Spatial Disorientation Influences on Pilots' Visual Scanning and Flight Performance

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BACKGROUND: Adequate instrument scanning is considered an important countermeasure against spatial disorientation (SD). Remarkably, literature on the relation between SD and pilots' visual scanning is scarce. The objective of this simulator study was to investigate the influence of SD on pilots' visual scanning and flight performance.

METHODS: In a ground-based SD simulator, 10 novice military pilots were asked to manually fly 3 circuits. Unknowingly to the pilots, the final circuit contained one visual and four vestibular SD events. Simulator motion, flight performance, pilots' gaze direction, and control inputs were recorded and analyzed. Afterwards the pilots filled in a questionnaire about their recognition of events.

RESULTS: Three of the five SD events significantly affected pilots' flight performance and gaze behavior. First, the false horizon during the cloud leans induced an unintended roll rate, $0.41 \pm 0.36^\circ \cdot \mathrm{s}^{-1}$, when the pilots were looking out the window. Second, the Coriolis illusion caused a 0.44 ± 0.18 s delay in the first glance to the attitude indicator and triggered an unintended roll rate, $1.25 \pm 1.33^\circ \cdot \mathrm{s}^{-1}$, and bank angle deviation of $3.4 \pm 3.7^\circ$ during the coordinated turn. Third, the somatogravic illusion affected pilots' pitch inputs on the stick, but this seems to be confounded by inaccurate simulation of the illusion.

DISCUSSION: This study provides direct experimental evidence that SD can evoke inappropriate control inputs and can influence the pilots' scanning behavior, even when SD is not recognized. We conclude that gaze tracking provides useful feedback on the pilot's instrument scan during SD simulator training when using appropriate scenarios and simulator motion.

KEYWORDS: eye movements, flight simulation, false horizon, leans, Coriolis, somatogravic illusion.

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Spatial disorientation (SD) occurs when a pilot has a false perception of the motion or orientation of the aircraft with respect to the Earth.[4,7] The root cause of SD is inadequate (e.g., unnoticed or ambiguous) feedback from the human sensory systems involved in spatial orientation, primarily the vestibular and visual system. A variety of SD phenomena are described in the literature (e.g., Gillingham and Previc[14] or Previc and Ercoline[34]), illustrating that SD may present itself in different ways to the pilot. According to a survey among military aircrew, the sensory illusions most frequently reported in flight depend on environmental conditions, type of aircraft, and the type of operation.[21] Yet an illusory sensation alone may not convey a safety risk as long as the pilot is aware of the sensation being false.[39] In this respect it is useful to distinguish between unrecognized (Type I), recognized (Type II), and incapacitating SD (Type III).[4,34]

The incidence of mishaps linked to SD in military aviation has been relatively constant throughout the years, accounting for about 30% of all fatal accidents.[13] Furthermore, SD has been identified as a contributing factor to a number of loss-of-control accidents in commercial aviation.[31] These statistics show the importance of addressing the risks of SD in pilot training. Apart from academic instructions, training programs include demonstrations in special ground-based devices and sometimes in flight.[7] In these training programs, pilots are told to rely on their visual scan of the cockpit instruments, so-called crosschecking,[11,19] as a countermeasure against SD.[2,34] Remarkably, scientific studies on the relation between SD and the

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crosscheck seem scarce. Most literature on pilot viewing behavior is related to topics such as display design,[5] situational awareness,[40,41,43] automation monitoring,[6,32,38] workload,[10,25] flight performance,[1,18] and pilot expertise[3,19,20] (see Ziv[44] for a review).

We found one study which specifically addressed the relation between SD and the instrument crosscheck.[9] In a special SD simulator, 10 nonpilot subjects experienced a disorienting Coriolis effect while performing a change in altitude and heading. The results showed that the SD event delayed the gaze shift toward the correct instrument. As the Coriolis effect is known to elicit an involuntary vestibulo-ocular reflex,[37] it is likely that this nystagmus interfered with the voluntary gaze shift toward the instruments.[12] Therefore, it would be interesting to investigate if other SD events with less physiological impact also affect the instrument crosscheck. In this respect, another study seems interesting which exposed pilots in a ground-based SD device to various SD events, including both vestibular and visual illusions.[35,36] However, the focus of that study was on the effects of sleep deprivation, without a direct relation between SD and the pilot's viewing behavior. The objective of the current study was to investigate the relationship between different unanticipated vestibular and visual SD events, varying in impact, on pilots' flight performance and instrument crosscheck.

METHODS

Subjects

Participating in this study were 10 Royal Netherlands Air Force (RNLAF) pilots who just finished elementary and advanced training for fixed wing aircraft on a Pilatus PC-7. As this group did not include female pilots, all participating pilots were men, with an age of 24.8 ± 2.2 yr (mean ± SD), having 135 ± 75 flight hours on powered aircraft, and 27 ± 22 h in a simulator. All pilots were proficient with instrument meteorological conditions (IMC) and instrument landing system (ILS) approach. The pilots were invited to participate in a gaze tracking study, but they were not informed about the SD aspects. Before the experiment, all pilots signed an informed consent stating that the details of the experiment had been sufficiently explained and that they participated voluntarily. The experiment was conducted with approval of the institutional ethics committee and was in accordance with the (revised) Helsinki Declaration.

Equipment

The experiment was performed in the AMST Airfox Advanced Spatial Disorientation (ASD) simulator which is used by the RNLAF for SD demonstrations. The simulator features a hexapod motion platform with an additional turn table for sustained yaw motion. Out-the-window visuals are projected on a double-curved screen, at about 1.5 m from the eye-reference point, with a 2048 × 1536 pixels projector at 60 Hz and a contrast ratio of 500,000:1, creating a field of view of 120° horizontally and 90° vertically (60° upwards and 30° downwards). The generic cockpit is equipped with three flat monitors to present the instruments, a central stick with force feedback, pedals, throttles, flaps, and gear levers. Control inputs, flight parameters, and simulator motion are logged at 200 Hz. The simulation of the Pilatus PC-7 aircraft has some fidelity differences with the real aircraft, such as a larger cockpit and shift of instruments, lack of stand-by instruments, torque indication in percent rather than psi, localizer and glideslope indications on the Horizontal Situation Indicator (HSI) rather than the Attitude Director Indicator (ADI), larger pitch attitudes, and a lack of force feedback on the pedals. In consultation with PC-7 instructor pilots, these aspects were considered acceptable.

