Spatial Disorientation Survey Among Military Pilots

Helena J.M. Pennings; Esther A.P.B. Oprins; Hans Wittenberg; Mark M.J. Houben; Eric L. Groen

BACKGROUND: Spatial disorientation (SD) remains a significant cause of accidents and near accidents. A variety of training methods have been used to assist pilots to anticipate the SD problem. The value of such training in the prevention of disorientation has been difficult to assess.

METHODS: To study transfer of SD awareness training, we related reported incidents to the content and frequency of SD awareness training received. The questionnaire was completed by 368 out of 495 pilots; 189 currently flying fixed-wing, and 150 flying rotary-wing aircraft. On average, their age was 38, and they had 2466 flight hours on-type.

RESULTS: Respondents gave high ratings for the importance of SD training and their awareness of SD, the latter being one of the training objectives. The amount of SD training received by respondents was positively correlated with ratings for appreciation and importance. Self-rated awareness was positively correlated with the number of reported SD experiences. Although the correlations were below 0.50, the results provide an indication that SD training is effective. In total, respondents reported 5773 SD experiences, 195 of them resulting in a serious risk for flight safety. Narratives of these serious events show that, in many cases, pilots managed their SD by carefully checking the flight instruments, and also by good crew coordination.

DISCUSSION: The results of the survey provide some evidence, although based on subjective reports, for transfer of SD training. The results of the SD experiences can be used to improve the SD training in terms of content and frequency.

KEYWORDS: flight safety, training, illusion, simulator.

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Spatial disorientation (SD) occurs when pilots have a false perception, or a lack of awareness of their position or motion with respect to Earth.[21] When unrecognized, SD can have catastrophic consequences, as revealed by mishap figures showing that SD persistently causes about 30% of fatal aviation accidents.[11,19,21,22] To mitigate the risks of SD, various training methods have been used to assist pilots to anticipate the problem.[7]

Military aircrew receive extensive technical and tactical training in order to safely operate the aircraft and effectively perform their missions. In addition, aircrew should be trained to deal with unpredictable, or atypical situations.[6] As it is impossible to practice every event that might occur in reality, training should include variable or prototypical situations which require generic problem solving.[9,14,15] Because evidence from real incidents is scarce, it is difficult to determine the transfer to the operational environment.[2] Nevertheless, it is generally considered useful to let aircrew recognize and manage their own response to unexpected situations, which may involve startle and surprise. For example, a recent simulator study showed that unpredictable training scenarios improve sensemaking skills, and reduce the startle response in the participating pilots.[15]

Recognition of one's own response by self-experience is also an important element of spatial disorientation (SD) awareness training. In the 1990s the Royal Netherlands Air Force (RNLAF) developed an SD awareness training program, in short "SD training," in response to a number of mishaps which were linked to controlled-flight-into-terrain. An (unpublished) survey among RNLAF fighter pilots at that time showed that all of them had experienced SD in-flight, and 26% of them indicated that SD had resulted in a near-accident. Based on these outcomes, an SD training program was developed comprising

From TNO and the Center for Man in Aviation, Royal Netherlands Air Force, Soesterberg, The Netherlands.

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Address correspondence to: Dr. Helena J.M. Pennings, Kampweg 55, 3769 DE Soesterberg, The Netherlands; heleen.pennings@tno.nl.

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lectures, as well as ground-based demonstrations of typical SD phenomena. Initially, the demonstrations merely involved passive exposure to basic SD illusions, such as the Coriolis sensation on a rotating chair.[12] As the demonstrations did not involve a cockpit environment or flying task, they were particularly suitable for student pilots who had just started their flight training. Today the RNLAF uses more advanced ground-based devices, e.g., the Advanced Spatial Disorientation (ASD) simulator or the Desdemona simulator (both manufactured by AMST-Systemtechnik GmbH, Ranshofen, Austria), with a cockpit mounted on a special motion platform capable of reproducing vestibular illusions. Such devices make it possible for experienced pilots to actively fly certain, type-specific SD scenarios.[3,4,16,20]

