraft display (Figure 3):

External display	Instruments panel	HUD
Middle Up Down Left Right	Altitude Direction Velocity Pitch Ball (Indicates both pitch and roll angles) Engine Fuel Radar Flaps Radio	Center Altitude Direction Velocity

Figure 3 – AOI marked over aircraft's display.

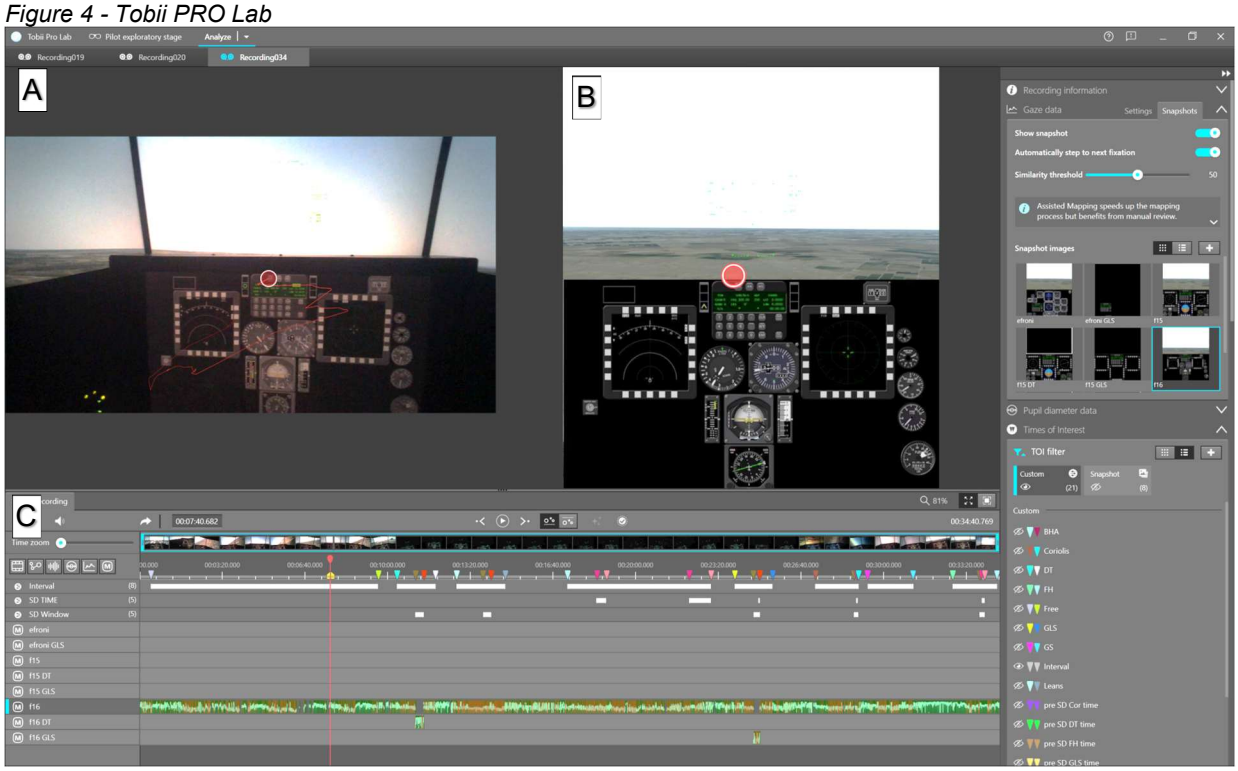


From left to right: (A) The T-6 aircraft does not have a HUD display, the marked AOIs are the external view and the instruments panel. (B) F-15 aircraft display of the instruments panel, the HUD, and the external view. (C) F-16 aircraft display of the instruments panel, HUD, and the external view.

Statistical analyses

The initial analysis of the eye-tracking was performed using the statistical analysis program of Tobii (Tobii PRO LAB) producing the eye-tracking parameters elaborated in Table 1 for each TOI and AOI (Figure 4). The parameters were then entered into Python 3.11 to create t-tests. Due to multiple comparisons made between SD and non-SD groups in the different illusions and AOIs, statistical significance was defined as 0.05 divided by the number of comparisons – 100, thus being $p<0.0005$.

Figure 4 - Tobii PRO Lab



The Tobii PRO lab statistical analysis program: (A): video recording from the eye-tracker. (B): a reference snapshot for the compatible aircraft display. (C): recording timeline with the following marks (up to down) - relevant event marks, interval, SD time, SD window and TOI marks, gaze mapping from video to snapshot affinity.

