Auditory Verbal Working Memory Load Effects on a Simulator-Induced Spatial Disorientation Event

Rafał Lewkowicz; Paweł Stróżak; Bibianna Bałaj; Piotr Francuz

INTRODUCTION: Working memory is an essential executive function for flying an aircraft and its limitations may jeopardize flight safety. This function is particularly critical when pilots have to struggle with spatial disorientation (SD) cues. This research aimed to assess the combined effect of the auditory *N*-back task (NBT) and simulator-induced SD cues on pilots' flight performance.

METHODS: Using an SD simulator, 39 male military pilots (control $N = 20$; age $M = 31.6$; $SD = 8.22$, experimental $N = 19$; age $M = 26.9$; $SD = 8.67$) were exposed to 12 flight sequences, where 6 contained an SD conflict—3 with vestibular illusions and 3 with visual illusions. Additionally, the pilots from the experimental group were asked to perform an auditory NBT involving sound stimuli (the sequential letter memory task) as they performed during oriented and disoriented flight conditions.

RESULTS: Pilots' flight performance from the NBT group were significantly worse than the control group in the approach and landing profiles involving visual illusions (for both nonconflict and conflict flight), and in the profile involving the false horizon illusion (only for the conflict flight). No increase in a pilot's susceptibility to SD was observed with any other profiles.

DISCUSSION: The current study provides support that pilots' cognitive workload can negatively impact flight performance. Pilots are not always aware of altered flight parameters, which may indicate that they have lost spatial orientation, mainly as a result of visual illusion. If problems occur in maintaining proper flight parameters, pilots should direct all available mental resources to regain their orientation and withdraw from any other parallel tasks.

KEYWORDS: spatial orientation, flight illusions, flight performance, dual task.

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A pilot's loss of spatial orientation, commonly described as spatial disorientation (SD), remains a common phenomenon and still poses a threat to flight safety.[7] Misleading acceleration stimuli or visual references (a vertical or horizontal position in relation to the ground, water, or obstacles) during flight are one of the leading causes of SD. The fact that the flight crew are not effectively monitoring the aircraft's flight parameters could indicate loss of their spatial orientation. SD is a typical physiological response to an abnormal force environment and it can affect experienced pilots as well as novices.

Spatial orientation is a crucial prerequisite for maintaining situation awareness and cannot exist unless the appropriate visual cues are available. While SD is likely to be an essential contributor to loss of situation awareness and human error, the interaction is complicated because acceleration stimuli to the vestibular organs degrade a person's well-being and performance even when SD is not experienced.[16]

Aviation incident and accident data suggest that SD mishaps and loss of situation awareness incidents frequently occur under similar conditions; namely, when there is a failure in perceiving the position (or motion) of the aircraft correctly. Such outcomes usually occur under conditions of distraction with other flight tasks or high workload. However, while distraction

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and workload are very significant accident contributors, they do not usually cause accidents in isolation from other factors. Instead, distraction becomes hazardous because one's attention is drawn away from cues concerning aircraft position while one's aircraft is flying close to the earth or other significant objects.

Lawson et al.[16] noticed that the problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body cues concerning orientation, which in the environment of flight are not veridical. In other words, they indicated that the problem of SD in flight is not caused merely by the formation of an incomplete mental model due to attentional limitations; instead, the problem is the creation of an incorrect, but persuasive, mental model due to the subconscious tendency of humans to rely upon vestibular orientation cues.

In most cases, SD is not recognized by the pilot, thus making research and analysis of this phenomenon and SD mishaps difficult.[22] SD can directly affect flight control and indirectly impair the pilot's cognitive performance,[9,29] which, in turn, reduces flight effectiveness. While there has been much work devoted to understanding how SD cues affect cognitive function[10,27] and psychomotor performance,[15] the nature of the reverse relationship between these constructs is not well understood. Therefore, the way in which cognitive processing can impair pilots' spatial orientation and pose threats to flight safety seems to also be relevant.

This approach for studying the SD phenomenon is presented in this paper. It was also applied in our previous studies,[18,19] which contributed to our understanding of how additional cognitive workload may have an effect on the response of pilots to SD events. We examined pilots' flight performance under SD conditions induced by visual and vestibular illusions while piloting a specially designed flight simulator. These studies have shown whether a change detection flicker task (CDFT)[18] and a duration discrimination task (DDT)[19] involving visual and sound stimuli, respectively, have any adverse effects on pilots' flight performance. We found that both the CDFT and DDT certainly increased pilots' cognitive workload, affecting their susceptibility to SD, especially in the profiles associated with visual-origin illusions (the approach and landing maneuvers). It was observed that even in the absence of an SD conflict, these additional tasks in the same cases could also influence pilots' perception and significantly affect their flight performance.