While the SD training has existed for several years, and complies with the military standard for aeromedical training of flying personnel (Standardization Agreement Normalization STANAG 3114), the RNLAF recognized the need to evaluate the pilots' appreciation of the training, and to relate it to the experienced in-flight SD events.[23] For this purpose a survey was distributed among the current population of RNLAF rotary-wing and fixed-wing pilots. The results of this survey are presented in this paper, addressing the following research questions: 1) how is SD training being appreciated?; 2) does the number of reported events depend on the amount of SD training received by pilots?; 3) which SD events are most commonly reported by pilots?; and 4) is there a difference in the (type of) reported events between pilots from rotary vs. fixed wing platforms? We expected that the number of reported SD experiences would be positively correlated with the frequency and type (e.g., basic vs. advanced) of SD training received. We also expected that the appreciation of the SD training would be positively correlated with the frequency and with the type of SD training received. Based on a similar survey performed by Holmes et al. among military flying personnel in the United Kingdom, we also expected certain SD experiences to be among the most commonly reported illusions such as "the leans," "loss of horizon," and "misleading altitude cues."[13] In addition, some differences were expected between different platforms, due to different operational capabilities and deployment.

METHODS

Subjects

A printed, retrospective questionnaire was administered between January 2017 and December 2017 to 495 RNLAF pilots who came to the Centre for Man in Aviation for their annual medical assessment. Participation was noninvasive, voluntary, and anonymous, therefore this study was exempted from IRB approval. In total, 385 questionnaires were returned (78% response rate). However, 17 participants answered less than 30% of questions about SD events, and these participants were excluded from the analysis. Hence, the results are based on the analysis of questionnaires from 368 pilots (74% completion rate): 241 operational pilots, 111 nonoperational pilots, and 15 retired pilots. One pilot did not report the current function. On average, the respondents' age was 38.2 (range 21 to 58).

Among the 368 respondents included in the analysis, there were 189 fixed-wing pilots (F-16, PC7, C130H, DC10, C17, Gulfstream, Dornier DO228, "other"), and 150 rotary-wing pilots (CH47D, AH64, NH90, AS532, EC135, "other"). For 29 respondents it was impossible to determine the current platform, as they reported none or multiple types. Without these 29 and "other", pilots could be divided into fixed wing fighter ($N = 92$), trainer ($N = 32$), transport ($N = 53$), rotary-wing transport ($N = 92$), and rotary-wing attack ($N = 54$).

Materials

The questionnaire consisted of three parts. The first part concerned demographic information and flight career. The second part addressed SD training received by the respondents, starting with an open-ended question about the number and type of training (i.e., lectures, basic or advanced ground-based demonstration, or in-flight demonstration). Next, 11 multiple-choice questions were included to evaluate memory of the training on a 6-point Likert-type scale (1 = totally disagree; 6 = totally agree). The 11 questions were designed based on three subscales: 1) appraisal of SD awareness training (5 items, e.g., "I thought the SD awareness training was boring") (Cronbach's $\alpha = 0.72$); 2) awareness of SD (5 items, e.g., "I take SD risks into account when preparing for night flights") (Cronbach's $\alpha = 0.79$); and 3) sensitivity to SD (1 item "I am less sensitive to SD, because I have a good sense of aircraft movements"). A factor analysis confirmed the presence of these subscales underlying the data (i.e., Eigenvalues > 1), together explaining 58.17% of the variance. Finally, this part of the questionnaire included two questions about the respondents' satisfaction with the SD training: "How do you appreciate the SD awareness training you followed on a scale from 0 to 10?" (0 = very bad and 10 = very good), and "How often would you like to follow a refresher training?" (ranging from never to 5 times per year).