Procedure

The pilots were requested to fly a common manual circuit three times, each lasting about 15 min. The first circuit (takeoff to first final approach) served to familiarize the pilots with the aircraft model, simulator environment, and circuit. This "Familiarization circuit" was excluded from the data analysis. During the second "Normal circuit," starting at the first go-around until the second final approach, pilots flew the circuit without any disturbances. During the third and final "SD circuit," starting at the second go-around until the final approach, five preprogrammed SD events were inserted, which were unexpected by the pilots.

All flight phases were flown in IMC conditions except for the crosswind leg, which was flown above the clouds. Radio settings for an ILS approach were set to show localizer and glide slope indications on the HSI. The simulated aircraft was positioned on the runway and ready for takeoff, followed by a climb to 3000 ft (914.4 m). At 2 nmi pilots were instructed to turn right toward the crosswind leg, flying straight and level at 500 ft (152.4 m) above the clouds at 180 KIAS, at which time they were instructed to look outside and check for traffic at 12 o'clock on the same level. At 7 nmi the instruction was to turn right toward downwind. After 1 nmi, one orbit to the left was made with a rate-one-turn, requiring a 28° angle of bank. Halfway through the orbit, the pilots were asked to look at the overhead magnetic compass, which required a pitching-up head movement. At 11 nmi the pilots were requested to perform a descending turn to 1500 ft (457.2 m), base leg, and subsequently to slow down to 110 KIAS, set flaps, and lower the gear. At the dogleg they were requested to change heading 45° and to intercept the ILS localizer and glideslope ("dogleg to final"). At 300 ft (91.4 m) a go-around was requested, requiring a pitch attitude of about 20° nose-up to climb at 110 KIAS.

The SD circuit included the following five SD events:

1) Somatogravic illusion—During the go-around the simulator instructor initiated a profile causing the simulator platform to tilt backward at a fixed preprogrammed pitch rate of $4° \cdot s^{-1}$ to a maximum pitch angle of 20° nose up. This profile is supposed to induce a sensation of excessive pitch, similar to what is known as the somatogravic illusion. The profile was triggered when the vertical velocity changed from descending into climbing. In the Normal circuit the maximum simulator pitch-up attitude amounted to about 6° during the go-around.

2) Cloud leans—while in the Normal circuit the crosswind leg was flown above a horizontal cloud deck; in the SD circuit this cloud deck was tilted 6° perpendicular to the flight direction. The sloping cloud deck was supposed to induce a cloud leans. To ensure that the pilots were not continuously looking at their instruments during the crosswind leg, in both circuits they were instructed to look out the window to visually search for traffic at 12 o'clock on the same level.
3) Coriolis illusion—In the orbit phase of the SD circuit, the yaw drive of the simulator's motion platform was accelerated with $1.0° \cdot s^{-2}$ up to a constant angular velocity of $60° \cdot s^{-1}$. Halfway through the orbit the pilots were instructed to briefly look at a magnetic compass placed on the overhead panel. This vertical head movement induced a Coriolis illusion in the pilot's roll direction due to the cross-coupling between the simulator yaw motion and the out-of-plane head pitch. In the Normal circuit the orbit was flown without this yaw stimulus, so that the same head movement did not induce a Coriolis illusion.
4) Postrotatory illusion—At the end of the orbit in the SD circuit, the sustained simulator yaw of $60° \cdot s^{-1}$ was stopped with a deceleration of $10° \cdot s^{-2}$ while the aircraft was leveled off at the instructed heading. This deceleration was supposed to induce a postrotatory illusion of yaw motion in the opposite direction.
5) Vestibular leans—In flight, the vestibular leans may arise after a subthreshold roll followed by a supra-threshold correction to straight and level, causing the illusion of leaning in the opposite direction as the preceding turn.[8,14] In the SD circuit this illusion was reproduced by asymmetric roll cueing, which means that the motion platform is not tilting during a turn, but it tilts to a sustained angle for about 15 s in the opposite direction when the aircraft is leveled off after the turn. This is supposed to induce a sensation of leaning to one side, possibly leading to a compensatory control input. In the Normal circuit the simulator applied conventional motion cueing, which means that it generated symmetric and short-lived motion cues both during the entry and the exit of the turn.

Measurements

The following simulator data were logged for off-line analysis: control inputs (e.g., pitch and roll inputs), flight performance (e.g., bank angle, heading, altitude, pitch rate) and simulator motion (e.g., simulator bank angle, pitch angle, yaw rate). The pilots' visual behavior was measured using an Ergoneers Dikablis Professional head-mounted binocular eye-tracking system featuring a 30-Hz wide angle scene camera (1920 × 1080 pixels, full HD) and two 60-Hz infrared eye-cameras (384 × 288 pixels). The supplied software allowed calibration of the gaze direction to world-fixed marker coordinates and relating the viewing behavior to so-called areas-of-interest (AOIs) within the visual scene. The following AOIs were defined: ADI, air speed indicator (Speed), altimeter (Alt), HSI, vertical velocity indicator (VVI), engine torque indicator (Torque), DME distance information (DMEdist), rate-one-turn coordinator (ROTcoord), and out-the-window (OTW).

Before the experiment and after each orbit flight phase, pilots were requested to systematically focus on the center of the different AOIs to verify the gaze tracking calibration and allowing post hoc recalibration when needed. The recordings from these calibration cycles showed a spatial accuracy within one visual degree, as the fixation marker stayed within 1.2 cm around the designated fixation points at a viewing distance of 69 cm.

After removal of blinks (artifactual glance split due to a closed eyelid) and fly throughs (artifactual fixation which is part of a saccade when the eye is moving between AOIs) to conform to ISO standards,[23,24] the following standard measures were derived from the data:

1) Percent time on AOI, which represents the AOI visual demand in terms of percent of time glances are within an AOI;
2) Mean glance duration is a measure for expressing the time it takes to perceive information from an AOI, which is defined by the mean duration of all glances to an AOI, whereas a glance is defined as maintaining visual gaze within an AOI which may be comprised of more than one fixation and saccades;
3) Link-value-probability represents the need for sharing attention between AOIs, expressed as the probability of a glance transition between two different AOIs.