On the other hand, the SD cues and the applied additional task (CDFT or DDT) did not have a more significant effect on flight performance, especially for the vestibular origin flight profiles. This observation seems to be consistent with the "posture first" principle, which states that when balance and orientation are disturbed, there is a natural tendency to revoke resources allocated to secondary tasks and direct them to regain orientation and stability.[12]

A possible alternative explanation for these findings is that because additional tasks are a measure of a cognitive process that is relatively fast and automatic, its impact might not be visible in the flight scenarios with vestibular illusions. Thus, it would be interesting to determine whether the influence of the SD cues on flight performance could be observed when a more complex cognitive process such as working memory is engaged.

The relationship between working memory and the pilots' flight performance in a flight simulator prior to and after sleep deprivation was examined by Lopez et al.[21] The researchers found that the Operation Span Task and Psychomotor Vigilance Test jointly accounted for 58% of the variance in flight performance, making them the main indicators for assessment of critical fatigue points and, also, showing that working memory can affect flight performance.

Different types of working memory load (i.e., the amount of information maintained in working memory) may have different effects on attentional selection depending on whether working memory load overlaps with mechanisms involved in target or distractor processing. A study on working memory and attention has shown that the visual attention can be top-down guided by working memory contents. Kim et al.[13] have examined whether the semantic match between working memory contents and distractors could capture attention, as well as the perceptual match. The authors concluded that concurrent working memory load does not always impair executive control; performance depends on how the contents of working memory and task-relevant information overlap.

Some studies indicate that visual[8] or auditory verbal[20] information held in the working memory can guide or capture attention during a visual search. This happens in a relatively automatic way, even when it is irrelevant and detrimental to the current task performance. Li et al.[20] demonstrated that the contents of verbal working memory would always capture attention at the earlier processing stage and could only be rejected at the later processing stage when the contents were aurally presented. Other studies have revealed that several factors such as message length[24] and complexity[28] affect the pilot's memory capacity necessary for following air traffic control instructions, as well as their ability to execute commands. Although the auditory system is not as heavily involved in human self-orientation,[4] it plays a significant role in the cockpit for communication and warning information. 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.[4]

This research aimed to investigate the combined effect of an auditory *N*-back task (NBT) and simulator-induced SD cues on pilots' flight performance in a specially designed flight simulator. The auditory NBT was imposed by the sequential letter memory task in which the subjects had to respond to the sound stimuli. In our investigation, we measured pilots' flight performance during a variety of disorientation conditions consisting of both visual and vestibular illusions.

We hypothesized that the flight performance in both disoriented (SD conflict) and oriented (control; nonconflict) flight profiles would be impaired by an auditory NBT. We were interested in determining whether the NBT could mitigate or enhance the impact of SD cues on a pilot's flight performance. It was expected that pilots performing NBT would become more disoriented than pilots who focused only on flight performance (control group).

METHODS

Subjects

Volunteering to participate in the study were 39 healthy male Polish military aviators. The subjects were randomly divided into two study groups: a control group (20 pilots; age M = 31.6; *SD* = 8.22; flight experience range 100–3600 h) and an experimental group (19 pilots; age M = 26.9; *SD* = 8.67; flight experience range 60–7200 h). All pilots were on active duty, with no previous experience with simulator-induced SD. All the pilots 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. Also, the pilots were not 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 before beginning the experiment.

Equipment

Simulator. This study was conducted using an integrated physiological trainer (Gyro-IPT; Environmental Tectonics Corporation, Inc., Southampton, PA, USA) located at the Military Institute of Aviation Medicine in Poland. 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 Gyro-IPT is particularly recommended for the training of pilots under induced SD conditions.[5] More details about this SD simulator can be found in our earlier paper.[19]

Flight scenarios. The simulator has several manufacturer-defined programmed disorientation profiles within the software. The strength of the disorienting stimuli in the selected profiles was evaluated based on conclusions from previous studies.[5,14] These SD conflicts simulated three well-known visual illusions and three well-known vestibular illusions.[5,22] The illusions were implemented in the six flight profiles. The three visual illusions included the following:

- Straight and level flight (S&LF) with a daytime false horizon illusion (created by a sloping cloud deck), a profile that demonstrates the predominance of peripheral vision in vision-based spatial orientation;
- Circle-to-land procedure (C-T-LP) with a nighttime constant shape illusion (created by an up-sloping runway), an illusion associated with the constancy of shapes expected by the pilot; and
- Straight-in approach (S-IA) with a 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:

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

These illusions represent a wide variety of mechanisms that can induce SD and are regarded as frequent and severe threats in aviation.[22]

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 specific disorientation cues were absent. This enabled us to directly compare flight performance parameters between the control and disorientation conditions for each flight profile. The remaining parts of the flight profiles were kept the same for the control and disorientation conditions.