The third part of the questionnaire contained questions about the type and severity of SD incidents experienced on-type. This part was derived from an earlier spatial disorientation survey of Holmes et al., listing 38 different SD experiences with a brief description, organized into five categories: 1) visual illusions (e.g., loss of horizon—SD caused by atmospheric conditions blending Earth and sky); 2) body sense illusions (e.g., the "leans"—leaning in response to false sensation of bank after recovery to wings level); 3) illusions related to the use of displays (e.g., problems interpreting spatial orientation information on head-down displays); 4) miscellaneous (e.g., SD caused by poor crew coordination); and 5) other (i.e., open ended question where respondents can add a missing SD illusion).[13] For each SD experience the frequency of occurrence could be rated as: "N/A" (not applicable to my current aircraft type), "Never" (applicable to my current aircraft type, but never caused SD), "Rarely" (1 or 2 episodes only), "Seldom" (in less than 5% of all sorties), "Occasional" (in 5–25% of all sorties), "Frequently" (in more than 25% of all sorties). Furthermore, respondents were asked to indicate the SD experiences which resulted in a risk for flight safety, either significant ("flight safety was not yet in danger but could have been") or severe ("flight safety was in danger"). The two options were: 1 = "all experienced SD illusions were of minor risk to flight safety"; or 2 = "for the following illusion the safety risk was significant or severe." Finally, some extra pages were included to allow respondents to describe one or more of the experiences which had resulted in significant or severe safety risks.

RESULTS

Table I shows the descriptive statistics of the main variables, and their correlations. The maximum Amount of SD training received amounted to four, with 28 respondents having had no SD training at all. The numbers of respondents receiving one, two, three or four courses of SD training amounted to 50, 93, 106, and 91, respectively. The average grading for SD training was 7.7, which on a Dutch 0–10 scale can be considered as "Good." On average, respondents preferred a frequency of one refresher training every 3 yr.

Apart from the correlation between Age and Flight hours ($r = 0.79$), all correlations were below 0.50, indicating predominantly small to medium associations.[8] Nevertheless, some significant correlations are interesting to mention. First, Age was negatively correlated with Amount of SD training, and with Appreciation for SD training. Second, Amount of SD training was positively correlated with Appreciation for SD training and Importance of SD training. Third, there was a positive correlation between Appreciation for SD training and Preferred refresher interval. Fourth, Awareness of SD was positively correlated with Age, Appreciation for SD training, Importance of SD training, and Number of marked SD experiences. Finally, the positive correlation between the Amount of SD training and the Number of marked SD experiences was only marginally significant ($P < 0.10$).

Fig. 1 shows the percentages of respondents who received different types of SD training, i.e., "no training," "lecture only," "basic ground-based demonstration," "advanced ground-based demonstrations," "in-flight demonstrations," and combinations thereof. The ground-based demonstrations were provided in simulators.

In total, 92.4% of respondents had received some form of SD training (ranging from lecture only to advanced ground based demonstrations in the Desdemona simulator). Basic ground-based demonstrations were received by 46.2% of respondents, and 30.7% of them received SD training in the more advanced Desdemona simulator (i.e., advanced ground-based demonstration). Given that in-flight demonstrations of SD are not part of the standard training curriculum of the RNLAF, it is remarkable that 44.0% of respondents indicated having received in-flight SD demonstrations (i.e., 5.7% in-flight only demonstrations, 25.8% in combination with basic ground demonstrations, and 12.5% in combination with advanced ground based demonstrations). We assume that in-flight demonstrations were performed on the initiative of individual instructors, happening more on an ad hoc basis than the ground-based demonstrations, or that in-flight demonstrations occurred as a side-effect of flying maneuvers in training.

In total, the 368 respondents marked 5773 SD experiences on type (all categories except N/A and Never), ranging from 0 to 35 (mean of 15.7) experiences per respondent (Table I). All 38 predefined SD experiences included in the questionnaire were reported. In total nine SD experiences were reported by more than 50% of the respondents: six related to visual illusions, two related to body sense illusions, and one to displays (night vision goggles, i.e., NVG).

