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ORIGINAL ARTICLE

Spatial disorientation cue effects on gaze behaviour in pilots and non-pilots

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Abstract

Spatial disorientation (SD) poses a serious threat to flight safety. A pilot's gaze behaviour that characterizes his/her visual perception and attention determines success in dealing with this phenomenon. Regardless of a pilot's experience or proficiency, sensory illusions can lead to differences between instrument indications and what the pilot "feels". Understanding how simulator-induced SD cues affect gaze behaviour in pilots and non-pilots is our interest and was addressed as the aim of this research. Using a SD flight simulator, 40 male (20 military pilots; 20 non-pilots) were exposed to 12 flight sequences. We measured and compared subjects' gaze behaviour and flight performance in response to three visual and three motion illusions across two groups (pilots vs. non-pilots) and flight type (non-SD vs. SD flight). From the applied SD cues only in three illusions (false horizon, somatogyral, and Coriolis), the difference in visual attention distribution in comparison with non-SD flight was observed. There was no interaction of expertise and flight type. The pilots had shorter mean fixation time than non-pilots, except for landings. For the same SD flight profiles, we found the changes of the subjects' gaze behaviour and flight performance. The SD cues affect both the pilots and non-pilots in the same way; therefore, being an expert in piloting aircraft does not reduce the susceptibility of the pilot to loss of their spatial orientation. Eye-tracking technology could be useful in the analysis of the pilots' attention and better understanding and training of pilots' flight performance during SD events.

Keywords Visual attention · Flight safety · Expertise · Spatial disorientation · Eye movements · Flight illusions

1 Introduction

Spatial navigation during flight is a cognitively complex and demanding task (Dahlstrom and Nahlinder 2009) that requires continuous monitoring of system parameters and the environment (Colvin et al. 2005). Especially, when changing a flying machine, pilots have to put in additional cognitive resources that are needed, while they are piloting the aircraft (Soo et al. 2016). Piloting depends on both the characteristics of the pilot and the conditions of the situation (van Erp 2007). Despite having had extensive training, experienced pilots can still have difficulties with some visual or vestibular distracting cues leading to the loss of spatial orientation. Spatial disorientation (SD) is the loss of the ability to correctly determine the position and movement of the airplane and the pilot relative to the ground or some other aircraft (Stott and Benson 2016). SD is one of the most critical factors leading to aircraft accidents, especially in military operations, often resulting in the death of the crew and passengers and substantial financial losses (Knapp and Johnson 1996). SD has been cited as the leading cause of 33% of all aircraft incidents, with a fatality rate of almost 100% (Gibb et al. 2011). Despite these incidents, data from 1947 to 2010 (Gibb 2010; Gibb et al. 2011) indicate that SD's role in incidents over the years is consistent; rates are

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not declining. It should be emphasised that up to 65% of SD cases are unrecognised (Previc and Ercoline 2004). Disoriented pilots are often not aware of their orientation error and, upon recognising that a conflict exists, often believe a flight instrument to be in error. All pilots are susceptible to the SD while flying at night, in various weather conditions, during extreme manoeuvres, and even in visual meteorological conditions.

Vision is the most important sense used in flight, because it allows pilots to quickly ascertain their position in space. Unfortunately, when flying without reliable external attitude or motion cues, only the conscious mind can correctly determine the correct orientation through the use of focal vision and attention to flight instruments. Although it is possible to establish spatial orientation through aircraft instrumentation and displays indirectly, orientation comes at a high cognitive demand. This high cognitive and attention demand on the pilot competes with other mission-specific demands such as decision-making and risk assessment for different courses of actions.

Due to human nature, the pilot's attention is often directed outside of the cockpit, where the potential for distraction is extensive. What the pilot sees outside of the cockpit can be misleading and provoke visual illusions, and the lack of scanning critical flight parameters (such as attitude, airspeed, altitude, or vertical velocity) can lead to SD. After vision, the vestibular system is the second most important sense in spatial orientation and can also provoke sensory illusions in pilots. However, if adequate external visual references are available, any disorienting vestibular inputs are ignored.

Aside from several methods of counteracting SD in flight, the key to preventing and coping with SD is to develop a useful instrument crosscheck (visual field scanning strategy), which provides a continuous source of accurate information related to aircraft attitude, motion, and position. When the pilot is distracted from cross-checking the instruments during intensive task phases of flight in marginal weather or reduced visibility conditions, the pilot's ability to recognise and resist SD is severely diminished. Therefore, it is essential for a valid instrument crosscheck to be developed early and established during all phases of flight.

Taking these into account, in the present study, we focused on determining effective strategies for searching the field of view (crosscheck) during flight that increase the pilot's susceptibility to loss of spatial orientation. We were curious as to whether the pilot's flying experience and skills predispose the pilot to greater resistance to flight illusions and, if so, which type of illusion. Information about how pilots use their eyes, while flying with the threat of SD is fundamental to a basic understanding of their cognitive mechanism and to simplification of the psychological processes that occur, while a pilot is controlling an aircraft's movement in the face of this phenomenon. If we know where a pilot is looking, we do not necessarily know what he is thinking, but we know something of what he is thinking about. In other words, we know the error signal inputs he is operating on.

Even though SD is still a common and insidious phenomenon, there are only a few studies that analysed eye movement during flight with visual or vestibular stimuli provoking SD (Cheung and Hofer 2003; Kowalczuk 2004; Kowalczuk et al. 2016). Cheung and Hofer (2003) measured the level of piloting task deterioration (deviation from the expected aircraft speed) after the occurrence of one specific type of SD—the Coriolis vestibular cross coupling-induced pitch illusion. This study was conducted only in non-pilots with no previous flight experience, but they were trained to maintain straight-and-level flight and in the procedures of attitude changing. During the pitch illusion, changes in scanning behaviours were observed. The disorientating condition increased the number of saccades and a delay in directing gaze at the appropriate measurement instrument (engine torque). Participants paid less attention to the airspeed and attitude director indicators when disoriented than when normally oriented. Thus, the Coriolis illusion affects both task execution and visual scanning. This study contained only one type of flight profile.

More elaborate studies on a group of expert pilots flying under SD conditions induced by a wide range of visual and vestibular illusions was performed by Kowalczuk (2004). Among all the physiological indicators including electrocardiography, heart rate, electronystagmography, and blood pressure, only eye movement was useful in determining the SD. The author indicated that visual flight instrument scanning was disrupted by SD, which was reflected in changes in oculomotor parameters.

The effectiveness of a scanning strategy can also be determined by comparing eye movements of experts and novices. Fitts et al. (1949) found that experienced pilots had more frequent fixations and shorter fixation duration on flight instruments. Bellenkes et al. (1997) confirmed this finding and also indicated that expert pilots' scanning strategies differed from those of novices in that they more effectively collected visual information, which left them with more cognitive resources to monitor less critical tasks and cope with changing task requirements. Ottati et al. (1999) and Kasarskis et al. (2001) found that experts showed differences in attention allocation, total number of fixations, and flight performance behaviour.

Although a pilot's experience and flight proficiency have a significant influence on visual behaviour and task performance, no one is immune to SD. The comparison between pilots' and non-pilots' gaze behaviour could demonstrate how their visual scanning changes during exposure to SD cues (not only in their instrument sampling behaviour but also in their instrument scanning behaviour). We are interested in (1) whether SD cues affect pilots and non-pilots in the same way and, if not, when it affects them differently, (2) whether natural gaze behaviour (untrained in effective scanning of the visual field) can cause non-pilots to cope better with SD than pilots, and (3) whether there are universal indicators for coping with SD.