To ensure that pilots experienced the visual conflicts, they were required to fly without an attitude directional indicator (ADI) during the sloping cloud deck interval (in the S&LF profile) and to perform a visual approach and landing on the illusory runway (in the C-T-LP and S-IA profiles) without any specific instrument glide path information. For a certain period of time in the S&LFART profile the pilots had to fly without ADI too. The above-mentioned flight instrument manipulations were performed in the same manner in both control and disoriented flight conditions. The general description of the flight profiles, including the specifications of disorientation cues, and flight instrument manipulation is given in our earlier paper.[19]

Memory task. We utilized the NBT, a sequential letter memory task in which subjects had to decide whether each letter (Polish consonants that were presented aurally) in a sequence matched the one that appeared *N* items ago (the 2-back version of this paradigm was used). More details about the NBT have been given in our previous paper.[27]

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. The training session was also intended 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 subjects 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 (the sequential letter memory task) were simultaneously presented to subjects in the experimental group to familiarize them with the NBT. 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 (NBT group), they were able to participate in the main experiment if they had accurately matched at least 70% of the letters in the sequence.

Subjects performed the NBT 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 the conflict flights. Both the control and NBT 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 exposure (12 flight profiles), participants completed a Polish version of the Simulator Sickness Questionnaire (SSQ).[3] 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 regarding severity and then are summed to yield three subscale scores (a nausea score, an oculomotor score, and a disorientation score) and a total score. The mean scores of the SSQ obtained after completing all flight profiles were referred to the scoring criteria of the SSQ to identify the severity of simulator sickness symptoms.[26]

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 perform an NBT with the sound stimuli simultaneously. 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 in our previous paper[19]) 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.

Statistical Analysis

A mixed analysis of variance (ANOVA) with repeated measures was conducted to investigate the impact of the NBT 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, NBT 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 the Bonferroni correction for multiple comparisons) was considered statistically significant. The effect size was estimated using the partial η^2 statistic. All analyses were conducted using the IBM SPSS Statistics 17 statistical package. In the analysis, the time and correctness of the response to the sound stimuli were omitted. These data were published in our earlier paper.[27]

RESULTS

All 39 subjects participating in the study completed the experiment. All pilots from the experimental group performed the NBT and did not interrupt its execution. Therefore, we assumed that the pilots' working memory and cognitive workload was at the same level during the flight simulation in the experimental group.

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. The scores of SSQ symptoms in the NBT group were $M = 1.38$ ($SD = 1.41$) for the nausea subscale, $M = 2.88$ ($SD = 2.31$) for the oculomotor subscale, $M = 1.81$ ($SD = 1.72$) for the disorientation subscale, and $M = 2.02$ ($SD = 1.59$) for the total score. The SSQ symptom scores from both controls and the NBT group were similar and reflect negligible symptoms of simulator sickness.[26]

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 I**, in addition to differences in performance during the conflict vs. nonconflict flight in the control and experimental groups.

Table I 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 the pilots were supposed to maintain S&LF (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 the 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 the visual approach along with glide slope during landing (an up-sloping or broader runway was present in the conflict flight).

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

FLIGHT PROFILE AND FLIGHT TYPE	CONTROL			NBT		
	N	M	SEM	*N*	M	SEM
S&LF (degrees)	20			17		
Nonconflict		0.46	0.48		0.08	0.35
Conflict		0.78	0.44		3.37	0.38
C-T-LP (ft/min)	19			17		
Nonconflict		−377.2	73.82		−54.9	21.23
Conflict		−919.4	90.08		−116	22.35
S-IA (ft/min)	20			16		
Nonconflict		−672.4	61.51		−203.1	17.84
Conflict		−795	119.52		−192.2	24.12
S&LFALT (degrees)	20			17		
Nonconflict		−0.93	0.77		−0.22	0.30
Conflict		−0.2	0.27		−3.49	2.36
RBT (degrees)	17			17		
Nonconflict		30.5	0.94		30.4	1.71
Conflict		27.2	1.71		27.1	1.86
S&LFART (degrees)	18			17		
Nonconflict		0.68	1.46		0.25	0.63
Conflict		3.37	1.96		5.45	3.62

NBT: *N*-Back Task; S&LF: straight & level flight; C-T-LP: circle-to-land procedure; S-IA: straight-in approach; S&LFALT: straight & level flight after left turn; RBT: right banked turn; S&LFART: straight & level flight after right turn; *N*: number of subjects; M: mean value; SEM: standard error of the mean.