Table II presents a ranking of all reported SD experiences based on the percentage of respondents reporting at least one episode of this experience. The three least frequently marked incidents were "graveyard spin" (8%), "flying carpet illusion" (12%), and "nystagmus following spin recovery" (12%). The three most frequently reported incidents were "false horizon (sloping clouds or terrain)" (76%), "loss of horizon due to atmospheric conditions" (70%), and "lack of altitude cues due to featureless terrain" (69%). In addition to the predefined list of SD experiences, two respondents mentioned the following experiences in free format: "ear block," "false sensation of height or depth," and "misinterpretation of relative position to a ship during deck landing." These experiences were not included in the analysis.

Table III shows the top 10 of most frequently noted SD incidents differentiating between rotary-wing (transport and attack) and fixed-wing (fighter, transport, and trainer) platforms (all

Table I. Descriptive Statistics and Correlations.

				PEARSON CORRELATIONS								
		M	SD	1	2	3	4	5	6	7	8	9
1	Age	38.22	9.37	-								
2	Flight Hours on Current Platform	1284.77	942.64	0.48**	-							
3	Flight Hours Total	2465.51	1901.16	0.79**	0.49**	-						
4	Amount of SD Training	2.49	1.22	−0.41**	−0.11*	-0.33**	-					
5	Appreciation for SD Training	7.66	0.94	−0.25**	−0.15*	-0.23**	0.21**	-				
6	Preferred Refresher Frequency	3.04	1.83	0.02	−0.01	−0.00	0.10	0.14*	-			
7	Importance of SD Training	5.10	0.56	−0.01	−0.02	0.03	0.12*	0.27**	0.07	-		
8	Awareness of SD	4.40	0.82	0.12*	0.08	0.09	−0.02	0.17*	0.01	0.19*	-	
9	Number of Marked SD Experiences	15.69	7.60	−0.08	0.07	−0.08	0.09	0.01	0.06	0.05	0.12*	-

* $P < 0.05$; ** $P < 0.001$. M = mean; SD = standard deviation. The column numbers 1 to 9 correspond to the numbered variables in the rows.

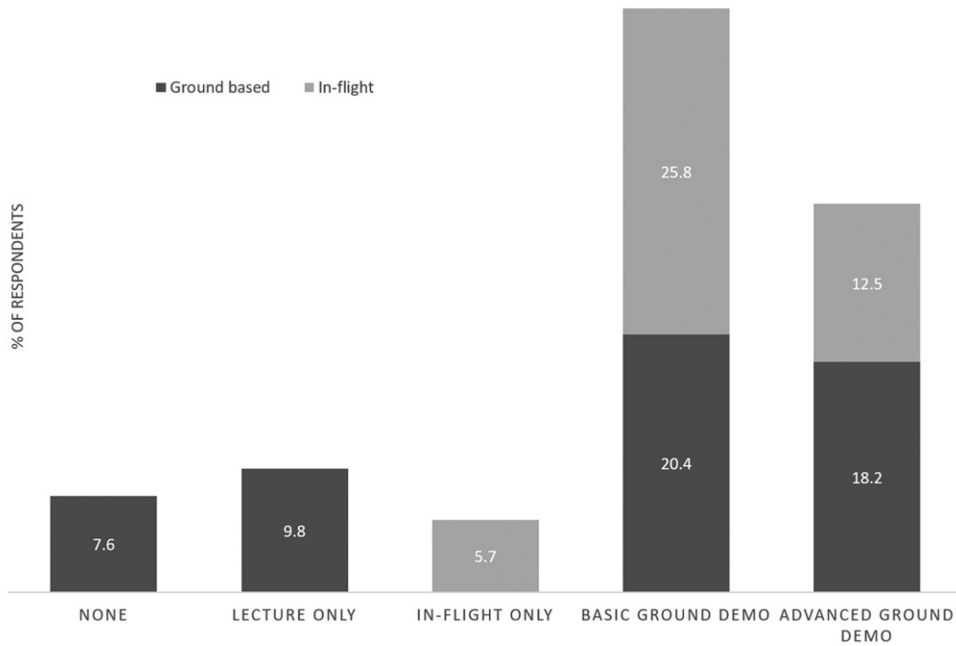

Fig. 1. Percentages of the respondents who received different types of SD training.

