Selective Auditory Attention and Spatial Disorientation Cues Effect on Flight Performance

Rafał Lewkowicz; Paweł Stróżak; Bibianna Bałaj; Piotr Francuz; Paweł Augustynowicz

INTRODUCTION: The auditory system is not as heavily involved in the pilot's spatial orientation as the visual and vestibular systems; however, it plays a significant role in the cockpit for communication and warning information. The aim of this research was to investigate the combined effect of selective auditory attention and simulator-induced spatial disorientation (SD) cues on pilots' flight performance. We hypothesized that the flight performance in both disoriented and oriented flight profiles would be impaired by selective auditory attention.

METHODS: Using an SD simulator, 40 male military pilots ($M = 31.9$; $SD = 7.41$) were exposed to 12 flight sequences, where 6 contained a SD-conflict, 3 with motion illusions and 3 with visual illusions. The pilots performed a duration discrimination task (DDT) involving sound stimuli while completing these profiles under SD-conflict and nonconflict conditions.

RESULTS: In five flight profiles tested, the DDT and SD cues increased the pilots' cognitive workload, adversely affecting their flight performance. In the approach and landing profiles involving visual illusions, significant differences between the control and DDT groups were found for both nonconflict and SD-conflict flight sequences, whereas differences were only significant between nonconflict and SD-conflict flights for the two vestibular SD profiles.

DISCUSSION: The results obtained partially support our hypothesis that performing the DDT, even in the absence of SD-conflict, significantly affects pilots' flight performance. In some cases, despite the large increase in cognitive workload, pilots did not activate the "posture first" principle. Pilots should be trained not to respond to auditory stimuli until they have recovered their spatial orientation.

KEYWORDS: flight illusions, spatial orientation, auditory system, selective attention.

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In order to counteract spatial disorientation (SD) in flight, several methods have been developed. These include visual, vestibular, auditory, somatosensory, and multisensory countermeasures.[19] Despite this, SD remains a common phenomenon and still presents a threat to flight safety.[8] In most cases, SD is not recognized by the pilot, making research and analysis of this phenomenon extremely difficult.[23] However, study of the tendency of humans to lose their spatial orientation remains under investigation.[24] SD can directly affect flight control and indirectly impair the pilot's cognitive performance,[10,31] which, in turn, reduces flight effectiveness. Some SD studies have suggested that experiencing a state of SD may lead to impaired cognitive function[9,27] and psychomotor performance.[16]

In the case of SD, regaining balance and orientation is a priority for the human cognitive system. Therefore, all available mental resources are directed to this purpose and withdrawn from any other concurrent tasks. This is a specific priority-setting mechanism that can be understood in the light of the "posture first" principle.[1] When disoriented, the pilot's attention should be focused on the sensory aspects of the situation in order to regain stability. Furthermore, his/her interpretation of instruments or radio communications, as well as accuracy of judgments and precision of flying maneuvers, will be impaired. Although the "posture first" principle has a high priority, aircraft pilots must still divide their attention across a wide range of sensory inputs. To help pilots cope with this, they

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employ selective attention. When confronted with two or more simultaneous tasks, aircraft pilots have to divide their attention to attend to one of these tasks while ignoring the other. From a selective attention perspective, flying an aircraft is a complex perceptual information processing task that calls for the perception, identification, processing, and adequate response to pertinent information, including visual, auditory, vestibular, and tactile information, among others.

An aircraft cockpit contains many different objects that compete for cognitive resources due to the limited processing capacity of the visual system. Therefore selective attention to one part of the visual field comes at the cost of neglecting other parts. The competition among multiple objects can be biased by both bottom-up sensory-driven mechanisms and top-down influences, such as selective attention, which has relevance for the proper functioning of human's spatial orientation system. Pessoa et al.[21] indicate that although, this competition is ultimately resolved within the visual cortex, the source of top-down biasing signals likely derives from a distributed network of areas in frontal and parietal cortex. Based on the fMRI studies[21] they reveal that biasing signals due to selective attention can modulate neural activity in the visual cortex not only in the presence but also in the absence of visual stimulation. Ungerleider and Mishkin's[29] concept of the biased competition model of attention implies that once attentional resources, are depleted, no further processing is possible.

It is worth mentioning that our ability to multitask is limited by the prefrontal cortex. Dux et al.[7] note that in contrast to perceptual and motor stages of information processing for multiple tasks that can proceed in parallel (e.g., visual perception and flight control), other information-processing tasks (e.g., cockpit for communication) reflect a central bottleneck. The bottleneck reflects the fact that a serial queuing of response selection occurs when multiple tasks involve overlapping processes.[20] These bottlenecks limit both what we can perceive and what we can act on in multitask settings. Although perceptual and response limitations are often attributed to independent information processing bottlenecks, it has recently been suggested that a common attentional limitation may be responsible for both.[22] It is possible to speculate that an information-processing deficit involving such a bottleneck would simultaneously increase the costs of distraction and facilitate the ease with which distractions could be ignored.