The present research aimed to answer the above questions and to understand how simulator-induced SD cues affect gaze behaviour in pilots and non-pilots. We hypothesised that gaze behaviour would be impaired in disoriented flight profiles as compared to non-SD (control) flight profiles, and pilots would be less impaired than non-pilots (i.e., we expected an interaction between expertise and SD). We also hypothesised that flight performance would decline in disorientation conditions as compared to control conditions. We also suppose that it could be possible to determine effective strategies for searching the field of view during SD flight.

In our investigation, we measured military aviators' and non-pilots' gaze behaviour during a variety of disorientation conditions consisting of both visual and vestibular illusions, while they were piloting a flight simulator. Our results contribute to the basic understanding of how simulator-induced SD cues and flight proficiency affect gaze behaviour and the ability to prevent or cope with SD. We conclude that, to enhance flight safety, there is a need to provide pilots with training for effective scanning strategies that will help them to maintain their spatial orientation, especially during the most vulnerable flight phases such as approach and landing.

2 Method

2.1 Participants

The experiment included a group of 40 male volunteers: an expert pilots group (*N* = 20; age: M = 31.6; SD = 8.22) and a non-pilots group (*N* = 20; age: M = 30.95; SD = 7.72). All pilots were military aviators actively flying fixed-wing military aircraft, but they had no exposure to simulator-induced SD. They had at least 100 h of flight experience (range 100–3600 h) and a commercial pilot license with permission to fly under instrument flight rules. All non-pilots had no previous flying or flight simulator experience, just like the novice group in the Cheung and Hofer's (2003) study.

All participants had normal or corrected-to-normal vision and no history of neurological disorders. They were allowed to wear contact lenses but not glasses; because of the eye-tracking apparatus, they wore throughout the experiment. All participants had normal vestibular function and a negative clinical history of vestibular symptoms (dizziness, vertigo, and disorientation). In addition, all participants reported normal sleep patterns, and none had ever experienced a seizure of any sort. They were not permitted to be currently taking any psychoactive medication (e.g., antihistamines, antidepressants, sleep aids, etc.). The Ethical Committee of the Institute of Psychology at John Paul II Catholic University of Lublin, Poland approved the study protocol. An informed consent form was completed by each participant before the experiment. All were paid for their participation.

2.2 Materials and equipment

This study was conducted using an integrated physiological trainer (Gyro-IPT; Environmental Tectonics Corporation, Inc., Southampton, PA, USA) located at the Military Institute of Aviation Medicine in Poland. For tracking oculomotor activity, mobile EyeTracking glasses (SensoMotoric Instruments GmbH, Germany) were used. The Vienna test system (Schuhfried 2013) was used to check and compare the participants' cognitive resources.

Unlike a typical flight simulator, the Gyro-IPT allows the operator to program sustained and transient motions in consent with the motions generated by the simulation model of an aircraft (the TS-11 Polish jet trainer aircraft). The Gyro-IPT does not replicate the aircraft that the pilots usually fly. However, the flight instruments represent typical indicators that are applied in pilots' aircraft. The simulator has a three-axis (roll ± 30°, pitch ± 15°, and yaw 360°) motion base and visual scene (Out-the-window—OTW). These indicators provided all the necessary visual and motion flight simulation required in this study. The simulator was equipped with a data acquisition system, so that flight data were readily recorded for analysis in real time from the participant's flight profile status. A one-way visual and a two-way audio communication system allowed the participant to interact with the investigator and allowed the investigator to monitor the participant continuously.

Simulator-induced SD consisted of three vestibular origin and three visual origin illusions. These illusions were implemented in the six flight profiles. The three visual illusions included the following profiles:

- Straight-and-level flight (S&LF) with daytime false horizon illusion (created by a sloping cloud deck), a profile that demonstrates the predominance of peripheral vision in vision-based spatial orientation.
- The circle-to-land procedure (C-T-LP) with shape illusion (created by an up-sloping runway), an illusion associated with the constancy of shapes being expected by the pilot.
- Straight-in approach (S-IA) with constant size illusion (created by a narrower runway), an illusion associated with the constancy of sizes being expected by the pilot; constancy of shape and constancy of size illusions may be particularly strong when flying over unknown terrain or approaching an unknown airport.

The three vestibular illusions included the following:

- Straight-and-level flight after left turn (S&LFALT) with somatogyral illusion, a profile that demonstrates the false sensation of rotational motion (or lack of rotational motion) resulting from an erroneous perception of the strength and direction of actual rotation.
- Right banked turn (RBT) with Coriolis illusion, a demonstration of the effect of cross stimulation of semi-circular canals occurring when the head is moved during fixed rotational motion.
- Straight-and-level flight after the right turn (S&LFART) with lean illusion, whereby the perception of leaning position is disturbed due to the limited sensitivity of vestibular organs.

In the control condition (non-SD flight), we implemented the same flight profiles (listed above) without SD cues. A total of 12 flight profiles (6 SD and 6 non-SD) were prepared for each participant.

The order of profiles was determined at random except profiles with the vestibular illusion cues. Due to the intense stimulation of the vestibular system and the ability to interact with other illusions (Kluch 2003), these flight profiles were always presented at the end of the study. Thus, participants performed nine profiles (three with illusions and six without illusions) in random order and then were exposed to the vestibular illusions (three in random order). The duration of one study was approximately 1.5 h (including measurement of cognitive resources, familiarising flight, and 12 flight profiles). Detailed descriptions of the flight profiles, including the specifications of disorientation cues, are given in Table 1 and are included in Lewkowicz et al. (2015).

Participants wore a head-mounted eye tracker during their flights. An eye-tracking monitoring system (SMI EyeTracking) was inside a pair of glasses with a total weight of 75 g, thus generating no additional physical or cognitive load. This system is a non-invasive device designed to study the overt visual attention of pilots during both real and simulated flight. It does not obstruct the pilot's view and does not restrict movement of the pilot's head, and the researchers can capture the pilot's gaze on every part of the cabin. The SMI EyeTracking glasses have an angular resolution of 0.5° and data-tracking frequency of 30 Hz. The device is equipped with automatic parallax correction and post-hoc calibration mechanisms. The headpiece scene camera records an interior image of the cabin simulator. Between flight profiles, the eye tracker was validated and recalibrated if necessary with a three-point calibration method.

Two tests measuring attention (SIGNAL S1; reliability: for correctness Guttman's $\lambda 2 = 0.78$, and for reaction time Guttman's $\lambda 2 = 0.80$) and memory (CORSI S3; Cronbach's $\alpha = 0.81$) from the Vienna Test System (Schuhfried 2013) were used to check and compare the cognitive resources of pilots and non-pilots.

2.3 Procedure

Participants performed the following three tasks: the Vienna Test System (SIGNAL S1 and CORSI S3 tests), a familiarisation flight in the Gyro-IPT simulator, and 12 flight profiles in the simulator.