categories except N/A and Never). In this top 10, 4 SD experiences were common for all 5 platform types: "sloping horizon," "loss of horizon due to atmospheric conditions," "misleading altitude cues," and the "leans." Two SD experiences were common in four platform types: "lack of altitude cues due to featureless terrain" and "tumbling sensation (Coriolis)." One SD experience that was common between three platform types was "G excess." Six SD experiences were common for two platform types: "loss of horizon due to sand/snow," "night approach (black hole approach)," "autokinesis," "misinterpretation of relative position in formation flight," "undetected drift (rotary wing only)," and "NVGs." Finally, 7 SD experiences in the top 10 were tied to only 1 platform type: "false sense of yaw," "elevator illusion," "postroll illusion," "false sensation of pitching up," "false sense of pitching down," "SD using FLIR," and "distraction/task saturation."

Regarding the safety risk of the SD experiences, the two most right columns in Table II list how often each SD experience resulted in a significant or severe safety risk. Among all reported SD experiences, there were 152 (1.4%) incidents with a significant risk, and 43 (0.4%) incidents with a severe risk. There appears to be no clear relationship between the rank of an SD experience and the number of associated safety incidents. For example, the "leans" was ranked as number four of most reported experiences (67%) and resulted in two significant and no severe incidents. In comparison, "loss of horizon due to brown out, white out, spray out" was ranked number 13 (45% of respondents), and resulted in 26 significant and 10 severe incidents. The explanation for this particular difference may be that the "leans" is a common illusion which can be experienced anywhere in flight, while "loss of horizon due to sand/snow" typically occurs during a rotary wing landing (or hovering) close to the ground, where it creates an immediate safety risk. The vicinity of the ground may also apply to the 21 significant and 4 severe incidents reported for "undetected drift" (ranked 35), as well as the 7 significant and 3 severe incidents reported for the "black hole approach" (ranked 13).

The open question at the end of the questionnaire invited many respondents to provide—more than 160 in total—narratives of specific incidents, mostly comprising a significant or severe safety risk, but also some minor safety events. As an example of the latter, several F-16 pilots described regularly experiencing the leans when flying as wingman behind a lead aircraft or tanker aircraft, in instrument meteorological conditions (IMC). According to one F-16 pilot, the leans is frequently addressed in briefings, so that the community is quite aware of this illusion. Still, in some cases the leans resulted in an uncomfortable situation, prompting the pilot to initiate a "lost wingman" procedure, and countering SD by making use of cockpit instruments. Another minor safety event reported by F-16 pilots was a false sensation of nose-down pitch upon lowering of the landing gear in rain or snow, where the reflection of the rotating landing light produced an upward optic flow. In one case the disorienting sensation coincided with a failure of the head up display (HUD), prompting the pilot to perform a go-around. Misleading optic flow was also a factor in several serious safety incidents during helicopter landings in brown out conditions, in particular with NVGs. Many of the reported serious incidents were managed by a careful cross-check of the flight instruments, sometimes by simultaneously aborting the maneuver, and often by handing over the control to the other pilot (crew coordination).

DISCUSSION

The survey described in this study was aimed at investigating the transfer of SD awareness training which has been given to RNLAF pilots since the 1990s. The results showed that 92.4% of the respondents received some kind of SD training, ranging from lectures to advanced demonstrations. The remaining 7.6% did not get any form of SD training. The negative correlation observed with age seems to indicate that for some older pilots the SD training was introduced after their initial flight training.

Concerning the first research question on the appreciation of SD training, the results showed that this was the case. The training was considered relevant by pilots, as evidenced by an

Table II. Ranking of the Reported SD Incidents (N = 368).