Results

Demographics

Data were collected from cadets and active aircrew members. Within these groups, they were divided into navigators and pilots. The active aircrew members were further divided into F-15 and F-16 aircraft (Table 4).

Table 4 - participants demographics

Position	Navigator cadet	Pilot cadet	Navigator	Pilot	Navigator	Pilot
Aircraft	T-6		F-15		F-16	
n	5	10	3	4	10	13
Percentages	11%	22%	7%	9%	22%	29%
Average age	19.5	19.5	38.2	40.4	36.0	38.1
Number of flight profiles	20	42	20	28	81	92
Profiles details	All 5 participants overwent the 4 profiles.	All 10 participants overwent the 4 profiles, 2 performed BHA twice.	2 of the participants overwent the 7 profiles, 1 performed BHA twice, 1 performed DT twice, 1 did only 4 profiles*.	All 4 participants overwent the 7 profiles.	All 10 participants overwent the 7 profiles, 7 performed BHA twice, 4 performed DT twice.	All 13 participants overwent the 7 profiles, 1 performed DT twice.

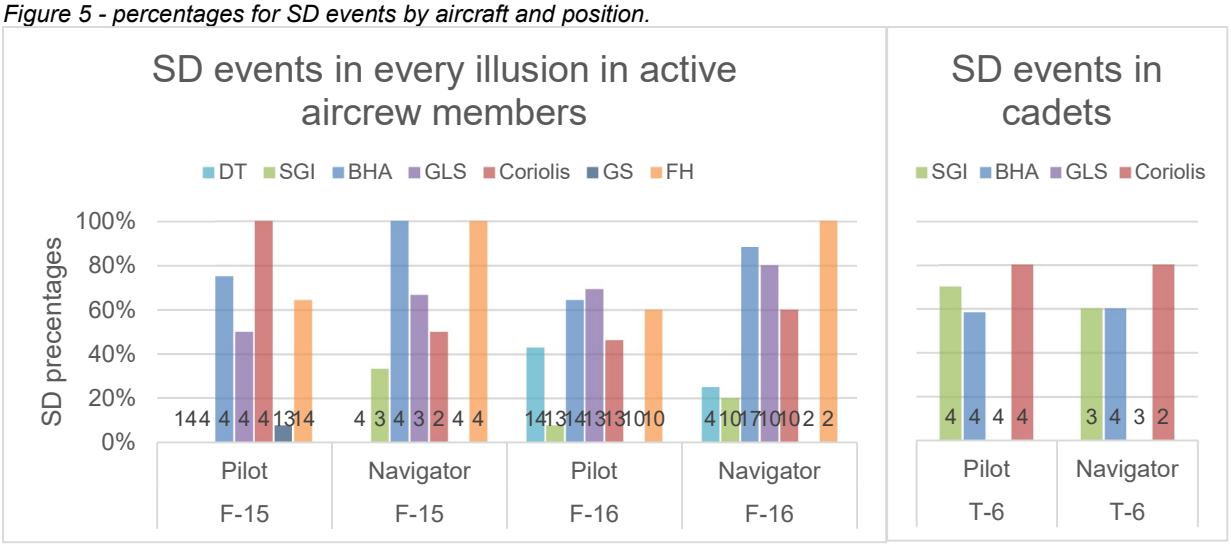
**Due to an eye-tracker malfunction one navigator only performed 4 profiles (DT, SGI, GLS, and BHA)*

Active aircrew members (n=30, average age = 37.74±5.46) performed all 7 profiles. Some participants performed BHA and DT twice, and 1 did not complete the entire procedure (as elaborated above in Table 4), summing to 221 profiles. Flying cadets (n=15) did only

4 of those profiles as elaborated above in Table 3, and 2 pilot cadets performed the BHA profile twice, summing to 62 profiles. Overall, 283 profiles were taken for analysis. The flight experiment of the aircrew members was deduced from their age, as they started the pilot course at 18, the flight experiment of the flying cadets is when undergoing the SD training is 1.5 years.

Out of the 283 profiles, 136 profiles contained an SD event. The percentages of flight profiles containing an SD event were calculated per group (Figure 5).

Figure 5 - percentages for SD events by aircraft and position.