In view of the visual dominance over the vestibular system, the auditory system is not as heavily involved in self-orientation.[5] However, the auditory system plays a significant role in the cockpit for communication and warning information. Auditory ergonomics seems to be a workable countermeasure, especially for vestibular SD. It gives an advantageous way to decrease pilot workload and reduce reaction times while also giving the pilot spatial orientation cues. Auditory cues in the cockpit have long been used to support the spatial orientation of the pilot, mostly in the form of single frequencies and voice communications given monaurally.[5] Lyons et al.[18] investigated the effect of an acoustic orientation instrument that displayed airspeed as a sound frequency (repetition rate), vertical velocity by amplitude modulation rate (increase shown by increased pitch) and bank angle by right/left lateralization (louder signal on the side that was in the same direction as the bank). This display was presented to pilots using earphones after they had processed the auditory signal to map the actual aircraft flight data.

Studies of selective auditory attention often show that people pay little attention to irrelevant tasks, except when the voice transmitting the ignored message changes from male to female (the emergency warnings in modern aircrafts have female voices) or when the ignored message involves the name of the listener.[13] For example, when the pilot is concentrating on the task of flight control, he/she will tend to respond to a communication or radio call which involves his/her call sign.

The above-mentioned knowledge that SD can impair the cognitive performance of pilots while flying is obviously important for aviation. However, the way in which cognitive processing can impair pilots' spatial orientation and pose threats to flight safety are also interesting.

The aim of this research was to investigate the combined effect of selective auditory attention and simulator-induced SD cues on the pilots' flight performance in a specially designed flight simulator. Selective auditory attention was imposed by the duration discrimination task (DDT) based on measurement of the subject's response to the sound stimuli (tones). The DDT is well-established measure of selective attention[25] which tracks fundamental cognitive processes that are engaged during complex human behaviors, including piloting an aircraft. We hypothesized that the flight performance in both disoriented and oriented (control) flight profiles would be impaired by selective auditory attention. We were interested in determining whether the DDT could mitigate or enhance the impact of SD cues on flight performance. It was expected that pilots performing DDT would become more disoriented than pilots who focused only on flight performance (control group).

In our investigation, we measured pilots' flight performance during a variety of disorientation conditions consisting of both visual and vestibular illusions. We did this as part of a larger study that investigated overall flight performance, cognitive performance, and instrument scanning.

METHODS

Subjects

Forty healthy male Polish military aviators volunteered to participate in the study. The subjects were randomly divided into two study groups: control group (20 pilots; age $M = 31.6$; $SD = 8.22$; flight experience range 100–3600 h), and experimental group (20 pilots; age $M = 32.3$; $SD = 6.6$; flight experience range 380–2900 h). All pilots were active-duty, with no experience with simulator-induced SD. All served in an off-duty function during the testing, and were paid for their participation. They had normal visual acuity and were screened to rule out any auditory or vestibular disorders. In addition, they were not permitted to be currently taking any psychoactive medication (e.g., antihistamines, antidepressants, sleep aids, etc.). All pilots reported normal sleep patterns.

The protocol was approved by the Ethics Committee of the Institute of Psychology at John Paul II Catholic University of Lublin, Poland. An informed consent form was completed by each subject prior to beginning the experiment.

Equipment

This study was conducted using an integrated physiological trainer (Gyro-IPT; Environmental Tectonics Corporation, Inc., Southampton, PA), located at the Military Institute of Aviation Medicine in Poland. This SD simulator has a three-axis (roll ± 30°, pitch ± 15°, and continuous 360° yaw) motion base. It also has a one-channel, high-resolution, noncollimated out-the-window visual display, with a total field-of-view of ~28° vertically by ~40° horizontally (when viewed from the design-eye position). The simulator is equipped with a data acquisition system so that flight data in real-time from the subject's flight profile status are readily recorded for analysis. A one-way visual and two-way audio communication system allowed the subject to interact with the investigator, as well as allowing the investigator to continuously monitor the subject. The closed-loop control capability creates an interactive environment in which the pilot maintains control of the simulator while being exposed to a number of vestibular and visual illusions. For ease of experimental design in inducing the desirable disorientation scenario, the Gyro-IPT motion base can also be programmed to change its position independent of the pilot's control (stick) inputs. Unlike a normal flight simulator, the Gyro-IPT allows the operator to program sustained and transient motions in concert with the motions generated by the simulation model (the TS-11 Polish jet trainer aircraft). The Gyro-IPT is particularly recommended for the training of pilots under induced SD conditions.[6]

The simulator has several manufacturer-defined programmed disorientation profiles within the software. The strength of the disorienting stimuli in the selected profiles were evaluated based on conclusions from previous studies.[6,15] These SD conflicts simulated three well-known visual illusions and three well-known vestibular illusions.[23] These illusions were implemented in the six flight profiles. The three visual illusions included the following:

1. 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;
2. circle-to-land procedure (C-T-LP) with nighttime constant shape illusion (created by an up-sloping runway), an illusion associated with the constancy of shapes expected by the pilot; and
3. straight-in approach (S-IA) with nighttime constant size illusion (created by a narrower runway), an illusion associated with the constancy of sizes expected by the pilot.