RANK	TYPE	ILLUSION	% PARTICIPANTS	*N* SIGNIFICANT	*N* SEVERE
1	V	False horizon (sloping clouds or terrain)	76	7	2
2	V	Loss of horizon (atmospheric conditions)	70	12	3
3	V	Lack of altitude cues due to featureless terrain	69	13	2
4	BS	The leans	67	2	0
5	V	Misleading altitude cues (e.g., small trees, sloping or narrow runway)	66	3	3
6	V	Black hole approach	58	7	3
7	BS	Coriolis illusion	57	1	0
8	V	Misinterpretation of relative position in formation flight	51	10	2
9	D	SD while using NVG	50	12	1
10	BS	Postroll illusion	48	2	0
11	O	Distraction or task saturation	45	4	3
12	V	Autokinesis	45	0	1
13	V	Loss of horizon (brown out/white out/spray out)	45	26	10
14	BS	Elevator illusion	39	0	0
15	V	Dip illusion (misjudgment of position in night trail formation)	38	6	0
16	BS	Undetected drift or descent in hover (rotary wing only)	38	21	4
17	BS	G excess	37	0	0
18	V	Moth effect (too close in on a single light source)	36	1	0
19	V	Vection (sensation of yaw caused by anticollision lights in clouds/fog)	36	1	0
20	D	Flight instrument confusion on entry to IMC	35	4	1
21	V	Vertigo caused by flickering lights	30	2	0
22	BS	False sense of pitching up during accelerating flight or takeoff	30	2	0
23	BS	Pitching down sensation during deceleration (somatogravic illusion)	29	1	0
24	V	Inappropriate use of sun, moon or northern lights as a vertical cue	28	0	1
25	D	SD caused by HMD (e.g., ANVIS/ODA/JHMCS)	28	1	0
26	D	SD using FLIR, or other targeting aids	27	5	3
27	BS	False sense of inversion, e.g., after an abrupt level off	27	1	0
28	D	Misinterpretation information on head-down display	26	1	1
29	D	Roll reversal error	24	0	0
30	O	SD caused by poor crew coordination	21	0	1
31	V	SD while using a drifting/descending flare as reference	21	1	0
32	V	Misinterpretation of relative position with respect to a ship	18	2	2
33	O	Giant hand illusion	17	0	0
34	D	SD due to (proven) instrument malfunction	16	2	0
35	D	Misinterpretation of information on HUD (F-16)	15	1	0
36	V	Nystagmus following spin recovery	12	0	0
37	O	Flying carpet illusion	12	0	0
38	BS	Graveyard spin	8	1	0

V = visual illusion, BS = body sense illusion, D = displays, O = other.

average Appreciation for SD training of "Good," as well as high ratings for Importance and Awareness. The mean scores of 5.1 for Importance, and 4.4 for Awareness (both on 1–6 scales) indicate that respondents considered the training important and also take SD into account during their flights and flight preparation. The positive correlation between Amount of SD training on the one hand, and Appreciation for SD training and Importance, on the other hand, suggests that pilots become more appreciative when they receive more SD training.

Regarding the second research question, in a similar survey among 752 aircrew of the UK Royal Air Force, Holmes et al. found that respondents who had received (in-flight) SD training reported more SD experiences than those who had not received any in-flight training.[13] Another survey among 2582 aircrew from the U.S. Air Force also showed that aircrew who had received previous in-flight training reported more illusions in flight.[19] Our results did not convincingly confirm this finding: the positive correlation between the Amount of SD training and the Number of noted SD experiences was only marginally significant. A possible explanation is that the SD experiences in the survey were self-explained, so that selecting the ones encountered during flight may not require prior knowledge or training. In this respect, the observed significant (positive) correlation between the Awareness rating and the number of marked SD experiences is revealing, because SD awareness is an important learning objective of the training.