In addition, the following gaze metrics were analyzed for specific time segments, depending on the type of SD event:

4) Number of saccades, i.e., the number of brief, fast movements of the eyes that change the point of fixation;
5) Time delay, defined as the time between an event and the gaze toward a certain AOI;
6) Maximum glance duration, representing the longest glance duration to an AOI;
7) Number of glances to an AOI; and
8) AOI time segments, from the glance time histories we determined the time segments when a pilot was looking at a certain AOI, which allowed for direct correlation between gaze direction and flight performance.

Immediately after completing the flight, pilots were asked to fill out a questionnaire consisting of two parts. The first part contained the following questions to check if the simulator environment and workload were perceived as representative:

1) Familiarity with the simulator environment on a rating scale from 0 (not) to 10 (very familiarized);
2) Proficiency to perform the requested flight tasks on a rating scale from 0 (not) to 10 (very proficient); and
3) Mental workload of the different flight phases, on a rating scale from 0 (no) to 10 (extreme workload).

The second part contained rating scales addressing the type of any noticed unexpected event and its location in the circuit. On a scale from 0 (no effect) to 10 (large effect), for each of the noticed events, the pilots were asked to rate the perceived impact on: level of surprise (i.e., emotional and cognitive response to unexpected events[28]), startle (i.e., a highly physiological reaction to a sudden stimulus[28]), mental workload, instrument scanning, and flight performance.

During the experiment pilots were asked to rate their motion sickness symptoms regularly according to the TNO misery scale, MISC.[16,30,42] The stop criterion for the instructor was a MISC of 7 (medium nausea), while the subject could stop at any time. The pilots were continuously monitored via video and two-way voice communication.

The entire study was completed in 4 work days, distributed over 2 mo. Most pilots were invited in pairs. For each pilot, the experiment lasted approximately 1.5 h, including an introduction, signing the informed consent, filling out questionnaires, calibration of measurement equipment, and flight time.

Statistical Analysis

For every dependent variable, differences between the Normal and SD circuit were analyzed by means of a paired nondirectional *t*-test. In the results, the mean and standard deviation of variables will be reported. Effects were considered statistically significant with $P < 0.05$. Effect sizes of Cohen's $d = 0.2$, 0.5, or 0.8 were considered small, medium, and large, respectively.

RESULTS

All pilots completed all conditions without significant motion sickness effects ($\text{MISC}_{\text{max}} \leq 2$). One pilot did not fill out the complete postexperiment questionnaire, so the subjective results are based on nine pilots. Furthermore, because of recording issues, two gaze tracking data sets were incomplete, so the analysis of gaze tracking measures is based on eight pilots. For these pilots, average AOI coverage in each flight phase was higher than 75%, which is considered adequate to good quality.[29]

The postexperiment questionnaire confirmed that the pilots ($N = 9$) were familiar with the PC-7 simulator environment after flying the first circuit (rating of 7.0 ± 1.0). They judged the simulator good enough to perform the requested flight tasks (8.3 ± 0.7).

Considering the workload, the pilots rated the Level turn (2.7 ± 1.0), Orbit (2.9 ± 0.8), and Straight-and-Level flight (1.8 ± 1.0) as low workload; the Climb (4.2 ± 1.2) and Climbing turn (4.7 ± 1.6) as medium workload; and the Go-Around (6.0 ± 1.2), Descending turn (6.1 ± 1.2), ILS capture (5.6 ± 1.6), and ILS approach (6.8 ± 1.1) were rated as high workload flight phases. Subject matter experts confirmed that these workload levels were representative for a normal circuit.

Table I shows the SD events reported after the experiment, as well as the perceived impact in terms of surprise, startle, mental workload, instrument scan, and flight performance. The only intentionally inserted SD event reported by all pilots was the Coriolis illusion, which received moderate to high ratings on all effects. One pilot noticed the simulator yaw rotation just before he was requested to check the overhead magnetic compass. As a result, he expected a Coriolis sensation, which was reflected in low ratings on surprise (rating of 1) and startle (rating of 3). The cloud leans and somatogravic illusion were reported by five, respectively four pilots, with moderate impact. The postrotatory illusion and vestibular leans were reported by only one individual pilot each, where vestibular leans was rated particularly surprising (rating of 8).

Besides the SD events, some unplanned events were reported, such as 'unexpected vertical speed,' 'magnetic compass turns,' and 'flying too low.' These events sometimes induced relatively high ratings on surprise and startle (see Table I).

In the following sections the results of the SD events will be presented with respect to the effect on flight performance, gaze behavior, and recognition. An overview of all measured variables for each SD event and the observed significant effects is presented in **Table II**.

Regarding the somatogravic illusion, **Fig. 1** shows time histories of the aircraft and simulator motion, control inputs, and visual behavior of one pilot during the go-around in the Normal and SD circuit. In both circuits, the go-around was initiated by pulling aft on the stick. On average, maximum stick deflection amounted to 35.1 ± 4.9% in the Normal circuit, compared to 40.5 ± 5.5% in the SD circuit, which was statistically significant [$t(9) = -3.331$, $P = 0.009$, $d = 1.04$]. After 6.0 ± 2.0 s, on average, the pilots slightly released the aft pull on the stick for climbing with constant speed. The amount of stick release was computed as the difference in pitch control input (maximum minus minimum value) during the first phase of the go-around climb, starting at the onset of the somatogravic illusion in the SD circuit, which was 3.0 s after the go-around start. The results show that the release of the aft pull was larger in the SD circuit compared to the Normal circuit [31.7 ± 6.2% compared to 25.7 ± 9.4%, respectively, $t(9) = -2.958$, $P = 0.016$, $d = 0.75$]. Irrespective of the larger initial aft pull and larger release of the stick in the SD circuit, the average stick deflection did not differ between both circuits. This may explain why the aircraft's maximum pitch rate did not significantly differ between the circuits. Nevertheless, maximum aircraft pitch was lower in the SD circuit (21.3 ± 0.7°) than the Normal circuit [22.1 ± 0.6°, $t(9) = 2.509$, $P = 0.033$, $d = 1.14$].

Closer inspection of the simulator motion in the two upper plots of Fig. 1 shows that in the SD circuit the preprogrammed simulator pitch only started 3 s after the initiation of the go-around. The simulator pitch increased at about $4° \cdot s^{-1}$ to a maximum angle of 20° nose-up. In contrast, in the Normal circuit the simulator pitch motion immediately started at the initiation of the go-around, reaching a maximum of 6° nose-up. The initial lack of motion and subsequent open-loop motion feedback during the go-around in the SD circuit may have affected flight performance and gaze behavior.