After completing the SIGNAL S1 and CORSI S3 tests, all pilots were given 5–10 min of "free-flight" to become reacquainted with the operational characteristics of the simulator and the pressure on the control stick. This was also intended to minimise the impact of individual differences

Table 1 General description of six flight profiles

Profile	Duration of profile	Disorientation condition	Control condition	Flight instrument manipulation
S&LF	190 s	The slope of cloud deck tilted 10° rightward from 19,000 to 21,000 ft	No tilt of the cloud deck	From 130 to 160 s blackout of attitude director indicator
C-T-LP	166 s or runway level achieved	Nighttime runway up-sloped 10°	No up-sloped runway	None
S-IA	90 s or runway level achieved	Nighttime runway narrowed in width from 300 to 150 ft	Runway 300 ft wide	None
S&LFALT	290 s	$76^\circ\cdot\text{s}^{-1}$ of sustained yaw (at $+0.4^\circ\cdot\text{s}^{-2}$) stop yaw rotation in 217 s of flight (at $-15^\circ\cdot\text{s}^{-2}$)	No programmed acceleration stimulus	None
RBT	210 s	$70^\circ\cdot\text{s}^{-1}$ of sustained yaw (at $+0.5^\circ\cdot\text{s}^{-2}$) stop yaw rotation in 173 s of flight (at $-2^\circ\cdot\text{s}^{-2}$)	No programmed acceleration stimulus	None
S&LFART	150 s	$68^\circ\cdot\text{s}^{-1}$ of sustained yaw (at $+1^\circ\cdot\text{s}^{-2}$) stop yaw rotation in 84 s of flight (at $-4^\circ\cdot\text{s}^{-2}$)	No programmed acceleration stimulus	From 92 to 105 s blackout of attitude director indicator

in flight experience between pilots and the various strategies for performing concurrent cognitive tasks that might have been applied by participants in different flight profiles. The familiarisation flight profile included the essential elements of pilotage with the approach-to-landing manoeuvre. All non-pilots that had no previous flying or flight simulator experience were trained to be proficient in maintaining straight-and-level flight and 30 deg bank angle, in the procedures for changing attitude, and in the approach-to-landing manoeuvre. They were trained to perform a standardised procedure of visual crosscheck on the instrument displays and to actively monitor attitude, altitude, heading, and airspeed in a systematic manner. This training ensured that all non-pilots could demonstrate a basic level of eye–hand coordination proficiency in flying the simulator. The familiarisation flight lasted approximately 30 min. If a participant performed all flight manoeuvres in the training session within the predefined limits (Lewkowicz et al. 2015), he or she could participate in the main part of the study.

Participants were instructed that their task was to complete all flight profiles according to the flying instructions given. They focused their attention solely on correctly performing these tasks and did not report their sensations. All participants completed the study at the same time of day (between 10:00 and 16:00).

2.4 Gathering and pre-processing of data

We collected data from psychological tests (SIGNAL S1 and CORSI S3 from the Vienna Test System), flight parameters for conflict and non-SD flight profiles (heading, altitude, vertical velocity, and bank angle from the aircraft simulated in the Gyro-IPT), and eye movement with an interior view of the simulator's cabin (via eye tracker). For all flight profiles in the disorientation condition, only specific flight parameters (described below) were analysed after the onset of disorientation cues. For the control conditions, the same specific flight parameters from the corresponding parts of the conflict flight profiles were analysed. For bank angle, heading, and altitude in the S&LF, S&LFALT, RBT, and S&LFART flight profiles, pilots were supposed to maintain level wings during flight (while the sloping cloud deck was visible or during the post-rotatory illusion in the conflict flights). In the RBT profile, while tilting the head in pitch and roll, pilots were supposed to maintain a 30° bank (Coriolis illusion in the conflict flight). For vertical velocity in the C-T-LP and S-IA flight profiles, pilots were instructed to maintain visual approach along with glide slope during landing (an up-sloping or a narrower runway was in the conflict flight).

To evaluate participants' gaze behaviour, the areas of interest (AOIs) in the image of the monitor screen taken by the headpiece scene camera (Fig. 1) were established. We distinguished the following six areas: attitude director indicator/artificial horizon (ADI), altimeter (ALT), airspeed indicator (ASI), heading indicator (HI), vertical speed indicator (VSI), instruments controlling the engine (Engi), and out-the-window (OTW). These AOIs allow the analysis of gaze time on those specific areas inside and outside of the cockpit.

Analysis of the percentage of time of visual fixation in the AOI allowed us to specify which part of the visual scene was the most explored. Researchers often divide AOIs into instruments related to navigation, technical condition, and OTW (Huemer et al. 2005; van de Merwe et al. 2012).

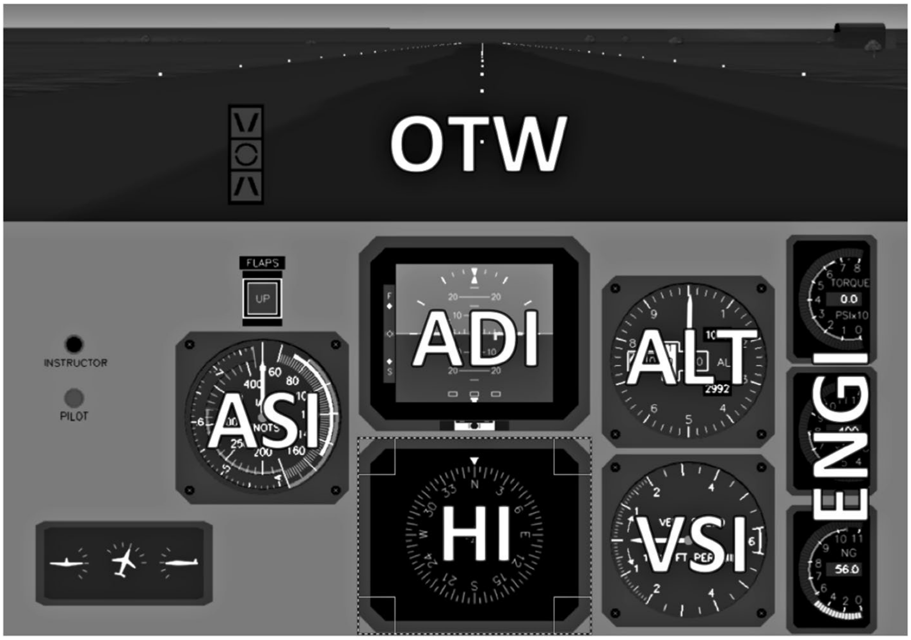


Fig. 1 Areas of interest at flight simulator monitor screen

Regardless of the phase of flight, the pilot's eye movement is an excellent measure of performance. Visual attention distribution during flight can be measured as the percentage of fixation time in a specified AOI (see Dehais et al. 2017).

We used the average fixation time as an indicator of overt visual attention. Average fixation time allowed us to estimate cognitive load for participants in SD and non-SD flight profiles. The duration of fixation provides information on the amount of cognitive processing devoted to areas of interest (Rayner 2009).

To calculate the duration of fixation on each AOI, we needed to account for head movement. The eye tracker recorded eye-movement parameters based on the participant's head position. Therefore, when the participant moved his head and his gaze fixation was constant (focused on an AOI), the eye tracker detected this as a change in gaze position. To calculate the absolute position of the eye, the independent coordinates of each AOI from the video recorded with the camera on a moving head were extracted. This was done according to the procedure described in the previous research (Bałaj et al. 2016).

For a detailed analysis, we identified fragments of oculomotor data storage during the occurrence of SD cues and corresponding portions of the control condition profiles (non-SD flight). The same time-based segment of flight profiles for SD and non-SD flights were identified (see Table 1). Visual attention distribution was analysed separately for each flight profile in fragments after SD cues were applied and in parallel fragments for the flight profiles in the control condition. We measured the percentage of time gazing at each AOI in the flight simulator display (ADI, ALT, ASI, HI, VSI, Engi, and OTW).

2.5 Statistical analysis

We analysed the influence of expertise (two inter-group levels: pilot, non-pilot) and flight type (two levels with repeated measures: SD flight and non-SD flight) on six flight profiles in the simulator. Dependent variables were deviance from in-flight performance indicators (heading, altitude, vertical velocity, and bank angle), average fixation time, and percentage of time gazing at each AOI (ADI, ALT, ASI, Engi, HI, OTW, and VSI).

To assess the occurrence of the SD incidents and differences between analysed groups (pilots and non-pilots), we calculated the quality of flight parameters. For each flight profile, separate ANOVAs with repeated measures (non-SD and SD flights) and the grouping variable (non-pilots and pilots) were carried out.