To our surprise there was a positive correlation between appreciation for SD training and preferred refresher interval, which seems to imply that respondents with a higher appreciation of SD training preferred a longer interval between refreshers. A possible explanation is that respondents who judge themselves as more competent, need less frequent refreshers. In general, retention of acquired competences is a challenge in periods of nonuse, and refresher training may help to maintain a certain level of competence.[1]

Regarding the third research question, respondents reported on average 15.7 SD experiences, indicating that their awareness

Table III. Top 10 Rank and Percentage of Reported SD Experiences Divided Per Platform.

		N PLATFORM TYPES	RW TRANSPORT ($N = 92$)		RW ATTACK ($N = 54$)		FW FIGHTER ($N = 92$)		FW TRANSPORT ($N = 53$)		FW TRAINER ($N = 32$)	
			RANK	%	RANK	%	RANK	%	RANK	%	RANK	%
V2	Sloping horizon	5	1	91.3	2	88.9	3	85.9	1	73.6	1	93.8
V3	Loss of horizon due to atmospheric conditions	5	7	84.8	5	83.3	5	81.5	2	71.7	3	71.9
V4	Loss of horizon due to sand/snow	2	4	87.0	1	92.6	-	-	-	-	-	-
V7	Night approach (Black hole approach)	2	6	84.8	-	-	-	-	3	67.9	-	-
V8	Lack of altitude cues due to featureless terrain	4	3	90.2	3	88.9	2	87.0	4	56.6	-	-
V9	Misleading altitude cues	5	5	85.9	6	83.3	8	76.1	5	54.7	7	62.5
V10	Autokinesis	2	10	58.7	-	-	-	-	9	45.3	-	-
V11	False sense of yaw	1	-	-	-	-	-	-	8	47.2	-	-
V15	Misinterpretation of relative position in formation flight	2	-	-	8	72.2	4	81.5	-	-	-	-
B1	Tumbling sensation (Coriolis)	4	-	-	9	72.2	6	79.4	7	47.2	5	65.6
B2	G-excess	3	-	-	-	-	9	73.9	10	39.6	10	53.1
B3	Elevator illusion	1	-	-	-	-	-	-	-	-	9	56.3
B6	Postroll illusion	1	-	-	-	-	-	-	-	-	4	68.8
B7	Leans	5	9	75.0	10	70.4	1	88.0	6	52.8	2	93.8
B8	False sensation of pitching up	1	-	-	-	-	-	-	-	-	6	62.5
B9	False sense of pitching down	1	-	-	-	-	-	-	-	-	8	62.5
B10	Undetected drift (R/W only)	2	2	90.2	4	85.2	-	-	-	-	-	-
D4	NVGs	2	8	80.4	-	-	7	78.3	-	-	-	-
D5	SD using FLIR	1	-	-	7	74.0	-	-	-	-	-	-
O3	Distraction/task saturation	1	-	-	-	-	10	71.7	-	-	-	-

The column "number of platforms" indicates whether an SD experience occurs in the top 10 of 1, 2, 3, or 4 platforms.
V = visual illusion, B = body sense illusion, R/W = rotary-wing, D = displays, O = other.

of SD was generally high. The least frequently reported SD experience ("graveyard spin") was reported by 8% of respondents, which is comparable to the 7% found by Holmes et al.[13] The highest ranked SD experience in Holmes' survey was the "leans," reported by 92% of their respondents. In our study the "false horizon due to sloping clouds or terrain" was most frequently reported by 76% of all respondents ("leans" was ranked fourth). It is not clear to us why the percentages for the highest ranked SD experiences differ between both studies (92% vs. 76%), as the distribution of fixed-wing and rotary-wing pilots in both samples seems rather similar. Nevertheless, 7 of the top 10 of most reported SD experiences are the same among both surveys. Overall, 8% of surveyed pilots had experienced a severe episode of SD adversely affecting flight safety.