The general gaze behavior metrics during the go-around showed that the pilots' visual attention primarily focused on the ADI (52.6%), HSI (13.7%), Speed (12.1%), and to a lesser extent on the Alt (8.6%). This is also reflected by relatively high link-value-probabilities between ADI and Speed (32.3%), ADI and HSI (21.7%), and between ADI and Alt (20.2%), as shown in

Table I. Postexperiment Reporting of Intentionally Inserted SD Events and Other Unplanned Events, Accompanied with Subjective Ratings on the Effects.

			HOW DID THE EVENT AFFECT YOU: 0 (NO EFFECT) TO 10 (LARGE EFFECT); $N = 9$				
CIRCUIT: NORMAL/SD	**UNEXPECTED EVENTS**	**REPORT EVENT $N = 10$**	**SURPRISE**	**STARTLE**	**MENTAL WORKLOAD**	**INSTRUMENT SCAN**	**FLIGHT PERFORMANCE**
Intentionally inserted events							
SD	Somatogravic illusion	4/10	5.5 ± 3.1	3.8 ± 2.2	4.3 ± 1.7	4.0 ± 2.4	3.3 ± 2.2
SD	Cloud leans	5/10	4.8 ± 2.9	2.2 ± 1.6	2.8 ± 0.5	2.8 ± 1.0	1.8 ± 1.0
SD	Coriolis	10/10	7.0 ± 2.6	5.5 ± 2.6	5.3 ± 2.4	5.7 ± 2.2	5.2 ± 2.1
SD	Postrotatory effects	1/10	5	4	3	3	0
SD	Vestibular leans	1/10	8	4	4	3	2
Unplanned events							
N	Feeling of crosswind	1/10	5	2	2	2	2
N	Seat-of-the-pants	1/10	1.5	1	1	1	1
N	Unexp. vertical speed	1/10	7	6	6	6	5
N & SD	Deviate from localizer	2/10	6.0 ± 0	3.0 ± 0	3.0 ± 0	1.5 ± 2.1	3.0 ± 0
N	Incorrect power	1/10	5	3	6	3	6
SD	Magn. compass turns	1/10	9	8	3	0	1
SD	Turning too fast	1/10	3	3	3	4	2
N	Flying too low	1/10	7	9	−/−	−/−	−/−

Fig. 2. These values did not significantly differ between the Normal and SD circuit.

The additional gaze behavior metrics were analyzed for the first 5 s of the go-around. This analysis showed significant differences between the Normal and SD circuits for maximum glance duration on the ADI as well as the airspeed indicator. Maximum glance duration on the ADI was longer in the SD circuit (1.89 ± 0.96 s) than in the Normal circuit (1.23 ± 0.65 s) [$t(7) = -2.416$, $P = 0.046$, $d = 0.81$]. Conversely, maximum glance duration on the airspeed indicator was shorter in the SD circuit (0.35 ± 0.08 s) than in the Normal circuit (0.58 ± 0.28 s) [$t(7) = 2.402$, $P = 0.047$, $d = 1.13$]. It thus seems that, due to the simulator overpitch, pilots looked longer at the ADI at the cost of looking at air speed.

To illustrate the effect of the cloud leans, **Fig. 3** shows the time histories of aircraft bank angle and viewing behavior during the visual search phase in both the Normal circuit and the SD circuit. In the first 30 s of the SD circuit, the aircraft bank angle increased almost every time when the pilot was looking at the OTW (indicated by light gray vertical bands), followed by a correction of this unintended roll back to wings-level, when he looked at the ADI again (indicated by dark gray bands). In the figure, this behavior is most apparent between 24 to 27 s. Remarkably, after about 30 s this pilot seemed to permanently shift his attention to the cockpit instruments, disregarding the OTW visuals for the remainder of this flight phase.

Analysis of the time histories of all pilots during the entire visual search phase did not show statistical differences in flight performance between the SD and Normal circuit. However, restricting the analysis to the segments where the pilots were looking at the OTW showed a significant roll rate ($0.41 \pm 0.36° \cdot s^{-1}$) in the direction of the slope of the cloud deck in the SD

Table II. Overview of the Measured Variables for Each SD Event and the Significant Effects.

SD EVENT & VARIABLE	NORMAL CIRCUIT	SD CIRCUIT	t	P	COHEN'S d
Somatogravic					
Max stick deflection	35.1 ± 4.9%	40.5 ± 5.5%	$t(9) = -3.331$	$P = 0.009$	1.04
Stick release	25.7 ± 9.4%	31.7 ± 6.2%	$t(9) = -2.958$	$P = 0.016$	0.75
Max pitch angle	22.1 ± 0.6°	21.3 ± 0.7°	$t(9) = 2.509$	$P = 0.033$	1.14
Max glance ADI	1.23 ± 0.65s	1.89 ± 0.96s	$t(7) = -2.416$	$P = 0.046$	0.81
Max glance Airspeed	0.58 ± 0.28s	0.35 ± 0.08s	$t(7) = 2.402$	$P = 0.047$	1.13
Cloud leans					
Roll rate when OTW	$0.036 \pm 0.29° \cdot s^{-1}$	$0.41 \pm 0.36° \cdot s^{-1}$	$t(7) = 3.239$	$P = 0.014$	1.15
Correcting roll rate ADI	–	$-0.32 \pm 0.35° \cdot s^{-1}$	$t(7) = -2.583$	$P = 0.036$	0.91
Number glances ADI	45.3 ± 25.7	64.3 ± 29.8	$t(7) = -2.709$	$P = 0.030$	0.68
Glance duration ADI	0.62 ± 0.20s	0.44 ± 0.15s	$t(7) = 4.616$	$P = 0.002$	1.04
Coriolis					
Roll rate	$-0.005 \pm 0.45° \cdot s^{-1}$	$-1.25 \pm 1.33° \cdot s^{-1}$	$t(9) = 3.209$	$P = 0.011$	1.26
Bank angle deviation	0.5 ± 3.7°	3.4 ± 3.7°	$t(9) = -2.881$	$P = 0.018$	0.77
Glance time delay	0.80 ± 0.11s	1.24 ± 0.24s	$t(7) = -6.677$	$P < 0.001$	2.32
Number of saccades	6.6 ± 2.6	10.6 ± 4.0	$t(7) = -3.434$	$P = 0.011$	1.20
Postrotatory					
Max roll input	0.18 ± 2.9%	−3.3 ± 2.0%	$t(9) = 2.966$	$P = 0.016$	1.39
Vestibular leans					
Variance bank angle	0.82 ± 0.71°	2.7 ± 2.8°	$t(9) = -2.382$	$P = 0.049$	0.94