The raw bank averages are presented as absolute values because we were merely interested in whether the bank was increased or decreased due to the presumed illusion.

In **Table II**, the results of ANOVA tests of within-subjects effects (nonconflict vs. conflict flight) and between-subject effects (control vs. NBT 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 ($P < 0.001$), RBT ($P = 0.015$), and S&LFART ($P = 0.038$) profiles. A significant effect of group type (control vs. NBT group) was observed for the S&LF ($P = 0.021$), C-T-LP ($P < 0.001$), and S-IA ($P < 0.001$) flight profiles (Table II). The effect of condition or group type was not significant for the rest of the profiles.

A significant interaction between group (control vs. NBT group) and flight type (nonconflict vs. conflict) appeared in the S&LF [$F(1,35) = 13.451$, $P = 0.001$, $\eta^2 = 0.278$] and C-T-LP [$F(1,34) = 22.995$, $P < 0.001$, $\eta^2 = 0.403$] flight profiles. **Fig. 1** shows the effect of NBT and the visual illusion cues on the 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 NBT 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 conflict flight only in the S&LF profile ($P < 0.001$). The differences between the conflict and nonconflict flights were statistically significant for the NBT group in the S&LF profile ($P < 0.001$) and the control group in the C-T-LP profile ($P < 0.001$) (Fig. 1).

In **Fig. 2**, the effects of NBT and the vestibular illusion cues on the 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 NBT groups or between the conflict and nonconflict flights, as seen in Table II.

DISCUSSION

Since in the present study applied flight profiles represented various scenarios that differ in the flying conditions and flight parameters, we refrained from formulating predictions regarding in which flight profiles the subjects would be most susceptible to SD. The results showed that the pilot's interpretation of instruments, as well as the accuracy of judgments and precision of flying maneuvers, were impaired. The NBT and SD cues employed in our study influenced the pilots' flight performance in three profiles. For the C-T-LP and S-IA profiles, we found significant differences between group type (control vs. NBT) in both the nonconflict and conflict flights (Fig. 1). For the S&LF profile, the differences between group types were only in the conflict flight. The cognitive load exerted by the NBT on the flight performance in these profiles should be more significant in the disorientation conditions than in the control conditions. However, only in the S&LF (for the NBT group) and C-T-LP (for the control group) profiles were the flight performance among subjects different between nonconflict and conflict flight. Moreover, in the case of the S&LF profile, an adverse flight performance toward the acting false horizon illusion was observed. It is also interesting to note that in this profile, where there was no ADI for a certain period of a time, the NBT also impaired pilots' flight performance in the nonconflict flight, albeit nonsignificantly. Based on the above findings, we can conclude that

Table II. Tests of Within-Subjects Effects and Between-Subjects Effects.

FLIGHT PROFILE	DF	WITHIN-SUBJECTS EFFECTS (NONCONFLICT vs. CONFLICT FLIGHT)			BETWEEN-SUBJECTS EFFECTS (CONTROL vs. NBT GROUP)		
		F	*P*	η^2	*F*	*P*	η^2
S&LF	(1,35)	19.999	<0.001	0.364	5.857	0.021	0.143
C-T-LP	(1,34)	36.17	<0.001	0.515	57.464	<0.001	0.628
S-IA	(1,34)	1.182	0.285	0.034	31.648	<0.001	0.482
S&LFALT	(1,35)	1.229	0.275	0.034	1.122	0.297	0.031
RBT	(1,32)	6.095	0.019	0.160	0.007	0.935	<0.001
S&LFART	(1,33)	4.696	0.038	0.125	0.109	0.744	0.003

NBT: *N*-Back Task; S&LF: straight & level flight; C-T-LP: circle-to-land procedure; S-IA: straight-in approach; S&LFALT: straight & level flight after left turn; RBT: right banked turn; S&LFART: straight & level flight after right turn.