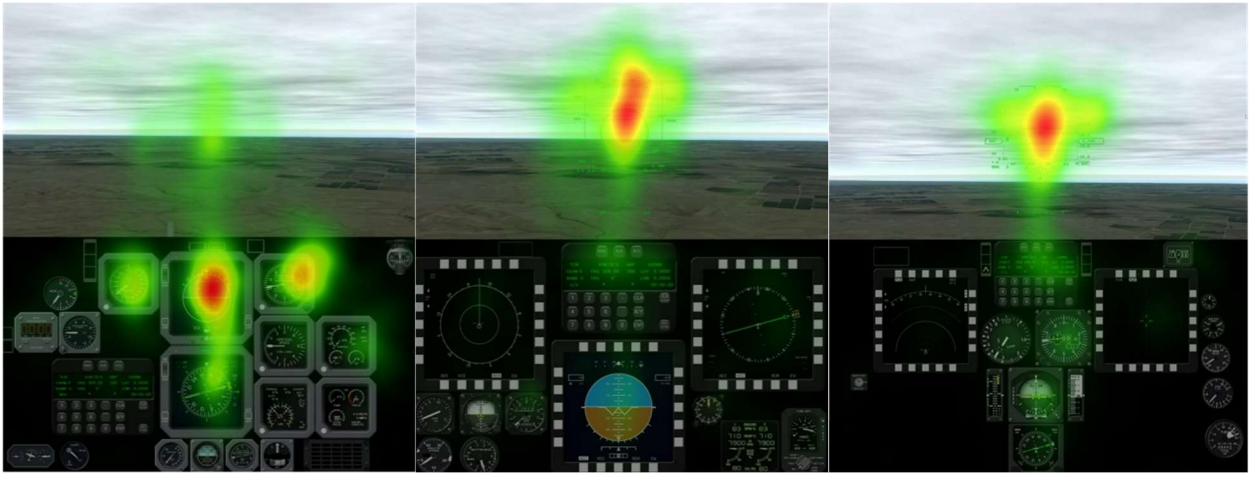


The total number of flight profiles for each category is shown at the bottom of each graph bar. Of them, the percentage of SD events induced out of the total flights is presented.

Eye-scanning patterns

The eye gaze throughout the flight was analyzed to create heatmaps (see Figure 6).

Figure 6 - gaze heat map



Heat map of each cockpit display as calculated in the Tobii pro lab program using the Tobii I-VT (Fixation) gaze filter, from left to right: T-6, F-15, F-16. Colors closer to red indicate more fixation in the area throughout all flight profiles.

The heat map showed that T-6 pilots and cadets, visit the instruments more than the external view, particularly on the ball instrument that indicates the roll and pitch degree, while F-15 and F-16 pilots visit the HUD more. The percentage of the intervals spent fixating on the different AOI categories is brought in Table 5:

Table 5 - fixation time to AOIs

	Instruments	*HUD*	*Outside view*
Nav	3.92%	28.26%	36.77%
Pilot	11.63%	25.20%	34.53%
Nav Cadet	38.87%	0	9.24%
Pilot Cadet	40.14%	0	10.40%

SD window analyses:

When examining differences in eye scanning patterns in GLS illusion among active pilots (11 SD cases out of 17 sorties) we found that there was a higher average duration of