For the average fixation time, which is an indication of the cognitive load associated with visual information processing, we performed an ANOVA with repeated measures. We selected two repeated-measures factors, flight profile (six levels) and flight type (two levels), and one between-participants factor, expertise (two levels). Analyses were accompanied by Greenhouse–Geisser adjustments for violations of sphericity (when deemed appropriate according to Mauchly's test of sphericity) and were corrected where needed.

We performed MANOVAs (of gaze time at AOIs as dependent variables) with repeated measures (SD and non-SD flights) and a between-participants factor (pilots and non-pilots). Pairwise comparisons were made with Bonferroni correction for multiple comparisons.

A threshold of $p < 0.05$ was used for determining statistical significance. The effect size was estimated using the η_{p}^2 statistic. Simple effect comparisons were performed with the Bonferroni correction for multiple comparisons. All analyses were conducted using IBM SPSS Statistics 17 statistical package.

3 Results

All 40 participants performed 12 flights. Some participants reported dizziness and slight but brief nausea; however, there were no lasting symptoms of motion sickness. Due to technical issues and malfunctions of the apparatus, a full set of flight parameters was not collected (see degrees of freedom in Table 3).

3.1 Vienna test

There was no difference between pilots and non-pilots in visual attention accuracy (VA hits and VA errors) or average detection time (VA timing; see Table 2). For visual memory, there was no difference in direct block memory span (VM-span) between pilots and non-pilots.

3.2 Flight parameters

The defined flight profiles represented various scenarios that differ in the flying conditions given and flight parameters that must be maintained. This can influence the effects of SD cues on flight performance. Therefore, we refrained

Table 2 Differences between pilots and non-pilots in visual attention and visual memory

	Pilots M (SD)	Non-pilots M (SD)	*t*	*df*	*p*
VA hits	53.53 (3.95)	52.05 (3.27)	1.25	36	0.219
VA errors	1.84 (2.27)	1.89 (1.41)	− 0.09	36	0.932
VA timing	0.85 (0.17)	0.81 (0.18)	0.59	36	0.556
VM-span	6.32 (1.06)	5.68 (0.88)	2	36	0.053

Table 3 Main effects of flight type (SD/non-SD flight) and group (pilots/non-pilots) on flight parameters for each flight profile

Flight profile	Dependent variable	Factors	F	df (1,2)	p	η_p^2	Obs. power
S&LF	Altitude	Flight type	2.15	1.37	0.151		
		Group	10.14	1.37	0.003	0.21	0.87
		Flight type * group	0.08	1.37	0.779		
	Heading	Flight type	35.79	1.37	0.001	0.49	1
		Group	0.38	1.37	0.542		
		Flight type * group	2.09	1.37	0.157		
C-T-LP	Heading	Flight type	1.65	1.36	0.207		
		Group	0.53	1.36	0.47		
		Flight type * group	7.11	1.36	0.011	0.17	0.74
S-IA							
S&LFALT	Bank angle	Flight type	7.67	1.35	0.01	0.18	0.75
		Group	1.74	1.34	0.196		
		Flight type * group	4.51	1.34	0.049	0.11	0.51
RBT	Altitude	Flight type	9.3	1.31	0.005	0.23	0.84
		Group	0.01	1.31	0.947		
		Flight type * group	1.27	1.31	0.268		

from formulating predictions regarding which flight profiles would make participants most susceptible to SD. In this way, the results for each flight profile were analysed separately. The results are included in Table 3, and each flight profile is discussed in detail.

The analyses of specific flight parameters (the dependent variable in Table 3) have shown that, except for the S&LFART and S-IA profiles, there were significant influences of flight type or group. These significant differences for the others flight profiles are summarised in the following sections.

3.2.1 S&LF profile

The analyses have shown significant differences between the pilots (SD flight: M = 57.30, SD = 64.40; non-SD flight: M = 22.20, SD = 33.54) and non-pilots (SD flight: M = 242.26, SD = 312.75; non-SD flight: M = 190.37, SD = 234.54). In the non-SD flight, pilots showed significantly less deviation from the altitude indicator in comparison with the non-pilots. For the SD flight, both the non-pilots and pilots show more deviation in the heading (M = 1.56, SD = 1.74) compared to the non-SD flight (M = − 0.21, SD = 1.03), so there was an influence of SD cues on heading.

3.2.2 C-T-LP profile

An interaction between flight type (non-SD vs. SD) and group (non-pilots vs. pilots) for the heading was observed. A comparison of simple effects showed significant differences between the pilots (M = 110.37, SD = 109.58) and non-pilots (M = 34.47, SD = 112.60) for the SD flight ($F_{1,26} = 4.43$, $p = 0.042$). Only for non-pilots, a significant difference between the SD flight (M = 34.47, SD = 112.60) and non-SD flight (M = 111.95, SD = 111.79) was observed ($F_{1,26} = 7.81$, $p = 0.008$).

3.2.3 S&LFALT profile

An influence of SD cues (SD flight: M = − 0.11, SD = 0.32; non-SD flight: M = − 0.36, SD = 0.59) on bank angle was observed. We also observed an interaction of group and flight type for the S&LFALT profile on bank angle. Simple effect comparisons showed a difference between the SD flight (M = − 0.11, SD = 0.32) and non-SD flight (M = − 0.53, SD = 0.61) only for non-pilots ($F_{1,34} = 11.96$, $p = 0.001$).

3.2.4 RBT profile

For the RBT profile, participants had significantly greater variance in the altitude indicator in the SD flight (M = 24.3, SD = 44.25) than in the non-SD flight (M = − 7.39, SD = 68.68).

3.3 Oculomotor parameters

The average fixation time varied depending on the participant's group (non-pilots vs. pilots), flight type (non-SD vs. SD), and flight profile (see Table 4).

The pilots had shorter fixation time than non-pilots. The shortest average fixation time was observed in the S&LF and C-T-LP profiles, and the longest times were in the S&LFALT and S&LFART profiles. We also observed an interaction between group and flight profiles. The differences between the pilots and non-pilots were observed for most of the flight profiles (S&LF, S&LFALT, RBT, S&LFART) except from landings manoeuvres (C-T-LP, S-IA; see Fig. 2). For the pilots, we found no significant differences between the flight profiles.

3.4 Gaze distribution over AOIs

The percentage of gaze time at specific AOIs varied depending on the group (non-pilots vs. pilots) and flight type (non-SD vs. SD) for flight profiles. Results are shown in Tables 5 (multivariate) and 6 (univariate).

Table 4 Comparison of mean fixation times between groups, flight type, and flight profiles

Factor	*F*	*df* (1,2)	*p*	η_p^2	Obs. power
Group	9.37	1.37	0.004	0.2	0.85
Flight profiles	10.98	5.37	< 0.001	0.23	1
Flight type	3.22	1.37	0.081		
Flight type * group	1.91	1.37	0.176		
Flight type * flight profiles	2.75	5.37	0.056		
Group * flight profiles	6.32	5.37	< 0.001	0.15	0.97
Flight type * group * flight profiles	3.44	5.37	0.026	0.08	0.71

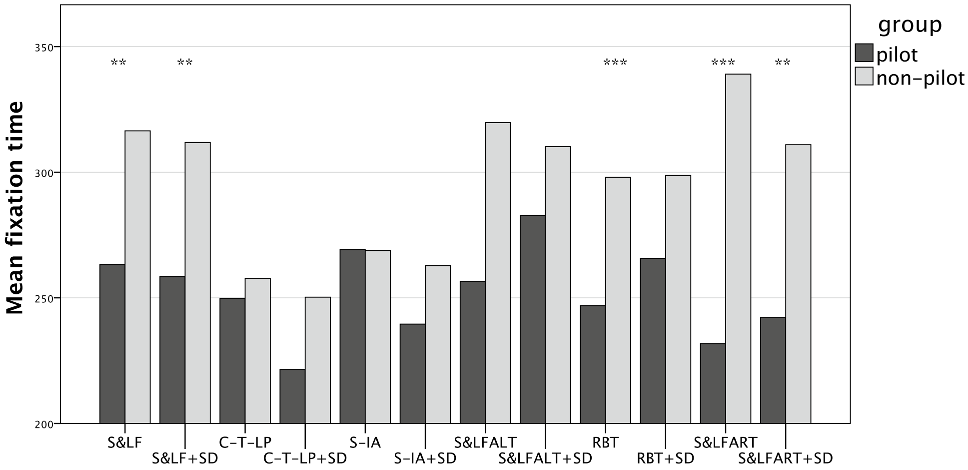


Fig. 2 Mean fixation time (ms) for pilots (dark bars) and non-pilots (bright bars) in each flight profile. Abbreviations on figures denote: + SD – SD flight, $^{**}p < 0.01$, $^{***}p < 0.001$