The three vestibular illusions included the following:

1. straight and level flight after left turn (S&LFALT) with daytime somatogyral illusion, a profile that induces the false sensation of rotational motion (or lack of rotational motion) resulting from erroneous perception of the strength and direction of actual rotation;
2. right banked turn (RBT) with daytime Coriolis illusion, which demonstrates the effect of cross-stimulation of semicircular canals that occurs when head is moved during fixed rotational motion; and
3. straight and level flight after right turn (S&LFART) with nighttime leans illusion, whereby perception of leaning position is disturbed due to the limited sensitivity of vestibular organs.

These illusions represent a wide variety of mechanisms that can induce SD and are regarded as common and serious threats in aviation.[23]

To ensure that pilots experienced the visual conflicts, they were required to fly without an attitude indicator (ADI) during the sloping cloud deck interval and to perform a visual approach and landing on the illusory runway without specific instrument glide path information.

Each flight profile was presented in two conditions, the disorientation condition (conflict flight), in which visual or vestibular disorientation cues were present, and the control condition (nonconflict flight), in which these specialized disorientation cues were absent. The remaining parts of the flight profiles were kept the same for the control and disorientation conditions. This enabled us to directly compare flight performance parameters between the control and disorientation conditions for each flight profile. The general description of the flight profiles, including the specifications of disorientation cues, are given in **Table I**.

The selective auditory attention involved a DDT with sound stimuli (tones). These stimuli were presented binaurally using headphones. The characteristics of the acoustic stimulus was defined based on previous the study.[26] Half of the stimuli were 1000 Hz sine wave tones of a short duration (50 ms), and the other half were 1000 Hz sine wave tones of a long duration (80 ms). The duration of both tones included 5 ms of rise and fall tones. Stimulus onset asynchrony was selected randomly from a range between 1600 and 2600 ms. The sound pressure level was set to 88.0 db [A weighted; db(A)].

The subjects had to discriminate between short and long tones by pressing one of two buttons located on the control stick in the cabin. The correspondence of the buttons to the short and long tones was counterbalanced, such that half of the subjects had to press the left button for short tones and the right button for long tones, with this order reversed for the other half of subjects. The stimuli were presented continuously throughout each flight profile, with the restriction that the tones were not presented at the same time as audio instructions. The distribution of short and long tones was pseudorandom, such that no more than four identical stimuli could be presented in a row. The total number of sound stimuli presented to subjects differed across flight profiles and across subjects due to the differences in time required by each subject to actually complete each profile. The 50/50 balance

Table I. The General Description of Six Flight Profiles.

PROFILE	DURATION OF PROFILE	DURATION OF DISORIENTATION CUES	DISORIENTATION CONDITION	CONTROL CONDITION	FLIGHT INSTRUMENT MANIPULATION
S&LF	190 s	30 s	Slope of cloud deck tilted 10° rightward from 19,000 ft to 21,000 ft	No tilt of the cloud deck	From 130 s to 160 s blackout of attitude director indicator
C-T-LP	166 s or runway level achieved	50 s	Nighttime runway up-sloped 10°	No up-sloped runway	None
S-IA	90 s or runway level achieved	30 s	Nighttime runway narrowed in width from 300 ft to 150 ft	Runway 300 ft wide	None
S&LFALT	290 s	Up to 30 s	76° $\cdot$ s^{-1} of sustained yaw (at +0.4° $\cdot$ s^{-2}) stop yaw rotation in 217 s of flight (at -15° $\cdot$ s^{-2})	No programmed acceleration stimulus	None
RBT	210 s	Up to 30 s	70° $\cdot$ s^{-1} of sustained yaw (at +0.5° $\cdot$ s^{-2}) stop yaw rotation in 173 s of flight (at -2° $\cdot$ s^{-2})	No programmed acceleration stimulus	None
S&LFART	150 s	Up to 30 s	68° $\cdot$ s^{-1} of sustained yaw (at +1° $\cdot$ s^{-2}) stop yaw rotation in 84 s of flight (at -4° $\cdot$ s^{-2})	No programmed acceleration stimulus	From 92 s to 105 s blackout of attitude director indicator

between short and long tones was held constant for each flight profile and each subject.

Procedure

The subjects were briefed on the study protocol and performed a training session to become acquainted with the operational characteristics of the simulator as well as the research procedure. This was also indented to minimize the impact of individual differences 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. They were given 5–10 min of "free-flight" including the basic elements of pilotage with the approach-to-landing maneuver. Sound stimuli were simultaneously presented to subjects in the experimental group to familiarize them with the DDT. They were required to discriminate between short and long tones as quickly and accurately as possible. If a pilot performed all flight maneuvers in the training session within the predefined limits,[17] he could participate in the main part of the study. For pilots in the experimental group (DDT group), they were able to participate in the main experiment if they had accurately detected at least 70% of sound stimuli.