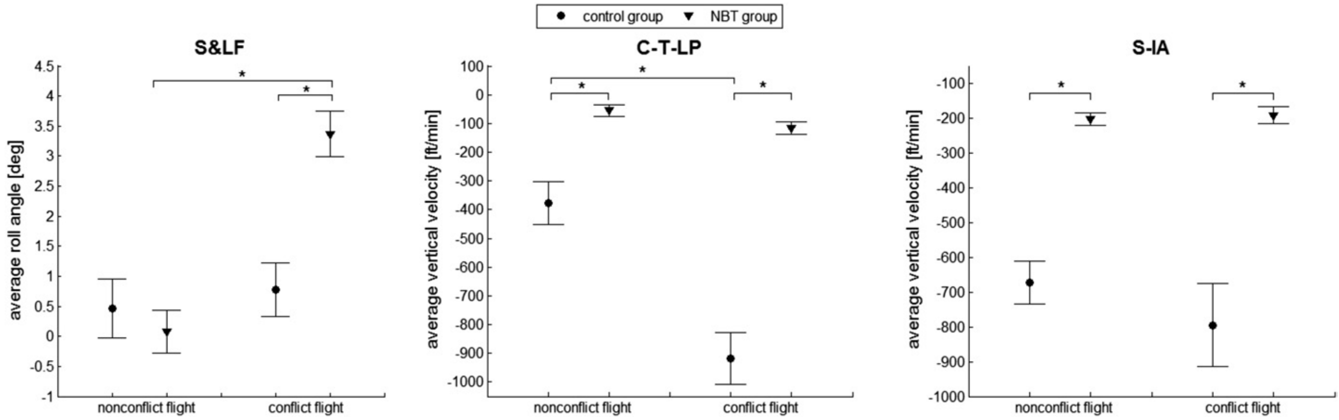

Fig. 1. The effect of NBT and the visual illusion cues on pilots' flight performance. The error bars represent the SEM; * $P < 0.001$.

the NBT employed in our study indeed increased the cognitive workload and affected the pilots' flight performance, even in the absence of the SD cues (visual illusions in the C-T-LP and S-IA profiles). These results support our hypothesis that the flight performance in both disoriented and oriented (control) flight profiles would be impaired by auditory verbal working memory load.

The described profiles (S&LF, C-T-LP, and S-IA) have the common feature of visual illusions (false horizon, constant shape, and size illusions, respectively). In the C-T-LP and S-IA 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 the NBT resulted in pilot errors that were related to improper vertical velocity (velocity was changed contrary to the stimulus causing the illusion). As mentioned before, this situation appeared to be 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 (primarily associated with nighttime), due to the growth requirements of piloting, thereby reducing the pilot's cognitive reserve.[31] The majority of all civil aviation accidents occur during the descent, approach, and landing phases of flight, when distraction and workload are higher, and the margin for positional error is lower than during the cruise portion of the flight. Approach and landing also represent a highly stressful situation that can impair the pilot's cognitive abilities. Task saturation from psychological stress may also impair cognitive performance as a result of disorienting situations. Bednarek et al.[1] 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. Their study indicated that individuals who can efficiently use attention resources, particularly switching of their attention to information of interest (ignoring unrelated information), may have better control of the aircraft. That is, they may recover faster or more efficiently in a disorienting situation.

A possible alternative explanation for these findings (differences between group type (control vs. NBT) for the S&LF, C-T-LP, and S-IA profiles) is that there is automatic encoding into working memory when items are verbalized and that verbal, as well as visual working memory, can guide visual attention.[25] Additionally, only central attention (concerning constant shape and size illusions) was found to be necessary for manipulating information in working memory.[6] It also seems obvious that the NBT is the most impaired when the cognitive workload is already high or the amount of available information is low. Therefore, the lack of ADI for a time (e.g., in the S&LF profile)