Table 5 Differences in gaze time at AOI (multivariate) between groups and flight type (non-SD vs. SD) for each flight profile

Flight profile	Factors	*F*	*df* (1,2)	*p*	η_p^2	Obs. power
S&LF	Flight type	2.49	7.32	0.037	0.35	0.79
	Group	2.89	7.32	0.019	0.39	0.86
	Flight type * group	0.84	7.32	0.561		
C-T-LP	Flight type	0.98	7.32	0.463		
	Group	8.18	7.32	< 0.001	0.64	1
	Flight type * group	1.34	7.32	0.263		
S-IA	Flight type	0.92	7.31	0.506		
	Group	3.11	7.31	0.013	0.41	0.88
	Flight type * group	1.18	7.31	0.343		
S&LFALT	Flight type	4.5	7.31	0.001	0.5	0.97
	Group	0.96	7.31	0.478		
	Flight type * group	1.88	7.31	0.108		
RBT	Flight type	3.55	7.31	0.006	0.44	0.93
	Group	0.97	7.31	0.468		
	Flight type * group	0.92	7.31	0.507		

Table 6 Differences in gaze time for relevant AOIs (univariate) between groups and flight type for each flight profile

Flight profile	AOI	Effect (more > less gaze time in AOI)	*F*	*df* (1.2)	*p*	η_p^2	Obs. power
S&LF	ALT	SD < non-SD	6.94	1.38	0.012	0.15	0.73
	ASI	SD < non-SD	5.76	1.38	0.021	0.13	0.65
	ASI	Pilots > non-pilots	12.42	1.38	0.001	0.25	0.93
C-T-LP	ADI	Pilots < non-pilots	24.1	1.38	< 0.001	0.39	1
	ASI	Pilots > non-pilots	21.95	1.38	< 0.001	0.37	0.95
	OTW	Pilots > non-pilots	8.11	1.38	0.007	0.18	0.79
S-IA	ADI	Pilots < non-pilots	14.6	1.37	< 0.001	0.28	0.96
	ASI	Pilots > non-pilots	6.66	1.37	0.014	0.15	0.71
	OTW	Pilots > non-pilots	8.34	1.37	0.006	0.18	0.8
S&LFALT	ALT	SD > non-SD	4.89	1.37	0.033	0.12	0.58
	HI	SD < non-SD	21.89	1.37	< 0.001	0.37	0.99
RBT	ADI	SD > non-SD	16.25	1.37	< 0.001	0.3	0.97
	ALT	SD < non-SD	13.67	1.37	0.001	0.27	0.95
	ASI	SD < non-SD	4.49	1.37	0.041	0.11	0.54

The results included in Tables 5 and 6 are discussed below in detail for each flight profile.

3.4.1 S&LF profile

The percentage of gaze duration at specific AOIs varied depending on the level of expertise (groups) and the occurrence of SD cues (flight type). Pilots gazed at the ASI longer than non-pilots (see Fig. 3; Table 6). During the SD flight involving a false horizon, participants gazed at the ALT and ASI less than in the non-SD flight.

3.4.2 C-T-LP profile

The percentage of gaze duration at specific AOIs varied depending on the level of expertise (groups). Pilots looked more at the OTW and ASI, while non-pilots gazed more at the ADI (see Fig. 4). There was no effect of constant shape illusion on oculomotor behaviour.

3.4.3 S-IA profile

The level of expertise (groups) differentiated the percentage of gaze duration at specific AOIs during the S-IA profile. Similar to the C-T-LP profile, pilots gazed more at the OTW and ASI, while non-pilots gazed more at the ADI (see Fig. 5). There was no effect of constant size illusion on oculomotor behaviour.

3.4.4 S&LFALT profile

The somatogyral illusion caused changes in the distribution of visual attention in the S&LFALT profile. In the SD flight, participants gazed more at the ALT and less at the HI (see Fig. 6). There was no effect of expertise.

3.4.5 RBT profile

Applying the SD cues (Coriolis illusion) resulted in changes of gaze distribution over the AOIs. In the SD

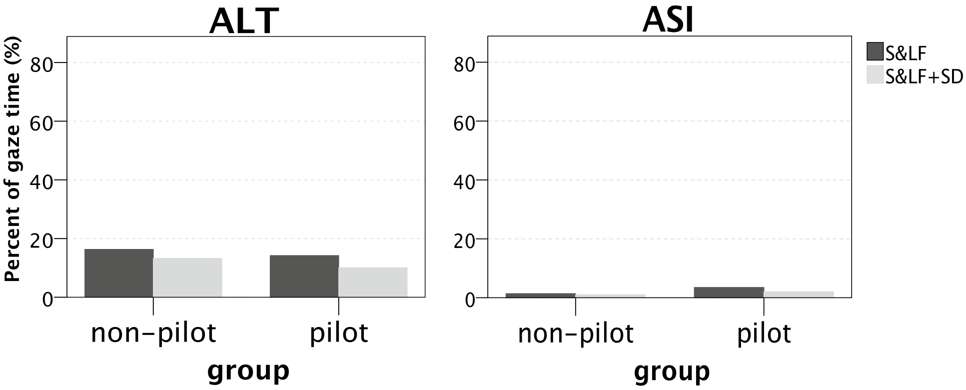


Fig. 3 Mean percentage of gaze time at the ALT and ASI for pilots and non-pilots in the S&LF profile with (bright) and without (dark) SD cues

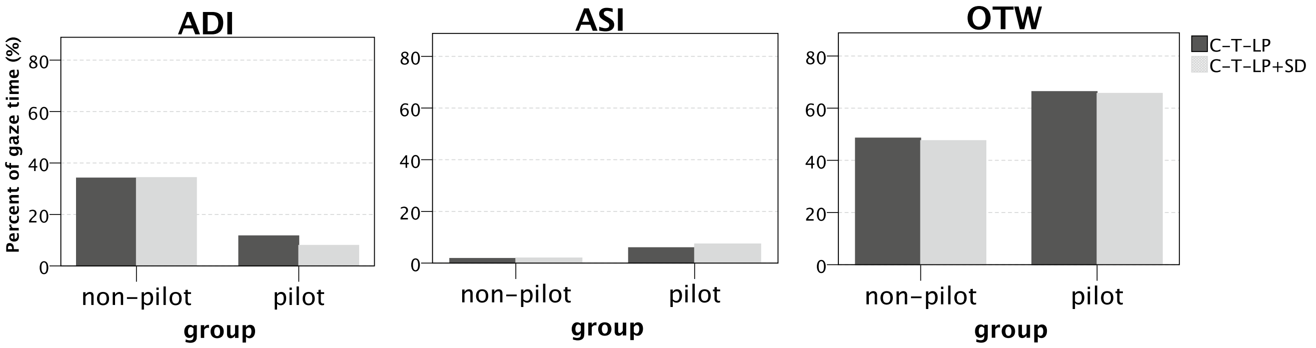


Fig. 4 Mean percentage of gaze time at the ADI, ASI, and OTW for pilots and non-pilots in the C-T-LP profile with (bright) and without (dark) SD cues