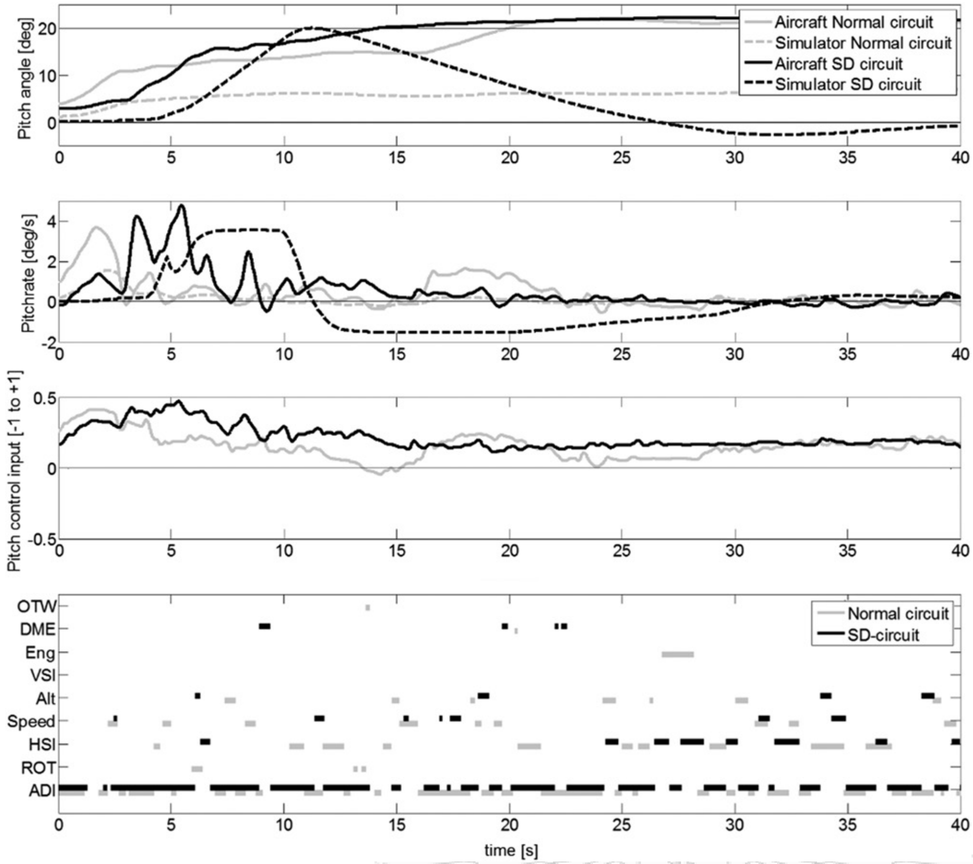


Fig. 1. Example time histories of the aircraft and simulator pitch angle, pitch rate, pitch control input, and visual behavior during the Go-Around flight phase of the Normal circuit (gray) and during the SD circuit (black).

circuit [$t(7) = 3.239, P = 0.014, d = 1.15$] followed by a correction in the opposite direction when they shifted their gaze from OTW to the ADI, with an average roll rate of $-0.32 \pm 0.35° \cdot s^{-1}$ [$t(7) = -2.583, P = 0.036, d = 0.91$]. In contrast, in the Normal circuit, mean roll rate did not significantly differ from zero ($0.036 \pm 0.29° \cdot s^{-1}$) when pilots were looking OTW.

According to the general gaze behavior metrics, analyzed for the entire visual search phase, pilots primarily focused on the OTW and ADI, with average values amounting to 33.8% and 28.4%, respectively, in the Normal circuit. Important visual transitions were found between the ADI and Alt (20.2%), ADI and HSI (17.6%), and ADI and OTW (17.3%) (see Fig. 2). These values were not significantly different in the SD circuit. However, the number of glances on the ADI was higher in the SD circuit (64.3 ± 29.8) than in the Normal circuit (45.3 ± 25.7) [$t(7) = -2.709, P = 0.030, d = 0.68$]. Also, the mean glance duration to the ADI was shorter in the SD circuit (0.44 ± 0.15 s) compared to in the Normal circuit (0.62 ± 0.20 s) [$t(7) = 4.616, P = 0.002, d = 1.04$]. Both measures indicate that the pilots made more, but shorter glances at the ADI during the cloud leans.

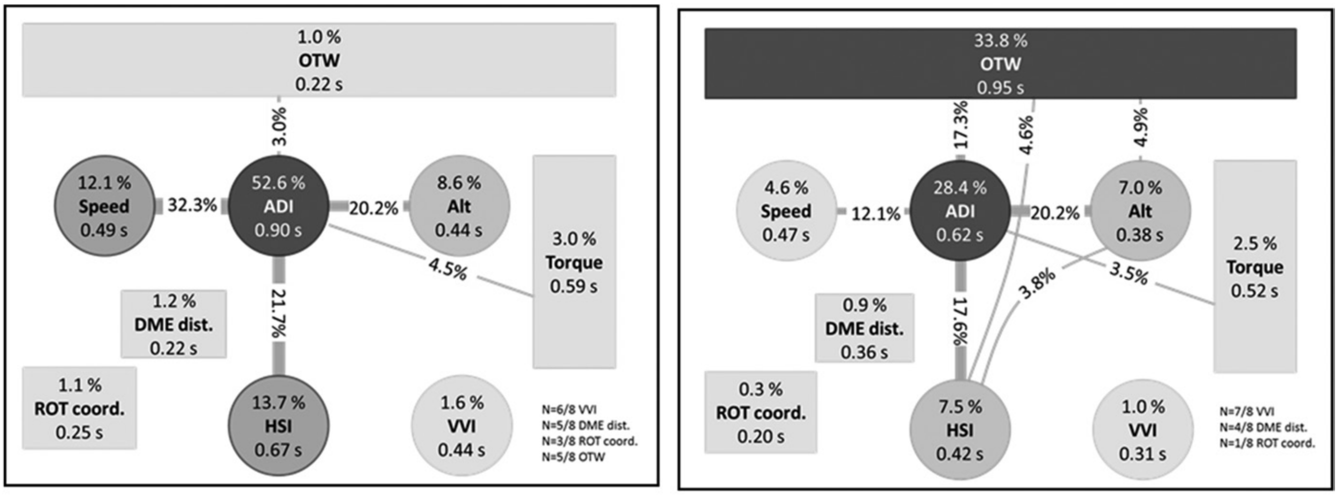
The effects of the Coriolis illusion are illustrated in **Fig. 4**, showing the time histories of aircraft bank angle, simulator yaw rate, and visual scanning behavior of one pilot during the orbit phase in both the Normal and SD circuits. The vertical lines halfway through the orbits of both circuits indicate the moments of the vertical head movement. Immediately after the head movement in the SD circuit, aircraft bank angle further increased from about −30° to −36°. The pilot corrected this bank angle as soon as the ADI was visually checked at about 61 s.