Subjects performed a selective attention task while completing the flight profiles. The order of the six flight profiles in the control (nonconflict flight) and disorientation (conflict flight) conditions (a total of 12 profiles) was randomly assigned for each subject. The pilots were not aware of the order of the flight profiles and which were conflict flights. Both the control (20 pilots) and DDT (20 pilots) study groups were exposed to the same flight profiles. Short breaks (about 2 min) were given between the profiles, during which the cabin of the simulator remained closed. Before and after simulator exposition (12 flight profiles) participants completed a Polish version of the Simulator Sickness Questionnaire (SSQ).[4] The SSQ is widely used in studies on SD to rule out the influence of simulator sickness on flight performance. The SSQ consists of 16 symptoms regarding motion sickness that can be caused in a flight simulator, which are rated in terms of severity and then are summed to yield three subscale scores (a nausea score, an oculomotor score, a disorientation score), and a total score. Mean scores of SSQ that were obtained after completing all flight profiles were referred to the scoring criteria of SSQ that reflect the severity of simulator sickness symptoms.[28] The main experiment lasted for approximately 60 min. Afterwards, subjects were paid and debriefed.

Subjects were instructed that their primary task was to complete all flight profiles according to the flying instructions given. Pilots in the experimental study group were asked to simultaneously perform a DDT with the sound stimuli. The pilots focused their attention solely on correctly performing these tasks, and did not report their sensations. Responses to the sound stimuli (reaction time and correctness) and flight parameters were recorded. All pilots completed the study at the same time of day (between 10:00 and 16:00).

During the flights, objective measures of flight performance based on flight parameters (altitude, bank or vertical velocity) were assessed. For all the flight profiles in the disorientation condition, only specific flight parameters (described below) were analyzed 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 analyzed. The following flight performance measures were recorded:

1) S&LF, measured as the amount of bank for 30 s after the time at which pilots attained their command heading of 060 and altitude of (to level off) 20,000 ft (a sloping cloud deck was visible in the conflict flights). The pilot experienced either a rightward-rotated cloud deck (leading to a perceptual conflict of left-bank and right-bank control inputs, expressed as a positive value), or no bank (in the nonconflict trials);
2) C-T-LP, measured as the vertical velocity for 30 s after the pilot began a visual approach to landing (an up-sloping runway was present in the conflict flight). The pilot's expected sensation is a feeling of being too high, leading to a steeper glide slope and a corresponding increase in vertical velocity;

3) S-IA, measured as the vertical velocity for 30 s after the pilot began a visual approach to landing (a narrower runway was present in the conflict flight). The pilot's expected sensation is feeling too high, leading to a steeper glide slope and a corresponding increase in vertical velocity;
4) S&LFALT, measured as the amount of bank for 15 s after the pilots attained their command straight and level flight. In the conflict flights, the cessation of sustained turning occurred upon rollout from a leftward-turn. The pilot is expected to perceive yawing or even leaning in the opposite direction to the turn;
5) RBT, measured as the amount of bank for 15 s after the command to tilt the head in pitch and roll, which should have caused an immediate rolling and pitching sensation due to the cross-coupled Coriolis motion caused by simulated cabin yaw rotation during the conflict flight; and
6) S&LFART, measured as the amount of bank for a 15-s period during which the attitude indicator was not displayed. In the conflict flights, the cessation of sustained turning occurred upon rollout from a rightward-turn. The pilot is expected to perceive yawing or even leaning in the opposite direction to the turn.

In the C-T-LP and S-IA profiles, we focused on vertical velocity even though the glide-path angle is an important parameter during the approach to landing. We assumed vertical velocity to be an appropriate parameter indicating the occurrence of an illusion in these profiles (illusions of constant shape and size of the runway).

Statistical Analysis

A mixed analysis of variance (ANOVA) with repeated-measures was conducted to investigate the impact of the DDT on flight profiles with induced SD. In the analysis, the conflict type represented the within-subject variable (nonconflict vs. conflict flight) and the experimental manipulation represented the between-subject variable (control vs. experimental, DDT group). An ANOVA was performed on the specific flight parameters recorded, and was performed separately for each flight profile. The assumption of normality was tested using the Kolmogorov-Smirnov test. All ANOVA analyses were accompanied by Huynh-Feldt adjustments for violations of sphericity (when deemed appropriate according to Mauchly's test of sphericity), and were corrected where needed. A significance level of $P < 0.05$ (after correction for multiple comparisons) was considered statistically significant. The effect size was estimated using the partial η^2 statistic. Simple effect comparisons were performed with the Bonferroni correction. All analyses were conducted using IBM SPSS Statistics 17 statistical package. In the analysis, the time and correctness of the response to the sound stimuli were omitted. These data will be addressed in a future publication.

RESULTS

All 40 subjects performed 12 flights. All pilots from the experimental group performed the DDT and did not interrupt its execution. Therefore, we assumed that the pilots' cognitive workload was at the same level during the flight simulation.