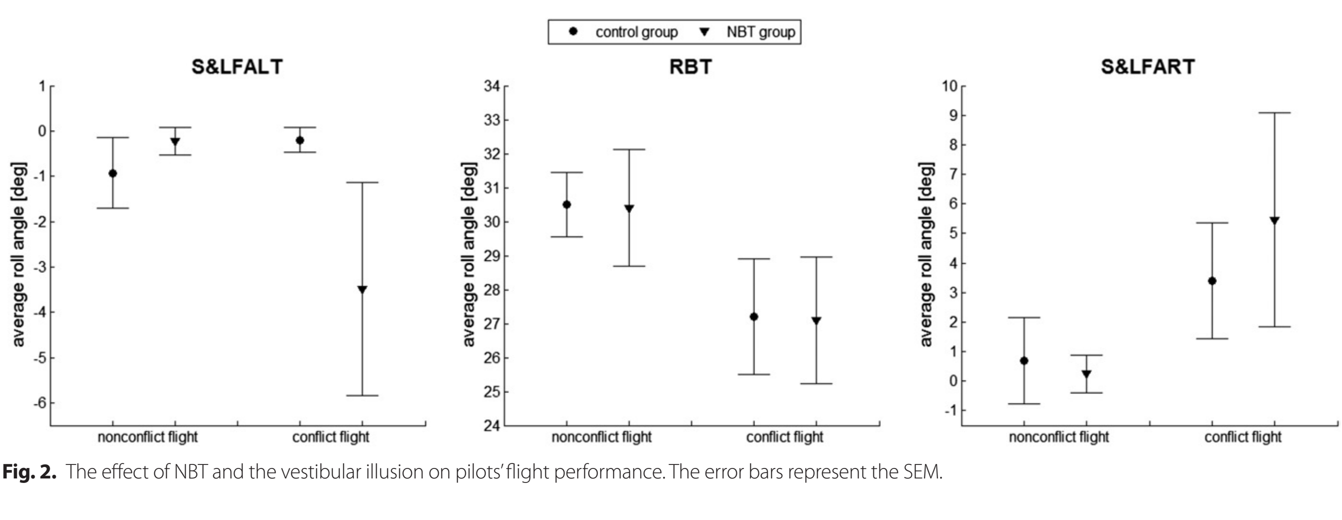

Fig. 2. The effect of NBT and the vestibular illusion on pilots' flight performance. The error bars represent the SEM.

and the sustained presence of visual illusions contributed substantially to the high workload under SD conditions.

Interestingly, however, a decrease in flight performance accuracy was found for the profiles mentioned above under the NBT conditions. This finding may be explained by the subjects being oblivious to disorientation, devoting their attention to the NBT, or that the task itself may have impaired their visual perception.[2] We assume that pilots performing the NBT may not have perceived the visual SD stimuli and, consequently, the visual illusions in the C-T-LP and S-IA profiles may not have appeared.

In the case of the vestibular-origin flight profiles (S&LFALT, RBT, and S&LFART), the cognitive load exerted by the NBT did not significantly affect flight performance (Fig. 2). Moreover, impairment of flight performance should be higher under the disorientation conditions than the control conditions. The lack of these effects can be explained by the fact that the pilots probably recognized SD. 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 another concurrent task could decline.[11]

Results of the cognitive performance of the NBT in this study were presented in our previous paper.[27] We reported that a decline in the NBT performance (correct response rate) did occur only in the S&LFART profiles (leans illusion) when disorientation cues were implemented. It could suggest that the leans illusion implemented in this flight scenario was the most challenging illusion regarding its capability to affect cognitive performance (working memory processes). This finding indicates that experiencing the somatogyral (S&LFALT profile) and Coriolis (RBT profile) illusions did not result in withdrawing attentional resources from the ongoing cognitive task in order to cope with this vestibular illusion. We can presume that the pilots were able to allocate sufficient encoding resources to flight instrument interpretation in these profiles while simultaneously allocating adequate responding resources to perform the NBT.

It is worth noting that in addition to performing two distinct tasks (visual and auditory tasks), in our study the pilots had to simultaneously perform flight control and respond to sound stimuli (by pressing the corresponding button on the stick control). Wickens[30] reported that the same resources are engaged in these response activities (control manipulation and switch activation). Consequently, performing two concurrent tasks requires more effort, potentially reducing their accuracy.

It is unclear, however, why the NBT and SD cues did not have a more significant effect on flight performance, especially for the S&LFALT, RBT, and S&LFART profiles under SD conditions induced by vestibular illusions. It is obvious that two factors made the conflict flight associated with visual illusion inherently more difficult: first, there was no ADI for a certain period of time (e.g., in the S&LF profile); second, the illusions lasted longer than in the other conflict flight conditions (e.g., the Coriolis and somatogyral illusions).

Another explanation for the lack of a more significant effect of the NBT on flight performance could be that different flight profiles contained different flight phases (straight and level flight, turn, approach, and landing), which could be associated with different levels of cognitive load and task requirements. It could also change how destructive the effect of the additional task may be with regards to maintaining a safe flight profile. This is particularly important when landing, as it seems necessary to withdraw attention from any additional tasks. In situations where the flight requires less cognitive involvement, the pilot can afford to perform additional tasks, because small deviations of flight parameters are not threatening (e.g., high altitude flying). Factors that possibly interfere with the influence of the cognitive workload on flight performance and SD should be taken into account for future studies. Moreover, it is not clear whether similar variations in flight performance would occur if different flight scenarios, illusions, or a stricter minimal pilot's flight-hour criterion are used.