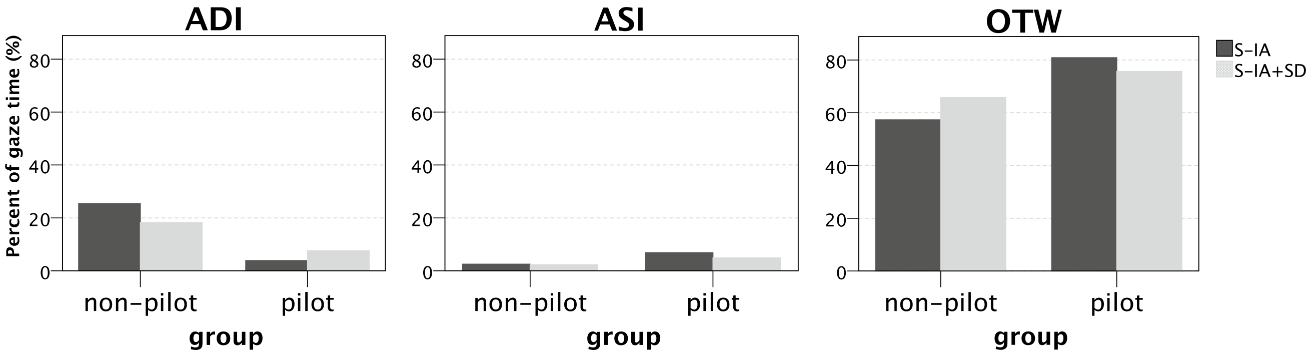
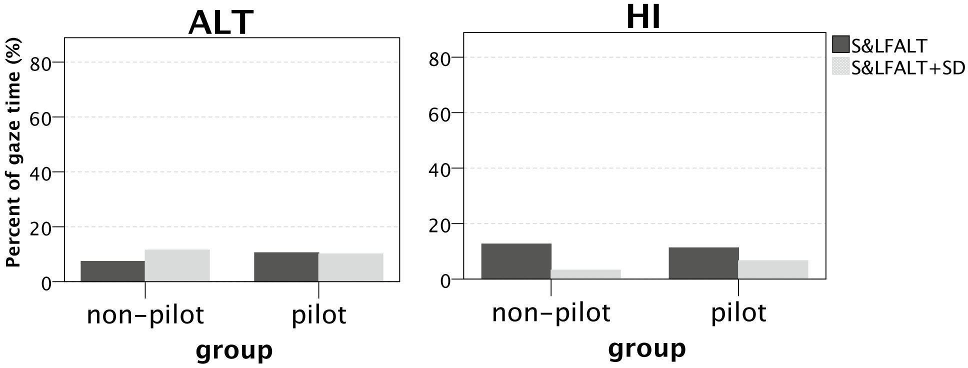


Fig. 5 Mean percentage of gaze time at the ADI, ASI, and OTW for pilots and non-pilots in the S-IA profile with (bright) and without (dark) SD cues

Fig. 6 Mean percentage of gaze time at the ALT and HI for pilots and non-pilots during S&LFALT with (bright) and without (dark) SD cues



flight, participants gazed more at the ADI and less at the ALT and ASI (see Fig. 7). There was no effect of expertise.

3.4.6 S&LFART profile

There were no differences between pilots and non-pilots in gaze distribution in the S&LFART profile. There was no effect of lean illusion on oculomotor behaviour.

4 Discussion

Our study aimed to understand how simulator-induced SD cues affect gaze behaviour in pilots and non-pilots. Comparing the trajectories of eye movements for pilots and non-pilots allowed us to determine their visual scanning strategies, which proved to be effective in flight performance. It is reasonable to assume that frequency of eye

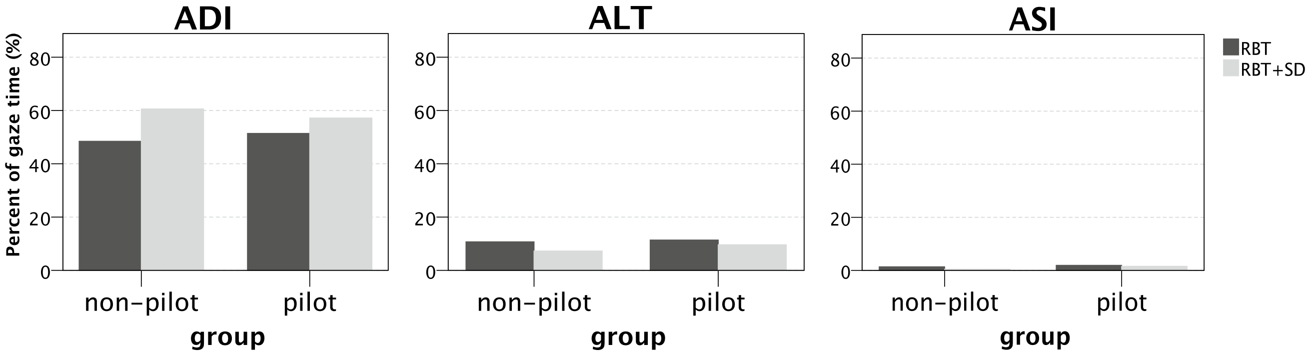


Fig. 7 Mean percentage of gaze time at the ADI, ALT, and ASI for pilots and non-pilots in the RBT profile with (bright) and without (dark) SD cues

fixations on any given flight instrument is an indication of the relative importance of that instrument. The time of fixation, on the contrary, might more appropriately be considered an indication of the relative difficulty of checking and interpreting particular instruments. We expected that the gaze behaviour would be impaired in disoriented flight profiles as compared to non-SD (control) flight profiles and would be less observed in pilots than in non-pilots. We also hypothesised that flight performance would decline in disorientation conditions as compared to control conditions.

The obtained results partially supported our hypotheses. The SD can cause inappropriate control actions (or lack of actions) that can lead to Loss of Control In-flight (LOC-I) or Controlled Flight into Terrain (CFIT), which are two of the most significant contributors to fatal aircraft accidents (Boeing Commercial Airplanes 2017). LOC-I refers to accidents in which the flight crew was unable to maintain control of the aircraft in flight, resulting in an unrecoverable deviation from the intended flight path. CFIT refers to accidents in which an airworthy aircraft, under pilot control, is unintentionally flown into the ground, a mountain, a body of water, or an obstacle. In a typical CFIT scenario, the crew is unaware of the impending disaster until it is too late.

Similar to Cheung and Hofer (2003), we showed that the Coriolis illusion (RBT profile) affects both piloting (change in altitude indicator) and visual scanning (change in gaze distribution) as participants looked less at the ALT and ASI and more at the ADI compared to the RBT profile with non-SD flight. More importantly, we contributed to knowledge about the impact of various SD cues on piloting in different flight profiles. In this way, we showed the impact of SD cues in the S&LF profile with a daytime false horizon illusion (change in heading, for both pilots and non-pilots), the S&LFALT profile with a somatogyral illusion (change in bank angle, only for non-pilots), and the RBT profile with a Coriolis illusion (change in altitude, for both pilots and non-pilots). Kowalczuk (2004) obtained similar results. However, he assessed the severity of SD during flight by a survey assessment of pilots and found that the S&LF, S&LFALT, and RBT profiles were most affected by SD cues. The study was conducted in the Gyro-IPT simulator using the same flight profiles as our study. It is worth noting that in the S&LFART profile (the lean illusion), there was no influence of vestibular stimuli on pilots' flight performance. Although in the Kowalczuk's (2004) study, the lean illusion was evaluated by pilots as high; in our experiment, there was no significant difference compared to the non-SD flight profile. This might be related to manipulation of the ADI display, which was hidden for 13 s (Table 1) in the S&LFART profile for both SD and non-SD flights. The lack of view of this instrument could, therefore, have affected the quality of maintenance of flight parameters.