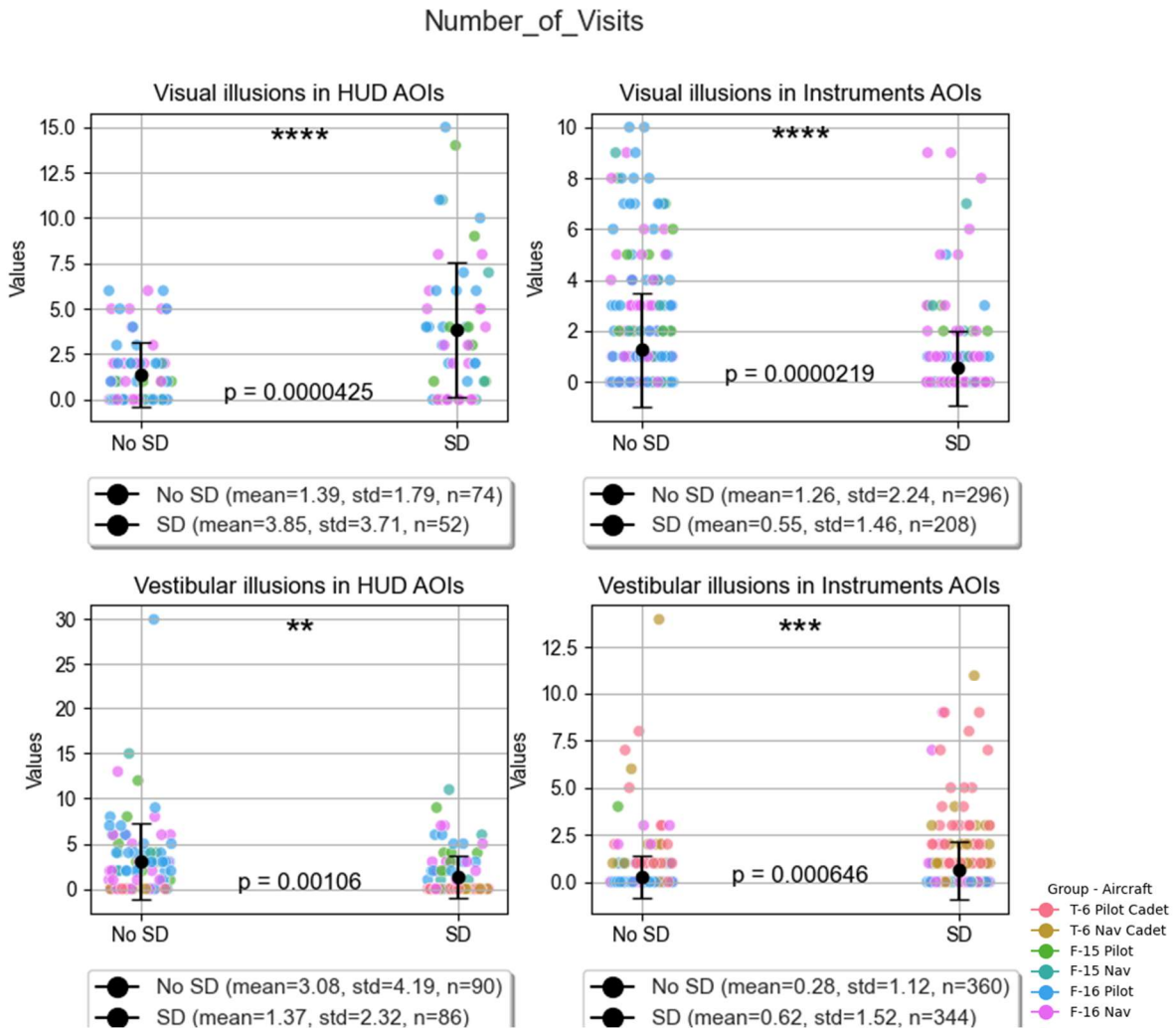
fixation to the altitude measure among those who didn't experience SD (p=7.84E-05). Across all participants (21 SD cases out of 45 sorties) it was found that those who experienced SD fixated and visited less the instruments AOIs, as they had less fixations and visits (respectively) on the ball (p=5.20E-05, 8.83E-06) and to the direction measure (p=1.13E-4, 2.66E-05), and a lower total duration of fixations and visits (respectively) to the ball (p=6.77E-05, 6.33E-05) and the direction (p=2.83E-4, 2.88E-4).

Across all participants in the SGI illusion (14 SD cases out of 45 sorties), preceding the SD window the group not experiencing SD had higher total duration visits on HUD (p=2.45E-4).

When splitting the illusions into two groups: visual illusions (DT, GLS, and FH) and vestibular illusions (SGI and Coriolis), and using both the pre-SD-window and the SD-window combined, three effects were shown for the number of visits measurement (Figure 7).

First, In the visual illusions, the HUD measurement was higher for the SD group (p=4.25E-5). Second the instruments' measurement was lower (p=2.19E-5) and finally in the vestibular illusions, the HUD measurement was higher for the instruments' measurement (p=6.46E-5)

Figure 7 - a summation of illusion categories



Discussion

In this study, we investigated eye-tracking patterns during exposure to common illusions that cause spatial disorientation (SD) during flight. We aimed to identify which eye-tracking patterns can be related to SD avoidance.

Among 284 flight profiles performed by 30 active aircrew members and 15 flying cadets, 136 SD events were identified across 7 flight profiles (Dark Takeoff, Somatogyral illusion, Black-Hole approach, Ground-lights and Stars, Coriolis, Graveyard Spin, and False Horizon). Dark takeoff and Somatogyral illusion were affected only and mainly (respectively) in navigators. False Horizon and Coriolis illusions had a higher effect on F-15 aircrew than F-16, and Ground-lights and Stars affected only active aircrew members as opposed to cadets. Visual illusions had a higher probability of causing SD events within participants who examined the instruments' panel measurements (altitude, pitch, and ball) in greater frequencies than the HUD. In contrast, vestibular illusions showed the opposite effect.

The study shows that no population avoided SD events completely, as they affected cadets and active pilots, and some illusions even affected active pilots to a greater degree than cadets. This result is similar to Bałaj's research showing that SD cues affected pilots and nonpilots similarly (Bałaj et al., 2018).