In addition to the strengths mentioned above for 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 pilots could have obtained various levels of accuracy of flight performance. This can occur due to the wide variability in the pilots' age and flight experience,[23] even though they were familiar with the flight maneuvers before the experiment. Secondly, the effect of SD cues on flight performance was somewhat complicated in that older, more experienced pilots would be more likely to recognize the SD conflicts. Webb et al.[29] 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 NBT 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] Therefore, it is not possible to precisely determine whether the impaired flight performance is due to cognitive decline associated with the illusion or because of performing the NBT.

Despite the limitations mentioned above, our findings indicate that auditory verbal working memory load adversely affects the pilots' flight performance, especially in the S&LF, C-T-LP, and S-IA profiles. This was observed regardless of whether the SD cues (visual illusions) were implemented, which indicates the overall lack of effect of the NBT during conflict flights. This finding partially supports our hypothesis that NBT, even in the absence of SD conflict, significantly affects flight performance. Although we found that the NBT 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 and S-IA profiles, the impact of the employed SD cues in the S&LF profile was intensified. A major reason for the negligible effect of the NBT during conflict flights was the variability of flight performance caused by differences in flying experience between pilots. In the future, to eliminate this variability, we suggest that a repeated-measures or matched-pair design be used.

Based on the conclusions mentioned above, we present a few key findings and recommendations. Firstly, pilots are not always aware of altered flight parameters, which may indicate that they have lost spatial orientation, mainly as a result of visual illusions. However, when problems in maintaining proper flight performance arise, pilots should direct all available mental resources to regaining orientation and withdraw from any other concurrent tasks. In other words, they should be trained to not respond to external stimuli (e.g., auditory and visual) until they have recovered their spatial orientation. Secondly, the NBT employed in this study affects flight performance regardless of whether the visual illusions were implemented; however, except for one (the false horizon illusion), these illusions do not increase a pilot's susceptibility to SD. Presumably the pilot's susceptibility to SD in the other profiles could be investigated further by determining if applied auditory tasks (message length and their complexity) would increase the verbal work memory load. Thirdly, the ability to retain information in an accessible state (working memory) is a critical aspect of human cognitive capacities, especially in aircraft pilots while maintaining their spatial orientation. Lastly, to confirm our results, future experiments should extend flight scenarios with better control of covariates and disturbing variables.