This control behavior was observed in 8 out of 10 pilots. Analysis of the flight performance data during the first 5 s after the head movement showed a significantly larger mean roll rate in the SD circuit ($-1.25 \pm 1.33° \cdot s^{-1}$) as compared to the Normal circuit ($-0.005 \pm 0.45° \cdot s^{-1}$) [$t(9) = 3.209, P = 0.011, d = 1.26$]. Correspondingly, maximum deviation from the required 28° angle of bank was larger in the SD circuit ($3.4 \pm 3.7°$) as compared to the Normal circuit ($0.5 \pm 3.7°$) [$t(9) = -2.881, P = 0.018, d = 0.77$].

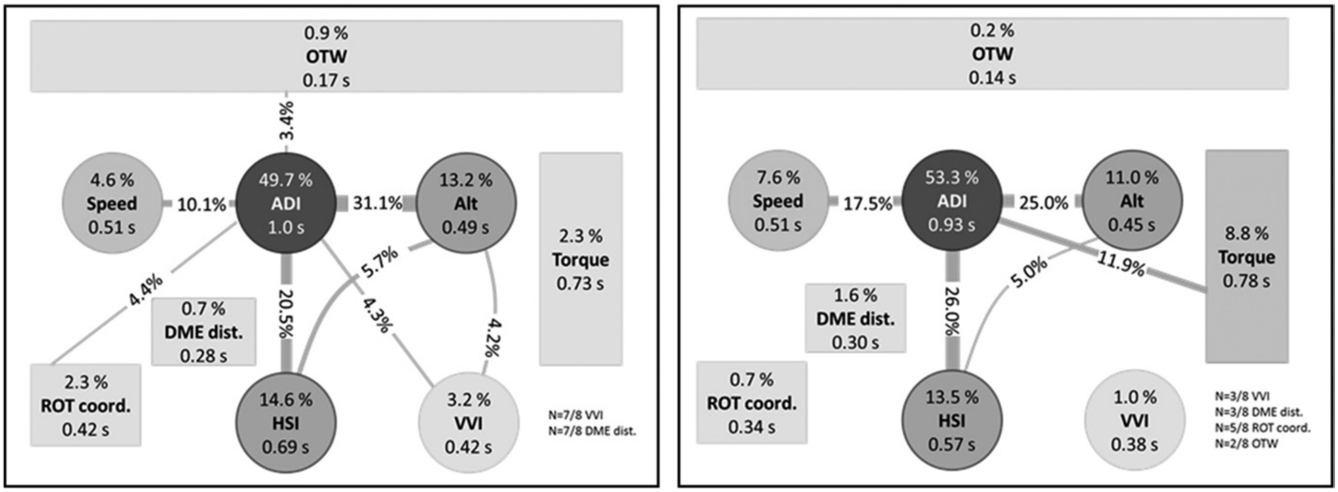
Analysis of the general gaze behavior metrics during the entire orbit showed that the pilots' attention was primarily on the ADI (on average, 49.7%), HSI (14.6%), and Alt (13.2%) in the Normal circuit, with most the important visual transitions between the ADI and Alt (31.3%) and between the ADI and HSI (20.5%) (see Fig. 2). These values were not significantly different in the SD circuit.

More detailed analysis of the gaze tracking data during the first 5 s after the head movement showed that the time delay until the first glance toward an instrument, which was the ADI in all cases, was longer in the SD circuit (1.24 ± 0.24 s) compared to the Normal circuit (0.80 ± 0.11 s) [$t(7) = -6.677, P < 0.001, d = 2.32$]. In addition, there was a significantly higher number of saccades in the SD circuit (10.6 ± 4.0) as compared to the Normal circuit (6.6 ± 2.6) [$t(7) = -3.434, P = 0.011, d = 1.20$].

The time histories in Fig. 4 also include the postrotatory effect during leveling off at the end of the orbit. In this example, the pilot adequately rolled back to wings level in the Normal circuit, while in the SD circuit he initially leveled off at wings level, but rolled back to about −8° angle of bank between 110 and 120 s. Analysis of the maximum roll control input during the first 5 s after leveling off showed a significant difference between the Normal circuit ($0.18 \pm 2.9\%$) and the SD circuit ($-3.3 \pm 2.0\%$) [$t(9) = 2.966, P = 0.016, d = 1.39$]. However, the average roll control input, mean bank angle deviation, and average roll rate were not significantly different between both



(a) Go-Around (b) Visual search



(c) Orbit (d) Descending turn

Fig. 2. Viewing behavior during: A) Go-Around, B) Visual Search, C) Orbit, and D) Descending turn of the normal circuit in terms of area-of-interest attention ratio, mean glance duration, and link-value-probability; $N = 8$.

circuits. Analysis of gaze tracking in relation to this postrotatory effect was limited to the number of saccades during the same timeframe, but did not yield significant differences between both circuits.

The effects of the vestibular leans on flight performance were investigated by analyzing the first 5 s after the descending turn. In both circuits, mean aircraft bank angle and roll rate did not significantly differ from zero. However, the variance of the bank angle was significantly higher in the SD circuit (2.7 ± 2.8°) as compared to the Normal circuit (0.82 ± 0.71°) [$t(9) = -2.382$, $P = 0.049$, $d = 0.94$], indicating that in the SD circuit it took more effort to achieve level flight due to the vestibular leans.