For SD flight profiles (S&LF, S&LFALT, and RBT) during which we observed deviations in flight parameters, we also found differences in visual attention distribution over AOIs between SD and non-SD flights. These findings could indicate that participants recognised the trajectory path problem and increased flight instrument scanning to regain aircraft orientation. Webb et al. (2010) indicated that recognition of SD increases a pilot's workload during a flight. A high workload task would demand more resources than are available, so flight performance would decline (Hendy et al. 2001). During the S&LF profile with the false horizon illusion, participants gazed less at the ALT and ASI. In the S&LFALT profile with somatogyral illusion, participants gazed more at the ALT and less at the HI indicator. For the RBT profile in the SD flight (Coriolis illusion), we found that participants gazed more at the ADI and less at the ALT and ASI compared to the RBT profile in the non-SD flight. This shows that SD disturbed the usual way of controlling flight parameters, which is demonstrated by the decreased gaze time on task-relevant parameters. This indicates that unexpected changes in climb-out or approach clearance might increase workload and interrupt an efficient instrument crosscheck.

Moreover, for the C-T-LP profile, we discovered an interaction between flight type (non-SD vs. SD) and group (non-pilots vs. pilots) for the heading. These results indicate that there was a specific search strategy in the field of view for non-disoriented pilots in comparison with disoriented pilots. Significant changes in the heading rate for the SD flight were observed only in non-pilots. We did not notice an effect of SD cues or an interaction with oculomotor indicators for the C-T-LP profile, but we found an effect of expertise on gaze distribution over the AOIs, as pilots devoted more time to OTW and ASI indicators, while non-pilots devoted more time to ADI.

During the approach-to-landing manoeuvre, pilots are particularly susceptible to becoming spatially disoriented because of the extra potential for distraction, channelised attention, and task saturation. Frequently looking outside of the aircraft during landing is quite typical for pilots. They need less time to scan flight instruments, but the risk of missing important new information increases, so they focus on OTW. There was no effect of constant shape (C-T-LP) or size illusion (S-IA) on oculomotor behaviour.

Among the visual cues, only the false horizon illusion in the S&LF profile resulted in a change in the distribution of visual attention on the ASI and ADI. In turn, among the vestibular cues, both the somatogyral (S&LFALT) and Coriolis illusions (RBT), but not the lean illusion, caused changes in the gaze distribution among the flight indicators. In addition, we found that pilots in comparison with non-pilots had a shorter average fixation time, which is consistent with the results of Kasarskis et al. (2001) and can be interpreted as lower cognitive effort in gaining and processing visual information. Differences between pilots and non-pilots in average fixation time were seen in most of the flight profiles (S&LF, S&LFALT, RBT, S&LFART) except approach and landing profiles (C-T-LP, S-IA). Rayner (2009) and Wierda et al. (2012) also found that expert pilots needed less effort, as indicated by mean eye fixation time, to perform a flight. However, expertise differentiated gaze distribution over AOIs during piloting tasks that require an approach-to-landing manoeuvre (C-T-LP, S-IA). Pilots devoted different percentages of time to different AOIs than non-pilots. Perhaps, this is related to adaptation to the requirements of the task. The pilots were looking more at OTW during these profiles.

We have demonstrated significant differences between pilots and non-pilots in oculomotor data in many flight situations. During the S&LF, C-T-LP, and S-IA profiles, non-pilots were looking less frequently at the ASI compared to pilots. Pilots compared to non-pilots were looking more at OTW and less at the ADI during landing profiles (C-T-LP, S-IA). However, for flights with vestibular cues, we no longer observed the differences between pilots and non-pilots in gaze distribution over the AOIs, although the differences in average fixation time remained.

Although the main effects of flight type and expertise were observed, there were no interactive effects except in one case. This means that both flight type and expertise affected the participants' flight performance and gaze behaviour, but their impacts were independent. We can see the effect of flight type on both pilots and non-pilots. In other words, being an expert in piloting aircraft does not protect against the influence of SD stimuli that impair their flight performance and gaze behaviour.

Finally, it is worth mentioning that while flight instruments are the sole source of accurate information, pilots can count on becoming disoriented unless they direct their attention to see and correctly interpret the information provided by the instruments. However, in SD conditions, this can be extremely difficult and cognitively demanding on the pilot.

4.1 Study limitations

Finally, some limitations of the present study can be identified. First, although the flight profiles employed in our study included basic flight manoeuvres, we realise that despite being familiar with these before the experiment, participants could have obtained various levels of accuracy of flight performance. This is especially true in the context of the wide variability in the age and flight experience of our pilots, which can be considered the leading cause of individual differences in their vulnerability to SD (Previc et al. 2007). Second, the effects of SD cues on flight performance were somewhat complicated in that older, more experienced pilots were more likely to recognise the SD conflicts. Webb et al. (2010) demonstrated that recognition of SD increases a pilot's workload during flight.

It should be noted that SD does not always increase workload. In an unrecognised SD, such as CFIT, the pilot is oblivious to the disorientation. Some aviation-based studies have demonstrated that cognitive processing is negatively affected during SD (Sen et al. 2002; Gresty et al. 2003, 2008). Third, the study did not include fatigue associated with the performance of flight manoeuvres. Moreover, it is not clear whether similar variations in gaze behaviour would occur if different illusions were used. Therefore, future studies are needed to confirm and presumably extend the observed effects to other flight scenarios while better controlling for confounding variables. It must not be forgotten that the pilot and the aircraft are a system that interacts with each other and as such should be examined (Carsten and Vanderhaegen 2015).

5 Conclusion

To summarise our research, despite the limitations mentioned above, this study contributes to our understanding of how simulator-induced SD cues affect pilots' and non-pilots' gaze behaviour and flight performance. This was achieved by examining gaze behaviour under SD conditions induced by a wide range of visual and vestibular illusions, while piloting a specially designed flight simulator.

The results showed that the SD cues employed in this study influenced participants' visual attention distribution over AOIs between SD and non-SD flights in the S&LF, S&LFALT, and RBT profiles. However, there was no interaction of expertise and flight type (non-SD vs. SD), which is consistent with our hypothesis that SD cues affect the pilots' and non-pilots' gaze behaviour in the same way. In these profiles, SD cues also adversely affected flight performance. These findings not only demonstrate that the simulator can induce SD events for these profiles, but they also indicate that applied SD cues can increase participants' cognitive workload. Recognition of SD increases a pilot's workload (Webb et al. 2010) and can demand more resources than are available, and thus flight performance can decline. These partially support our hypothesis that SD would impair the participants' gaze behaviour and have negative effects on their flight performance.

We also found significant differences between pilots and non-pilots in their oculomotor activity (average fixation time over selected AOIs) in the profiles associated only with visual illusions (S&LF, C-T-LP, and S-IA). This is partially consistent with our hypothesis that gaze behaviour was less impaired in pilots than in non-pilots. It is noteworthy that changes in flight performance were also found for these profiles. This finding suggests that the participants' attention was directed outside of the cockpit, where the potential for distraction is great and visual illusions are provoked. Without scanning important flight parameters, this can lead to SD.