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REFERENCES

1. Bednarek H, Truszczyński O, Wutke K. Cognitive determinants of pilots' effectiveness under a false horizon illusion. Int J Aviat Psychol. 2013; 23(3):267–287.
2. Berger CC, Ehrsson HH. The content of imagined sounds changes visual motion perception in the cross-bounce illusion. Sci Rep. 2017; 7(1):40123.
3. Biernacki MP, Kennedy RS, Dziuda Ł. Simulator sickness and its measurement with Simulator Sickness Questionnaire (SSQ). Med Pr. 2016; 67(4):545–555.
4. Bles W. Spatial disorientation countermeasures - advanced problems and concepts. In: Previc FH, Ercoline WR, editors. Spatial Disorientation in Aviation. Reston (VA): American Institute of Aeronautics and Astronautics; 2004:509–540.
5. Cheung B, Wong WT. Recommendation to implement Gyro-IPT for disorientation training at CFSAT. Downsview, Ontario (Canada): Defence and Civil Institute of Environmental Medicine; 1998. Report number: DCIEM-98-TM-59.
6. Fougnie D. The relationship between attention and working memory. In: Johansen NB, editor. New research on short-term memory. Lancaster (UK): Nova Science Publishers Inc.; 2008:1–45.
7. Gibb R, Ercoline B, Scharff L. Spatial disorientation: decades of pilot fatalities. Aviat Space Environ Med. 2011; 82(7):717–724.
8. Greene CM, Kennedy K, Soto D. Dynamic states in working memory modulate guidance of visual attention: evidence from an n-back paradigm. Vis Cogn. 2015; 23(5):546–560.
9. Gresty MA, Golding JF, Le H, Nightingale K. Cognitive impairment by spatial disorientation. Aviat Space Environ Med. 2008; 79(2):105–111.
10. Gresty MA, Waters S, Bray A, Bunday K, Golding JF. Impairment of spatial cognitive function with preservation of verbal performance during spatial disorientation. Curr Biol. 2003; 13(21):R829–R830.
11. Hendy KC, East KP, Farrell PSE. An information-processing model of operator stress and performance. In: Hancock PA, Desmond PA, editors. Stress, Workload and Fatigue, 1st ed. Mahwah (NJ): Lawrence Erlbaum Associates; 2001:34–80.
12. Kerr B, Condon SM, McDonald LA. Cognitive spatial processing and the regulation of posture. J Exp Psychol Hum Percept Perform. 1985; 11(5):617–622.
13. Kim S-Y, Kim M-S, Chun MM. Concurrent working memory load can reduce distraction. Proc Natl Acad Sci USA. 2005; 102(45):16524–16529.
14. Kowalczuk K. Wartość diagnostyczna parametrów fizjologicznych podczas wywoływanej dezorientacji przestrzennej [Diagnostic value of physiological parameters during evoked spatial disorientation]. Polski Przegląd Medycyny Lotniczej. 2003; 10(1):7–22 (in Polish).
15. Kowalczuk KP, Gazdzinski SP, Janewicz M, Gąsik M, Lewkowicz R, Wyleżoł M. Hypoxia and Coriolis illusion in pilots during simulated flight. Aerosp Med Hum Perform. 2016; 87(2):108–113.
16. Lawson BD, Smith SA, Kennedy RS, Kass SJ, Muth ER. Vestibular stimuli may degrade situation awareness even when spatial disorientation is not experienced. In: RTO HFM Symposium on Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures; La Coruña, Spain; 15–17 April 2002. Neuilly-sur-Seine (France): NATO RTO; 2002:1–21. Report No.: RTO-MP-086.
17. Lewkowicz R, Francuz P, Bałaj B, Augustynowicz P. Flights with the risk of spatial disorientation in the measurements of oculomotor activity of pilots. Polish J Aviat Med Psychol. 2015; 21(3):22–28.
18. Lewkowicz R, Fudali-Czyż A, Bałaj B, Francuz P. Change detection flicker task effects on simulator-induced spatial disorientation events. Aerosp Med Hum Perform. 2018; 89(10):863–872.
19. Lewkowicz R, Stróżak P, Bałaj B, Francuz P, Augustynowicz P. Selective auditory attention and spatial disorientation cues effect on flight performance. Aerosp Med Hum Perform. 2018; 89(11):976–984.
20. Li B, Li L, Wang A, Zhang M. Visual and auditory verbal working memory affects visual attention in the semantic matching. Acta Psychologica Sinica. 2018; 50(5):483–493.
21. Lopez N, Previc FH, Fischer J, Heitz RP, Engle RW. Effects of sleep deprivation on cognitive performance by United States Air Force pilots. J Appl Res Mem Cogn. 2012; 1(1):27–33.
22. Previc FH, Ercoline WR. Spatial disorientation in aviation: historical background, concepts, and terminology. In: Previc FH, Ercoline WR, editors. Spatial disorientation in aviation. Reston (VA): American Institute of Aeronautics and Astronautics, Inc.; 2004:1–36.
23. Previc FH, Ercoline WR, Evans RH, Dillon N, Lopez N, et al. Simulator-induced spatial disorientation: effects of age, sleep deprivation, and type of conflict. Aviat Space Environ Med. 2007; 78(5):470–477.
24. Risser MR, Scerbo MW, Baldwin CL, McNamara DS. Interference timing and acknowledgement response with voice and datalink ATC commands. Proc Hum Factors Ergon Soc Annu Meet. 2006; 50(1): 11–15.
25. Soto D, Humphreys GW. Automatic guidance of visual attention from verbal working memory. J Exp Psychol Hum Percept Perform. 2007; 33(3):730–737.
26. Stanney KM, Kennedy RS, Drexler JM. Cybersickness is not simulator sickness. Proc Hum Factors Ergon Soc Annu Meet. 1997; 41(2):1138–1142.

27. Stróżak P, Francuz P, Lewkowicz R, Augustynowicz P, Fudali-Czyż A, et al. Selective attention and working memory under spatial disorientation in a flight simulator. International Journal of Aerospace Psychology. 2018; 28(1–2):31–45.
28. Taylor JL, O'Hara R, Mumenthaler MS, Rosen AC, Yesavage JA. Cognitive ability, expertise, and age differences in following air-traffic control instructions. Psychol Aging. 2005; 20(1):117–133.
29. Webb CM, Estrada A, Kelley AM. The effects of spatial disorientation on cognitive processing. Int J Aviat Psychol. 2012; 22(3):224–241.
30. Wickens CD. The structure of attentional resources. In: Nickerson RS, editor. Attention and performance VIII. Hillsdale (NJ): Erlbaum; 1980:239–257.
31. Wilson GF. An analysis of mental workload in pilots during flight using multiple psychophysiological measures. Int J Aviat Psychol. 2002; 12(1):3–18.