The analysis of gaze tracking data for the first 5 s after leveling off showed no significant differences between the SD circuit and the Normal circuit. As shown in Fig. 2, during the descending turn the pilots primarily checked the ADI (53.3% on average), HSI (21.6%), and Alt (14.7%). Important viewing transitions were found between the ADI and HSI (26.0%), between the ADI and Alt (25.0%), between ADI and Speed (17.5%), and to a lesser extent between the ADI and Torque (11.9%).

DISCUSSION

The results of this study demonstrate that manual flight performance and gaze behavior of pilots were significantly influenced by both vestibular and visual SD events in a ground-based simulator. Special efforts were taken to hide the real objective from the participating pilots so that they did not anticipate the events. The postexperiment questionnaire confirms that this approach was successful, as the pilots reported to be surprised when they recognized one or more events. Nevertheless, the observed effects were quite subtle, and required specific analysis of performance and gaze tracking data, depending on flight phase, piloting task, and also type of SD. For example, the false horizon during the cloud leans had a marked effect on the pilots' roll input, triggering roll motion to align the aircraft with the false

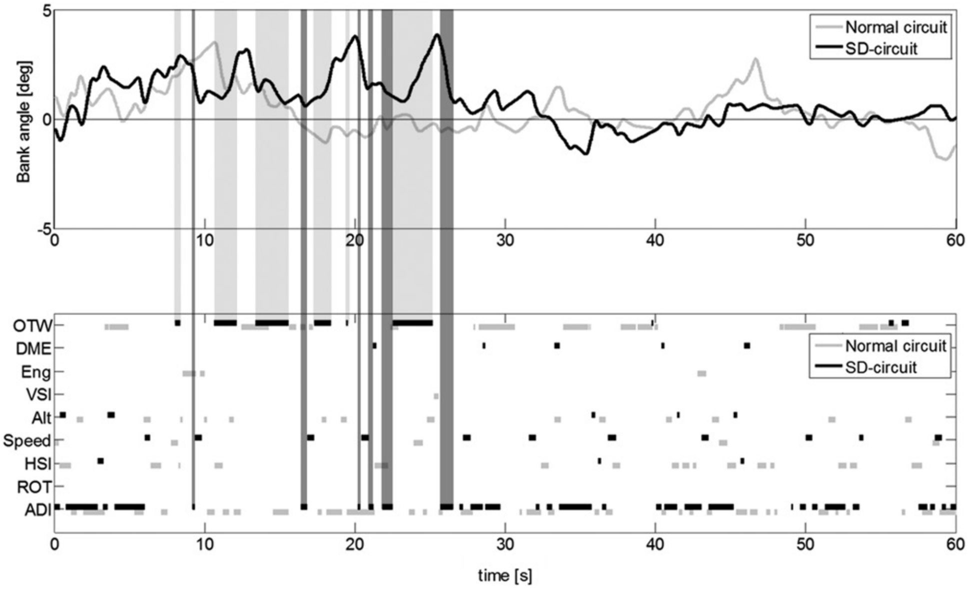


Fig. 3. Example time histories of the aircraft bank angle and visual behavior during the Visual Search flight phase of the Normal circuit (gray) and during the SD circuit (black) with a sloping cloud deck. To illustrate the effect of the cloud leans in the SD circuit, vertical bands are shown between 8 and 26 s to highlight when the pilot was looking at the OTW (light gray vertical bands) and ADI (dark gray bands).

horizon. This effect did not show from analysis of the entire visual search phase, but only became apparent after analysis of the episodes where pilots were looking at the OTW. Although this and other effects were subtle, it is easy to imagine how such effects can escalate in real flight when a pilot is under high workload, stress, or when being distracted from the basic flying task. This is even more so when considering that SD itself can consume cognitive resources and increase workload.[15]

Of the five investigated SD events, the somatogravic illusion, the Coriolis illusion, and the cloud leans produced significant effects on flight performance and gaze behavior, with effect sizes being medium to large. With respect to the somatogravic illusion, it was expected that pilots would reduce the nose-up attitude during the go-around as a result of an overpitch sensation. The results indeed showed more release of a nose-up control input in the SD circuit. However, this seemed to be related to a larger initial pull rather than a larger push. Closer inspection of the recorded simulator motion showed that in the SD circuit the preprogrammed platform pitch only started 3 s after the initiation of the go-around. As the pitch motion was passive, bearing no relationship to the pilots' control inputs, the go-around in the SD circuit was basically an open-loop flight task. In contrast, in the Normal circuit go-around the simulator continuously provided motion feedback to the pilots' control inputs, which can thus be considered a closed-loop task. The lack of motion feedback in the SD circuit go-around may explain why pilots (unconsciously) initially pulled further aft on the stick and showed a difference in viewing behavior. We conclude that the way the somatogravic illusion has been implemented in this simulator may be suitable for passive demonstrations, but may not be adequate for man-in-the-loop scenarios like the go-around maneuver. In this respect, it may be more adequate to adapt the simulator's motion driving algorithms to increase the simulator's pitch response to pilot control inputs, as explained by Lampton et al.[27] This shows that, although ground-based SD devices are getting close to reproducing many of the known SD illusions in a safe environment, exact reproductions of all SD illusions remain a challenge.

Similar to Cheung and Hofer,[9] we found that the Coriolis effect delayed the pilots' gaze shift toward the ADI. In addition, we found an increased number of saccades immediately after the head movement, indicating that the effect on gaze behavior was due to a physiological mechanism where the vestibulo-ocular reflex interfered with the instrument scan. As the effect was noticed by all pilots, it can be concluded that a constant yaw rotation of $60° \cdot s^{-1}$ was sufficient to induce a perceptible Coriolis illusion, which can therefore be considered "recognized" or Type II SD.

In contrast to such physiological effects, the cloud leans seemed to be related to a perceptual mechanism. Psychophysical studies in the laboratory have shown that a false horizon can induce a sensation of illusory self-tilt.[17,22] The results of the present study illustrate how such illusion can influence pilots' control inputs and viewing behavior in a manual flight task, even though the cloud leans was not always recognized by the pilots. This can thus be classified as "unrecognized" or Type I SD, which is a potential cause of loss-of-control accidents, where it may have contributed to inappropriate control inputs.[31]

The postrotatory illusion was only reported by one pilot and did not affect the pilots' control inputs, whereas it involved relatively strong deceleration from the sustained yaw motion. A previous study did show that a postroll illusion triggered unintended roll inputs.[33] However, in that study the pilots had no cockpit instruments available. Possibly, in the present study, the illusion was overshadowed by the preceding Coriolis illusion, which compelled the pilots to focus more on the instruments.