Based on the above-mentioned conclusions, the following points briefly summarise the findings reported in the present paper:

- There are specific changes in visual attention distribution for specific illusions (visual and vestibular). To determine the model of effective strategies for scanning the field of view during the particular illusion, more tests are needed. Future studies could presumably extend these effects to other flight scenarios while better controlling for confounding variables.
- Flight illusions (induced by visual or vestibular cues) may precipitate SD by keeping the pilot from maintaining an effective instrument crosscheck.
- There are no data indicating that natural gaze behaviour, not trained in effective scanning of the visual field, cause the non-pilots to cope better with SD than pilots.
- Aside from standard instrument scanning techniques (crosscheck), there are no gaze indicators showing how to cope with SD.
- Being an expert in piloting aircraft does not reduce the susceptibility of pilots to loss of their spatial orientation.
- Eye-movement recording offers an effective method of evaluating a pilot's attention and a better understanding of their activity and flight performance.

To enhance flight safety and to assist pilots who face a higher risk of disorientation, we also present the following recommendations:

- Pilots should be aware that what is seen outside of the aircraft might be confusing and could lead to visual illusions and sensory conflicts. For this reason, despite existing visual cues outside of the cabin, it is recommended to frequently read the flight instruments.
- When problems with maintaining proper flight performance arise, pilots must maintain spatial orientation and a state of visual dominance solely by reference to aircraft instruments, especially the attitude display.
- Through appropriate training of visual scanning strategies, pilots should learn to recognise environmental cues and risk-assess situations in which SD is more likely to occur.

Although military aviation pilots participated in our study, the conclusions mentioned above can also be applied to civil aviation pilots, especially to improve their training.

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References

Bałaj B, Francuz P, Sternal M, Matulewski J (2016) Compensation of head movements in the data registered with a headset eye tracker using the EVM* software package. Pol J Aviat Med Bioeng Psychol 22:21–29. https://doi.org/10.13174/pjambp.30.12.2016.02

Bellenkes AH, Wickens CD, Kramer AF (1997) Visual scanning and pilot expertise: the role of attentional flexibility and mental model development. Aviat Space Environ Med 68:569–579

Boeing Commercial Airplanes (2017) Statistical summary of commercial jet airplane accidents worldwide operations. Boeing, Seattle

Carsten O, Vanderhaegen F (2015) Situation awareness: valid or fallacious? Cogn Technol Work 17:157–158. https://doi.org/10.1007/s10111-015-0319-1

Cheung B, Hofer K (2003) Eye tracking, point of gaze, and performance degradation during disorientation. Aviat Space Environ Med 74:11–20

Colvin K, Dodhia R, Dismukes RK (2005) Is pilots' visual scanning adequate to avoid mid-air collisions. In: Proceedings of the 13th International symposium on aviation psychology, pp 104–109

Dahlstrom N, Nahlinder S (2009) Mental workload in aircraft and simulator during basic civil aviation training. Int J Aviat Psychol 19:309–325. https://doi.org/10.1080/10508410903187547

Dehais F, Behrend J, Peysakhovich V et al (2017) Pilot flying and pilot monitoring's aircraft state awareness during go-around execution in aviation: a behavioral and eye tracking study. Int J Aerosp Psychol 27:15–28. https://doi.org/10.1080/10508414.2017.1366269

Erp JBF van (2007) Tactile displays for navigation and orientation: perception and behaviour. Dissertation

Fitts PM, Jones RE, Milton JL (1949) Eye fixations of aircraft pilots. III. Frequency, duration, and sequence fixations when flying air force ground-controlled approach system. Report no AF TR 5967

Gibb RW (2010) Historical assessment of visual spatial disorientation. Aviat Space Environ Med 81:318

Gibb R, Ercoline B, Scharff L (2011) Spatial disorientation: decades of pilot fatalities. Aviat Space Environ Med 82:717–724. https://doi.org/10.3357/ASEM.3048.2011

Gresty MA, Waters S, Bray A et al (2003) Impairment of spatial cognitive function with preservation of verbal performance during spatial disorientation. Curr Biol 13:829–830. https://doi.org/10.1016/j.cub.2003.10.013

Gresty MA, Golding JF, Le H, Nightingale K (2008) Cognitive impairment by spatial disorientation. Aviat Space Environ Med 79:105–111. https://doi.org/10.3357/ASEM.2143.2008

Hendy KC, Farrell PSE, East KP (2001) An information-processing model of operator stress and performance. In: Hancock PA, Desmond PA (eds) Stress, workload, and fatigue. Lawrence Erlbaum Associate, Mahwah, pp 34–80

Huemer VMS, Hayashi M, Renema F, Elkins S, McCandless JW, McCann RS (2005) Characterizing scan patterns in a spacecraft cockpit simulator: expert vs. novice performance. Proc Human Factors Ergonomics Soc Annu Meet 49:83–87. https://doi.org/10.1177/154193120504900119

Kasarskis P, Stehwien J, Hickox J et al (2001) Comparison of expert and novice scan behaviors during VFR flight. In: Proceedings of the 11th international symposium on aviation psychology

Kluch W (2003) Badania fizjologiczne przebiegu restytucji narządu przedsionkowego u osób poddawanych przyspieszeniom w symulatorze GYRO IPT. Polski Przegląd Medycyny Lotniczej (in Polish) 4:399–415

Knapp CJ, Johnson R (1996) F-16 class A mishaps in the U.S. air force, 1975-93. Aviat Space Environ Med 67:777–783

Kowalczuk K (2004) Wartość diagnostyczna parametrów fizjologicznych podczas wywoływanej dezorientacji przestrzennej. Polski Przegląd Medycyny Lotniczej (in Polish) 10:7–22

Kowalczuk K, Gazdzinski SP, Janewicz M et al (2016) Hypoxia and coriolis illusion in pilots during simulated flight. Aerosp Med Hum Perform 87:108–113. https://doi.org/10.3357/AMHP.4412.2016

Lewkowicz R, Francuz P, Bałaj B, Augustynowicz P (2015) Flights with the risk of spatial disorientation in the measurements of oculomotor activity of pilots. Pol J Aviat Med Psychol 21:22–28. https://doi.org/10.13174/pjamp.21.03.2015.03

Ottati WL, Hickox JC, Richter J (1999) Eye scan patterns of experienced and novice pilots during visual flight rules (VFR) navigation. In: Proceedings of the human factors and ergonomics society annual meeting, vol 43, pp 66–70. https://doi.org/10.1177/154193129904300114

Previc F, Ercoline W (2004) Spatial disorientation in aviation, 1st edn. AIAA, Reston, Va

Previc FH, Ercoline WR, Evans RH et al (2007) Simulator-induced spatial disorientation: effects of age, sleep deprivation, and type of conflict. Aviat Space Environ Med 78:470–477

Rayner K (2009) Eye movements and attention in reading, scene perception, and visual search. Q J Exp Psychol 62:1457–1506

Schuhfried G (2013) Vienna test system: psychological assessment. Schuhfried, Mödling, Austria

Sen A, Yilmaz K, Tore HF (2002) Effects of spatial disorientation on cognitive functions. In: RTO HFM symposium on spatial disorientation in military vehicles: causes, consequences, and cures. La Corufia, Spain, 15–17 April, pp 1–3

Soo K, Mavin TJ, Roth W-M (2016) Mixed-fleet flying in commercial aviation: a joint cognitive systems perspective. Cogn Technol Work 18:449–463. https://doi.org/10.1007/s10111-016-0381-3

Stott JRR, Benson AJ (2016) Spatial orientation and disorientation in flight in Ernsting's aviation and space medicine, pp 281–319

Van de Merwe K, van Dijk H, Zon R (2012) Eye movements as an indicator of situation awareness in a flight simulator experiment. Int J Aviat Psychol 22:78–95

Webb CM, Estrada A, Kelley AM et al (2010) The effect of spatial disorientation on working memory and mathematical processing. USAARL report no. 2011-08. Fort Rucker (AL)

Wierda SM, Rijn H van, Taatgen NA, Martens S (2012) Pupil dilation deconvolution reveals the dynamics of attention at high temporal resolution. PNAS 109:8456–8460. https://doi.org/10.1073/pnas.1201858109