In the control group the mean scores of SSQ symptoms were $M = 1.46$ ($SD = 2.51$) for the nausea subscale, $M = 3.41$ ($SD = 2.12$) for the oculomotor subscale, $M = 1.90$ ($SD = 1.63$) for the disorientation subscale, and $M = 2.25$ ($SD = 1.52$) for the total score. These scores of symptoms in the DDT group were $M = 1.88$ ($SD = 2.72$) for the nausea subscale, $M = 3.63$ ($SD = 2.42$) for the oculomotor subscale, $M = 1.81$ ($SD = 1.52$) for the disorientation subscale, and $M = 2.44$ ($SD = 1.55$) for the total score. According to the scoring criteria of SSQ,[28] these are negligible symptoms of simulator sickness, and they do not differ significantly between groups.

Due to technical issues and malfunctions of the apparatus, no full set of data was collected. The number of pilots (N) who participated in the recorded flight is shown in **Table II**, in addition to differences in performance during the conflict vs. nonconflict flight in the control and experimental groups. Table II presents the average (M) and standard error of the mean (SEM) values for the different flight profiles. The bank angle in the S&LF, S&LFALT and S&LFART flight profiles was measured when pilots were supposed to maintain wing-level flight (while the sloping cloud deck was visible or during the postrotatory illusion in the conflict flights), and in RBT during tilting of the head in pitch and roll when pilots were supposed to maintain a 30° bank (Coriolis illusion was present in the conflict flight). The vertical velocity in the C-T-LP and S-IA flight profiles was measured when pilots were instructed to maintain visual approach along with glide slope during landing (an up-sloping or narrower runway was present in the conflict flight). The raw bank averages are presented as absolute values because we were merely interested in whether bank was increased or decreased due to the presumed illusion.

In **Table III**, the results of ANOVA tests of within-subject effects (nonconflict vs. conflict flight) and between-subject

Table II. Mean and Standard Error of Mean Obtained in Nonconflict and Conflict Flight Profiles.

FLIGHT PROFILE AND FLIGHT TYPE	CONTROL			DDT		
	N	M	SEM	*N*	M	SEM
S&LF	20	**[deg]**		20	**[deg]**	
Nonconflict		0.46	0.48		−0.68	0.26
Conflict		0.78	0.44		1.7	0.45
C-T-LP	19	**[ft/min]**		20	**[ft/min]**	
Nonconflict		−377.2	73.82		−97.9	21.06
Conflict		−919.4	90.08		−156.5	19.45
S-IA	20	**[ft/min]**		20	**[ft/min]**	
Nonconflict		−672.4	61.51		245.8	13.50
Conflict		−795	119.52		−203.5	15.94
S&LFALT	20	**[deg]**		20	**[deg]**	
Nonconflict		−0.93	0.77		0.08	0.17
Conflict		−0.2	0.27		−0.12	0.24
RBT	17	**[deg]**		20	**[deg]**	
Nonconflict		30.5	0.94		30.9	1.08
Conflict		27.2	1.71		23.45	3.35
S&LFART	18	**[deg]**		20	**[deg]**	
Nonconflict		0.68	1.46		1.8	0.59
Conflict		3.37	1.96		-2.32	2.11

N – number of subjects, M – mean value, SEM – standard error of mean

Table III. Tests of Within-Subjects Effects and Between-Subjects Effect.

		WITHIN-SUBJECTS EFFECTS (NONCONFLICT VS. CONFLICT FLIGHT)			BETWEEN-SUBJECTS EFFECT (CONTROL VS. DDT GROUP)		
FLIGHT PROFILE	df	*F*	*P*	η^2	*F*	*P*	η^2
S&LF	(1,38)	11.564	0.002	0.233	0.084	0.774	0.002
C-T-LP	(1,37)	41.491	<0.001	0.529	57.857	<0.001	0.61
S-IA	(1,38)	0.757	0.39	0.02	36.387	<0.001	0.489
S&LFALT	(1,38)	0.355	0.555	0.009	1.588	0.215	0.04
RBT	(1,35)	6.59	0.015	0.158	0.645	0.427	0.018
S&LFART	(1,36)	0.285	0.537	0.008	1.455	0.236	0.039

effects (control vs. DDT group) are presented. The within-subject analysis showed a significant effect of flight type (nonconflict vs. conflict flight) in the S&LF ($P = 0.002$), C-T-LP ($P < 0.001$) and RBT ($P = 0.015$) profiles. The between-subject analysis showed a significant effect of group type (control vs. DDT group) only in the C-T-LP ($P < 0.001$) and S-IA ($P < 0.001$) flight profiles (Table III). A significant interaction between group (control vs. DDT group) and flight type (nonconflict vs. conflict) appeared in the S&LF [$F(1,38) = 6.635$, $P = 0.014$, $\eta^2 = 0.149$], C-T-LP [$F(1,37) = 26.893$, $P < 0.001$, $\eta^2 = 0.421$] and S&LFART [$F(1,36) = 6.334$, $P = 0.016$, $\eta^2 = 0.15$] flight profiles.