With regard to the fourth research question, we found similarities as well as differences in the top 10 of most frequently reported SD experiences between platform types (i.e., fighter, trainer, transport, and rotary-wing). Some differences can be attributed to differences in operational capabilities, such as "undetected drift in descent or hover" being unique for rotary-wing platforms, and "G excess" being unique to fixed-wing platforms. In their survey, Matthews et al. reported the following top three of SD experiences for different platforms: the leans, atmospheric blending of Earth and sky, and misjudged position in night formation trail (fighter); black-hole approach, sloping horizon, and the leans (transport); the leans, atmospheric blending of Earth and sky, and Coriolis illusion (trainer); and undetected drift, misleading altitude cues, and brown out/white out (rotary wing).[19] As shown in Table III, all these are among the top 10 of SD experiences reported for the respective platforms in the current study.

A quantitative breakdown of SD experiences as used in the questionnaire does not reflect the potential impact of each SD experience on flight safety. As there have been very few mishaps involving RNLAF aircraft for the last few decades, it is difficult to surmise the types of SD which impose the biggest safety risk. In that sense, the narratives of near mishaps obtained in this survey provided detailed examples of how SD confused the pilot and jeopardized the safety of the flight. Some of the severe safety events reported for brown-out landings occurred years ago, and in the meantime the RNLAF has implemented special rotary-wing scenarios in the Desdemona simulator to allow pilots to cope with these conditions. In a similar way, some other examples described by the respondents are valuable to develop other simulator scenarios, which can be included in the SD training program.

Although we were able to collect a considerable number of questionnaires, the study was limited by its retrospective and subjective nature. This makes it difficult to find direct indications of positive transfer of training. Their answers may be prone to recall bias, because respondents had to reflect on their entire flight career to recollect their experiences with SD training and SD events. It is not unlikely that details about these incidents were forgotten. In this respect the questionnaire could be improved by including more direct questions. For example, a question could be included about the appreciation of each individual training episode, or a question whether the received SD training helped to overcome serious SD events. Alternatively, it may be interesting for future studies to use an event contingent recording procedure, or diary design, in which pilots record immediately after a flight whether they experienced any kind of SD illusion, together with the associated flight safety risk. Such (more) objective and real-time data could give a clearer picture of experienced SD and better evidence of transfer of training. Still, it cannot be excluded that pilots sometimes remain unaware of being disoriented (Type I SD), and unknowingly attribute an event to a technical failure. Also, pilots could be afraid to describe SD experiences or the severity of them, because the incident was not reported, or they are afraid that reporting the experience in the questionnaire may get them in trouble. The result of this is that, even with a recording procedure, SD will be underreported (reporting bias).

Today's technological advances make it possible to more objectively measure SD experiences, and assess how pilots solve problems with SD during simulator training. In a recent study, the flight data from an SD simulator were used to objectively assess the effect of the Coriolis illusion and the somatogyral illusion on pilots' SD.[5] A similar strategy was used in a recent case report to identify a pilot experiencing the rare giant hand illusion during training.[10] The use of simulator data may also improve training through development or more personalized learning trajectories.

Finally, it is interesting to note that the SD training program was developed by the RNLAF in response to a relatively high number of SD-related mishaps which happened after the introduction of the F-16 in the 1980s. Currently, the F-16 is being replaced by next-generation platforms, such as the F-35. This transition may create new SD risks. For example, next-generation platforms will be equipped with new sensor technologies and data linking capabilities, which may affect the pilot's workload and attention, both important factors in relation to SD.[17,18] Therefore it is important to evaluate whether next-generation platforms introduce new, maybe unknown, SD risks which should be included in the SD training.

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Authors and affiliations: Helena J.M. Pennings, Ph.D., Esther A. P. B. Oprins, Ph.D., Mark M. J. Houben, Ph.D., and Eric L. Groen, Ph.D., TNO, Soesterberg, The Netherlands; Hans Wittenberg, B.Ed., Center for Man in Aviation, Royal Netherlands Air Force, The Netherlands; and Eric Groen, Ph.D., Cranfield University, United Kingdom.

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