The vestibular leans was also recognized by only one pilot. A possible explanation is that the platform tilt to induce the vestibular leans after the descending turn amounted to only 3.6°, which is in the region of the human perception threshold of body tilt.[26] Hence, the platform tilt may have been barely perceptible to the pilots. Similar to our remarks on the reproduction of the somatogravic illusion in a ground-based SD device, the reproduction of man-in-the-loop vestibular leans may require amplified platform motion.

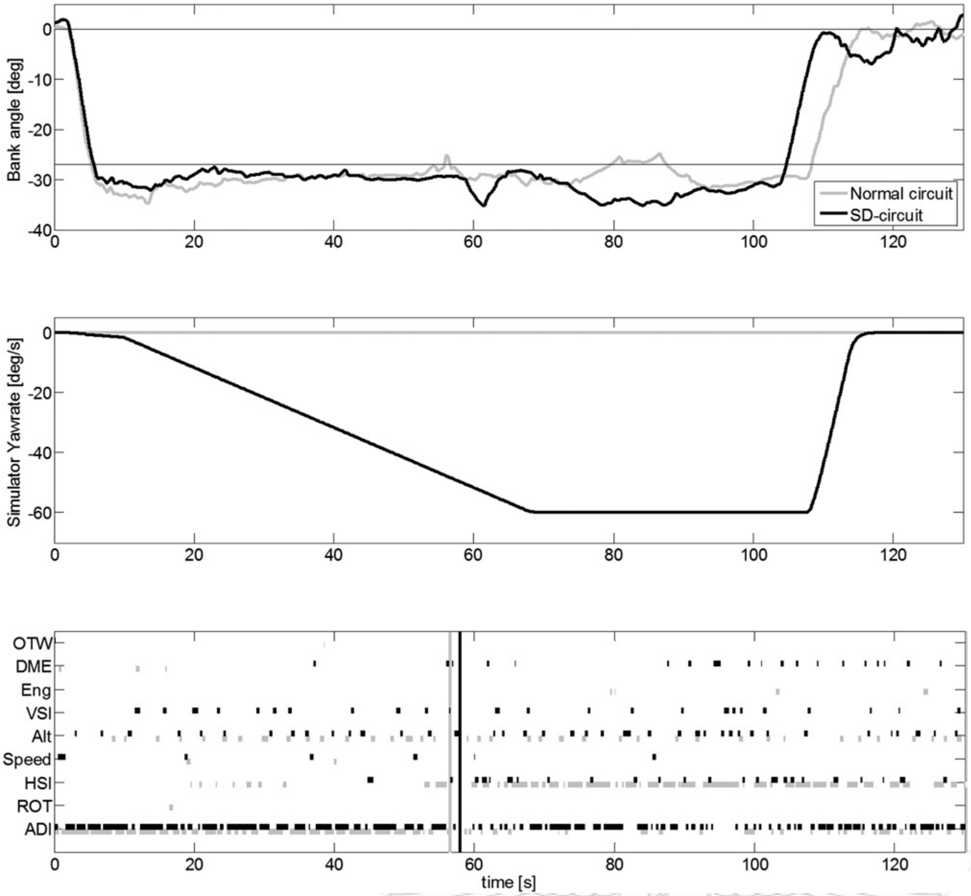


Fig. 4. Example time histories of the aircraft bank angle, simulator turntable yaw rate, and visual behavior during the orbit flight phases of the Normal circuit (gray) and SD circuit (black). For the SD circuit, the middle plot shows a leftward subthreshold simulator turntable yaw acceleration of $1° \cdot s^{-2}$ up to a $60° \cdot s^{-1}$ yaw rate from about 5 to 65 s. In the bottom plot, the vertical lines indicate the moment of subject's upwards head motion, which induced a Coriolis illusion in the SD circuit at about 58 s. At the deceleration phase in the SD circuit, at about 107 to 113 s, the simulator applied an above-threshold yaw deceleration of $10° \cdot s^{-2}$ to standstill, which induced a postrotatory illusion.

When generalizing the results of this study, some limitations should be considered. First, the participating RNLAF pilots were all novices who recently were trained to perform an adequate instrument scan. The advantage of this is that their level of expertise was comparable, resulting in a coherent group. However, the results may not directly apply to experienced pilots, as it is known that pilots' viewing behavior depends on the level of flight expertise.[3,19,20] Second, the PC-7 aircraft used here was equipped with a "round dials" cockpit, while pilots' gaze behavior can be different in a glass cockpit.[1,19] Third, similar to the approach of Previc et al.,[35,36] all SD events were presented in one, final circuit. It is possible that pilots started to suspect something after they noticed the first SD event. It may have been better to only present one unexpected SD to each pilot, but this was discarded for efficacy reasons. Still, the answers on the postexperiment questionnaire showed that pilots did not become fully aware of the purpose of the experiment. Fourth, there is a possibility that pilots noticed an event during the flight, but forgot to report it on the postexperiment questionnaire. Previc et al.[35,36] used another method, asking the pilots to make real-time call-outs as soon as they noticed any abnormality. Nevertheless, we decided to use a postexperiment questionnaire to avoid the risk that real-time call-outs would make the pilots aware of the possibility of upcoming unexpected events.

A practical application of this study can be to include gaze tracking in SD training. Gaze tracker technology has matured sufficiently to provide reliable feedback on a pilot's instrument scan and causes no interference with the flying task. In particular, the replay possibilities of recorded gaze tracking data projected over the cockpit instruments is a powerful tool to improve insight into individual scanning behavior.

In conclusion, spatial disorientation in flight may trigger inappropriate control inputs, causing deviations from the intended flight path and, ultimately, loss of control. An adequate instrument scan can be a lifesaver in such conditions. This study provides experimental evidence for a direct relationship between SD on the one hand, and pilots' visual scanning and control behavior on the other hand. The observed effects depended on the type of SD. The results showed that flight performance was affected even when the pilots did not recognize the SD event. It also appeared that not all preprogrammed events in a special SD simulator were adequate for use in a man-in-the-loop manner. We conclude that the combination of gaze tracking and appropriate SD scenarios in simulator training can improve the pilots' understanding of the relevance of instrument scanning in the prevention of SD.

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