Fig. 1 shows the effect of DDT and the visual illusion cues on pilots' flight performance. Comparison of simple effects (Bonferroni test) in the visual illusion flight profiles (S&LF, C-T-LP and S-IA) showed that the differences between the control and DDT groups were statistically significant for both the conflict and nonconflict flights in C-T-LP ($P < 0.001$) and S-IA ($P < 0.001$) profiles, whereas the differences were statistically significant for the nonconflict flight only in the S&LF profile ($P = 0.047$). The differences between the conflict and nonconflict flights were statistically significant for the control group in the C-T-LP profile ($P < 0.001$) and the DDT group in the S&LF ($P < 0.001$) profile (Fig. 1).

In **Fig. 2**, the effects of DDT and the vestibular illusion cues on pilots' flight performance are presented. In these flight profiles (S&LFALT, RBT and S&LFART), comparison of simple effects (Bonferroni test) showed that there were no statistically significant differences between the control and DDT groups (between-subject effects), as seen in Table III. The differences between the conflict and nonconflict flights were statistically significant only for the DDT group in the RBT ($P = 0.013$) and S&LFART ($P = 0.033$) profiles.

DISCUSSION

The results showed that the DDT and SD cues employed in our study certainly increased the pilots' cognitive workload and adversely affected flight performance in five profiles. In this study, 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 DDT and SD on flight performance, therefore, we refrained from formulating predictions regarding in which flight profiles subjects would be most susceptible to SD. In this way, the results for each flight profile were analyzed separately.

In the control group, the up-sloping runway (C-T-LP) was the only flight profile to yield a significant effect on the flight performance (Fig. 1). Thus, it seems that subjects suffered from unrecognized or incapacitating disorientation in this particular profile, whereas in other flight scenarios they were either not disoriented at all or the disorientation was recognized by the participants allowing them to control the aircraft properly. An alternative explanation is that for the C-T-LP profile the simulator can effectively induce SD.

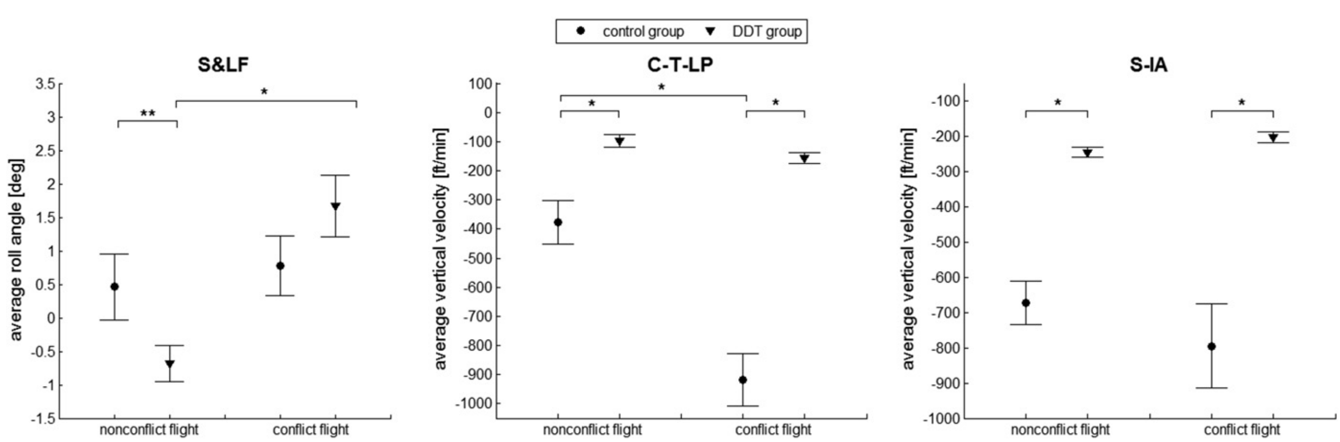

Fig. 1. The effect of DDT and the visual illusion cues on pilots' flight performance. The error bars represent the SEM; * $P < 0.001$, ** $P < 0.05$.

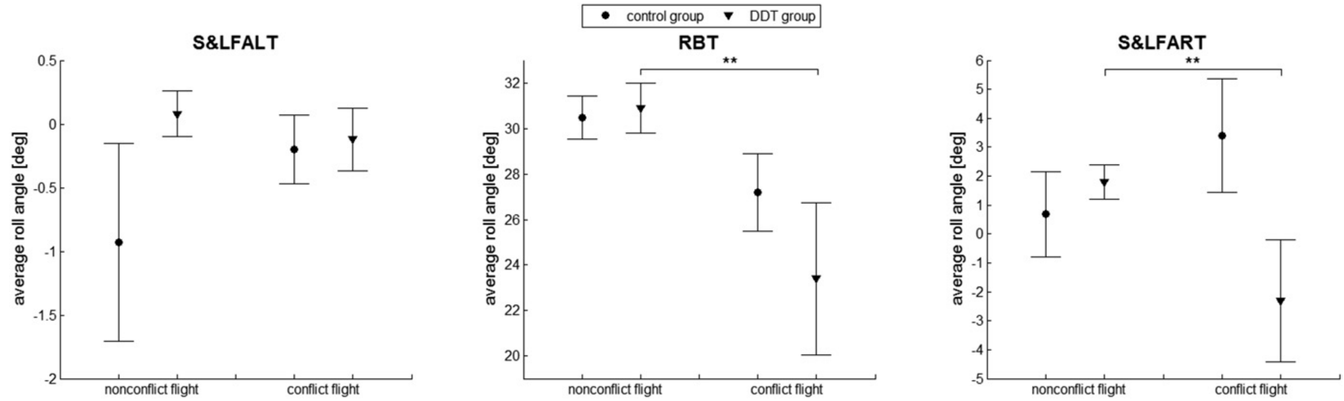

Fig. 2. The effect of DDT and the vestibular illusion on pilots' flight performance. The error bars represent the SEM; ** $P < 0.05$.