In a previous study performed on transportation pilots, HUD usage increased in critical flight stages, particularly in difficult weather conditions when there was an increase in the

amount of time the pilot spends looking out of the front window (Dill & Young, 2015). While the transportation pilots in that study used the HUD only 4% of the overall time, combat pilots in the current research engaged heavily on the HUD, around 90% of the overall time. This might be due to the need for high surrounding awareness as they must constantly assess external threats thus requiring a dynamic use of external visual information (Zhang et al., 2014), (Martins, 2016). This effect might have occured because the HUD allowed them to maintain visual contact with the external environment while monitoring critical flight data (Cummings et al., 2016), (Johnson et al., 2006).

Previous research identified efficient oculomotor strategies to minimize repetitive saccades to already analyzed or irrelevant stimuli and aligning attention with the task requirements. (Shapiro & Raymond, 1989). Our results across the two types of illusions presented to the aircrew members – visual vs. vestibular, it could be deduced that the HUD is irrelevant in visual illusions and those who visited it numerous times for longer durations and with larger pupil diameter succeeded less in the event of instruments shut down (GLS). Furthermore, higher perceptual efficiency was classified with more and shorter dwells at relevant AOI (Lounis et al., 2021). This finding is similar to our findings. In BHA it was found that more saccades and shorter duration of visits in the HUD, and in FH more and shorter visits, are linked to people who experienced SD, hence the HUD cannot be considered as beneficial to a better perception in those visual illusions.

In the vestibular illusions (SGI and Coriolis) an increased time spent examining the HUD and a decreased time examining the instruments panel was related to better performance and SD avoidance. This finding is supported by Yang’s comparison of how experts’ and

novices' scanning patterns change between easy and difficult routes (Yang et al., 2013). For the easy routes, experts spent less time scanning out the window (OTW) and had shorter OTW dwellings. In contrast, for the difficult routes, experts appeared to slow down their scan by spending as much time scanning out the window as the novices while also having fewer Map fixations and shorter OTW dwellings.

The focus specifically directed to the HUD rather than generally examining the OTW is supported by another study that found that experienced pilots have better SA performance and pay more attention to the HUD, but focus less outside the cockpit when compared with novice pilots (Yu et al., 2016). Another supporting finding to the increased need for HUD scanning during vestibular illusions comes from research where Coriolis was found to elevate the use of the HUD compared to other illusions and yielded a higher attentional load score (Kim et al., 2021).

Applications

Repeated spatial training using a simulated environment is beneficial to reduce spatial disorientation, as was shown by a study conducted on neurologic patients (Kober et al., 2013), as well as in pilots (Landman et al., 2018), (Qiu et al., 2023).

It was found that training eye movements based on knowledge acquired about which eye movement type was the most efficient for a specific task can improve performance in said task (Shapiro & Raymond, 1989). Thus, implementing the knowledge and training based on the current results can improve performance in flight profiles with high SD risk.

Another application of the learned differences between eye-scanning patterns leading to SD and avoiding them is a real-time alert system installed on aircraft during real flights, helping eliminate the fatal results of SD events (Peysakhovich et al., 2018).

Limitations

Although the procedure and sample size were pre-determined in the ethics protocols, the study was exploratory and not pre-registered, leading to multiple comparisons which weakened the significance of the results. Using the knowledge gained in this study research can create a more accurate procedure to create stronger effects and means to address them.

Conclusions

This study highlighted the role of targeted eye-scanning behaviors in mitigating SD, revealing that dynamic, broad scanning across instruments may reduce SD experience in various flight illusions. It found that flight profiles involving limited visual cues and thus a potential for visual illusions required higher attention to the HUD, while those with prolonged turns, thus a higher potential to vestibular illusions required greater attention to the instruments panel. It also found that SD risk remains throughout all experience levels. Training that involves lessons from the study regarding the importance of different instruments in different flight situations could improve SD resilience. Further research should broaden the findings beyond the scope of combat pilots only. In addition,

examining whether training using the knowledge accumulated in the study could potentially improve SD resilience.

Key points

- **SD Events**: 136 SD events across 7 flight profiles; specific effects varied by role and aircraft type.
- **Illusions and Eye-Scanning**: Visual illusions (DT, GLS, FH): Frequent HUD focus increased SD risk. Vestibular illusions (SGI, Coriolis): Increased HUD use improved performance.
- **HUD Usage**: Combat pilots rely heavily on HUD (90% usage). HUD is effective during vestibular illusions but less so during visual illusions.
- **Experience and SD**: Experience does not prevent SD; active pilots can be as affected as cadets.
- **Applications**: Simulated training and efficient eye-scanning strategies can reduce SD. Real-time alert systems may help mitigate SD during flights.
- **Conclusion**: Training focused on tailored eye-scanning and instrument use can enhance SD resilience.

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