For the C-T-LP and S-IA profiles, we found significant differences between group type (control vs. DDT) in both the nonconflict and SD-conflict flights (Fig. 1). The cognitive load exerted by the DDT on the flight performance in these profiles should be larger in the disorientation conditions than in the control conditions. However, the flight performance (average vertical velocity) among subjects in the DDT group were similar. This indicates that for both nonconflict and conflict flights, the DDT condition significantly affects pilots' spatial orientation. The lack of difference between nonconflict and conflict flights in the DDT group seems to be interesting, and worth explanation.

The above-described profiles (C-T-LP and S-IA) have a common feature, the visual illusions (shape and size illusions, respectively) associated with nighttime approach and landing. In these profiles, a pilot controls not only the flight velocity and orientation relative to the runway threshold, but also the altitude and/or vertical velocity. An additional cognitive load due to DDT resulted in pilot errors that concerned improper vertical velocity (velocity was changed contrary to the stimulus causing the illusion). As mentioned before, this situation appeared independent of the SD conflict (Fig. 1). This finding is representative of phases of flight with a high cognitive load, such as approach and landing maneuvers, due to the growth requirements of piloting, thereby reducing the pilot's cognitive reserve.[34] Approach and landing also represent a highly stressful situation that can impair the pilot's cognitive abilities. Task saturation from psychological stress may impair cognitive performance as a result of disorienting situations. Bednarek et al.[2] found that the cognitive predictors of an enhanced effect of SD for visual illusions included attention switching, selective attention, updating efficiency and working memory capacity.

A possible alternative explanation for these findings (C-T-LP and S-IA profiles) is that the competition among multiple objects (flight instruments and runway) can be biased by both bottom-up sensory-driven mechanisms and top-down influences, such as selective attention, which has relevance for the proper functioning of human's spatial orientation system. Pessoa et al.[21] indicate, that although this competition is ultimately resolved within the visual cortex, the source of top-down biasing signals likely derives from a distributed network of areas in frontal and parietal cortex. A further possible explanation for these results might be the automatic pilot's tendency, under a higher cognitive workload level, to reduce the steepness of the glide-path.

Taking the above into consideration, we suggest that the DDT greatly impairs the pilot's visual attention, and he/she may not have sufficient cognitive performance to evaluate their flight altitude based on information from outside of cabin and the altitude indicator. On the one hand, Wickens[33] states that different resources are employed for auditory input than for visual input, whereas on the other, the above assumption can be confirmed by recent studies[3,12] which state that sound can suppress visual perception. Therefore, we assume that pilots performing the DDT may not have perceived the visual SD stimuli, and consequently, the visual illusions may not have appeared.

We can conclude that the DDT employed in our study certainly increased the cognitive workload and affected flight performance, even in the absence of an SD conflict (visual illusions). This is also confirmed by the results of the S&LF profile (Fig. 1), as the DDT caused a statistically significant increase in the difference in heading for both the nonconflict and DDT groups. These results support our hypothesis that the flight performance in both disoriented and oriented (control) flight profiles associated with the visual illusions would be impaired by selective auditory attention.

The above observation suggests that, in the case of flight profiles associated with vestibular illusions that do not involve approach and landing maneuvers, the DDT should not significantly affect the pilot's flight performance. However, this was not the case for two (RBT and S&LFART) of the three vestibular SD profiles. These results indicate that the attention required to interpret flight instruments was compromised by sensorial stimulation (e.g., DDT), specifically for reestablishing orientation and stability. Although we did not include the DDT results in the analysis, according to the "posture first" principle,[14] if a pilot perceives a false sensation of motion, we expect that he/she would interrupt DDT execution to improve his/her spatial orientation. Interestingly, however, a decrease in flight performance accuracy was found for these profiles under DDT conditions. This may be explained by the subjects being oblivious to disorientation, devoting their attention to the DDT, or that the task itself may have impaired their visual perception.[3,12] Another possible explanation for this visual impairment is that in the case of the S&LFALT and RBT profiles a nystagmus may also occur.

It is worth noting that in addition to performing two distinct tasks (visual and auditory tasks), pilots had to simultaneously perform flight control and respond to sound stimuli (by pressing the corresponding button on the stick control). Wickens[32] reported that the same resources are engaged for these response activities (control manipulation and switch activation). As a result, performing two concurrent tasks requires more effort, potentially reducing the accuracy. This could also explain, in part, the results obtained in the RBT and S&LFART profiles.

In the case of the S&LFALT profile, the cognitive load exerted by the DDT did not significantly affect the flight performance. Moreover, impairment of the flight performance should be greater under disorientation conditions than control conditions. The lack of these effects can be explained by the fact that SD was probably recognized by the pilots. However, if SD is recognized, it increases the cognitive load of pilots, forcing them to divide their attention between coping with SD and performing a cognitive task. As a result, their performance of other concurrent task could decline.[11] In the current study, a decline in flight performance was not observed. One possible explanation could be that a decline in DDT performance did actually occur, but we are unable to confirm this as DDT results were not included in the analysis. However, if we assume that these results are accurate, an alternative explanation can be proposed. For this, the theory of perceptual attention is applied, which treats the visual or auditory system as a limited resource to be distributed among two or more competing stimuli. This is related to the concept of multitasking, in which more complex resources must be allocated to tasks. Resource theory is typically based on the data obtained in dual-task experiments, such as that performed in our study, in which subjects perform two concurrent tasks while their performance in each task is measured. The multiple resource theory[33] states that different resources are employed for auditory input than for visual input, as well as for voice responses than for manual responses. Thus, we can presume that the pilots were able to allocate sufficient encoding resources to flight instrument interpretation in the S&LFALT profile while simultaneously allocating adequate responding resources to perform the DDT.

It is unclear, however, why the DDT and SD cues did not have a greater effect on flight performance, especially for the S&LFALT, RBT and S&LFART profiles in the nonconflict flight. A possible explanation for this could be that DDT is a measure of selective attention, a cognitive process that is relatively fast and automatic, and its impact might not be visible in some of the flight scenarios.

Another issue is that different flight profiles exert different requirements on the primary task of piloting the aircraft, as well as on the concurrent cognitive tasks. For some of the flight profiles in which flying efficacy is extremely important (e.g., landing in the C-T-LP and S-IA profiles), it seems necessary to withdraw attention from any concurrent task the pilot is performing. For some other flight profiles (e.g., S&LFALT, RBT and S&LFART), pilots can allocate more resources to other tasks because deviations from the given flying parameters are relatively harmless. Future studies should account for factors that possibly interfere with the influence of the cognitive workload on flight performance and SD. Moreover, it is not clear whether similar variations in flight performance would occur if different flight scenarios or illusions are used.

In addition to the above-mentioned strengths of the present study, some limitations should also be considered. Firstly, although the flight profiles employed in our study included basic flight maneuvers, we realize that despite being familiar with these before the experiment, pilots could have obtained various levels of accuracy of flight performance. This is especially true in the context of the wide variability in age and flight experience of our participants, which can be considered the main cause of individual differences in the pilot's vulnerability to SD.[24] Secondly, the effect of selective auditory attention and SD cues on flight performance were somewhat complex in that older, more experienced pilots would be more likely to recognize the SD conflicts. Webb et al.[30] indicated that recognition of SD increases a pilot's workload during a flight. A high workload task would demand more resources than are available, thus performance on the task would decline.[11] Consequently, there is the potential for the pilot's workload to confound the effects of DDT on flight performance in SD-conflict and nonconflict flights. It should be noted that SD does not always increase the workload. In unrecognized SD, such as controlled flight into terrain, the pilot is oblivious to the disorientation. Some aviation-based studies have demonstrated that cognitive processing is negatively affected during SD.[9,10,27] Therefore, it is not possible to clearly determine whether the impaired flight performance is due to cognitive decline associated with the illusion or as a consequence of performing the DDT.

To sum up our research, despite the above-mentioned limitations, this study contributes to our understanding of the combined effects of selective auditory attention and simulator-induced SD cues on the spatial orientation of pilots.

The results obtained partially support our hypothesis that performing the DDT, even in the absence of SD-conflict, significantly affects pilots' flight performance. It is somewhat surprising that in some cases, despite the large increase in cognitive workload, pilots did not activate the "posture first" principle, whereby all mental resources are directed to regaining orientation when it is lost. We believe that subjects were probably oblivious to disorientation in these cases, and instead devoted their attention to the DDT.

Moreover, we found that the DDT mitigates the impact of SD cues on flight performance (probably due to the pilot's attention being distributed in a different manner such that visual illusions did not appear) in the C-T-LP, S-IA profiles, whereas in the S&LF, RBT and S&LFART profiles, the DDT was found to intensify the impact of the employed SD cues.

Based on the above-mentioned conclusions, we present a few key findings and recommendations. Firstly, in aviation settings, secondary tasks (DDT) require massive conscious processing, especially when relying on flight instruments. Secondly, pilots are not always aware of altered flight parameters, which may indicate that they have lost spatial orientation. However, when problems in maintaining proper flight performance arise, pilots should be trained to not respond to external stimuli (e.g., auditory, visual) until they have recovered their spatial orientation. Future studies are needed to confirm, and presumably extend these effects to other flight scenarios, while better controlling for confounding variables.

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