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14. ABSTRACT
Spatial disorientation mishaps are greater at night and with greater time on task, and sleep deprivation is known to decrease cognitive and overall flight performance. However, the ability to perceive and to be influenced by physiologically appropriate simulated SD conflicts has not previously been studied in an automated simulator flight profile. ***Methods:*** A set of 10 flight profiles were flown by 10 U.S. Air Force (USAF) pilots over a period of 28 h in a specially designed flight simulator for spatial disorientation research and training. Of the 10 flights, 4 had a total of 7 spatial disorientation (SD) conflicts inserted into each of them, 5 simulating motion illusions and 2 involving visual illusions. The percentage of conflict reports was measured along with the effects of four conflicts on flight performance. ***Results:*** The results showed that, with one exception, all motion conflicts were reported over 60% of the time, whereas the two visual illusions were reported on average only 25% of the time, although they both significantly affected flight performance. Pilots older than 35 yrs of age were more likely to report conflicts than were those under 30 yrs of age (63% vs. 38%), whereas fatigue had little effect overall on either recognized or unrecognized SD. ***Discussion:*** The overall effects of these conflicts on perception and performance were generally not altered by sleep deprivation, despite clear indications of fatigue in our pilots.

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RESEARCH ARTICLE

Simulator-Induced Spatial Disorientation: Effects of Age, Sleep Deprivation, and Type of Conflict

Fred H. Previc, William R. Ercoline, Richard H. Evans, Nathan Dillon, Nadia Lopez, Christina M. Daluz, and Andrew Workman

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Introduction: Spatial disorientation mishaps are greater at night and with greater time on task, and sleep deprivation is known to decrease cognitive and overall flight performance. However, the ability to perceive and to be influenced by physiologically appropriate simulated SD conflicts has not previously been studied in an automated simulator flight profile. ***Methods:*** A set of 10 flight profiles were flown by 10 U.S. Air Force (USAF) pilots over a period of 28 h in a specially designed flight simulator for spatial disorientation research and training. Of the 10 flights, 4 had a total of 7 spatial disorientation (SD) conflicts inserted into each of them, 5 simulating motion illusions and 2 involving visual illusions. The percentage of conflict reports was measured along with the effects of four conflicts on flight performance. ***Results:*** The results showed that, with one exception, all motion conflicts were reported over 60% of the time, whereas the two visual illusions were reported on average only 25% of the time, although they both significantly affected flight performance. Pilots older than 35 yr of age were more likely to report conflicts than were those under 30 yr of age (63% vs. 38%), whereas fatigue had little effect overall on either recognized or unrecognized SD. ***Discussion:*** The overall effects of these conflicts on perception and performance were generally not altered by sleep deprivation, despite clear indications of fatigue in our pilots.
Keywords: fatigue, motion, visual, illusion, flight profile, age.

SPATIAL DISORIENTATION (SD) is a major contributor to both military and civilian aviation accidents (1,4,12,19,21), with some recent accounts placing the percentage of broadly defined SD mishaps at ~30% (12). Spatial disorientation is generally categorized into "unrecognized" (Type I SD) and "recognized" (Type II SD) varieties, although a rarer form of SD known as "incapacitating" or Type III SD is also used (15).

There is a great deal of indirect evidence concerning the effects of fatigue on SD. First, the SD mishap rate is greater at night (14,21), and aviation mishaps also increase with continuous time on task (1,19). Moreover, fatigue degrades not only basic cognitive performance (2), but also flight performance, including the ability to maintain designated flight parameters (2,9,11). Finally, sleep deprivation leads to disturbances in visuomotor (8,11,17) and vestibular (5) function, which are important in spatial orientation. In particular, declines in vestibular sensitivity may underlie the increase in postural control sway that has been found to varying degrees during sleep deprivation (6,9,18,20).

Despite the above general evidence that fatigue degrades flight performance, only LeDuc et al. (9) directly compared responses to SD events under baseline and fatigued states. LeDuc et al. showed that fatigued UH-60 pilots required slightly more time to detect visual-motion conflicts (in drift, pitch and roll) in a helicopter simulator, although even under rested conditions, pilots required 1–2 min for detection of the events. No comparable simulator study has previously investigated SD susceptibility in fixed-wing pilots under rested and fatigued states.

The major purpose of this research, therefore, was to investigate the effects of fatigue in inexperienced and experienced fixed-wing U.S. Air Force (USAF) pilots on the perception and response to SD events in a specially designed flight simulator known as the Gyroflight Sustained Operations Simulator (GSOS). The GSOS, which is also known as the Gyro IPT-2® by its manufacturer (Environmental Tectonics Corporation, Inc., Southampton, PA), features the ability to insert visual and motion conflicts seamlessly into a normal flight-simulator aeromodel so as to simulate SD as it is experienced in actual flight. However, the ability to perceive and to be influenced by well-defined, physiologically appropriate SD conflicts has not been studied before in an automated simulator flight profile. We, therefore, measured the perceptual reports of pilots to illusory visual and motion conflicts (Type II SD) under fatigued and non-fatigued states, as well as the effects of poorly recognized conflicts on flight performance (Type I SD). We did this as part of a larger study that investigated overall flight performance, cognitive performance, and instrument scanning during a 34-h period of continuous

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wakefulness (16). We predicted that because of the general degradation of cognitive state, vestibular sensitivity, and flight performance with fatigue, as well as the specific problems in detecting visual-motion conflicts shown by LeDuc et al. (9), fatigued pilots in our study would be less able to recognize the presence of SD episodes, thereby leading to greater Type I SD.

METHODS

Participants

There were 10 volunteer military pilots who participated in this study. Of the 10 pilots (all men), 8 were active-duty pilots with the USAF while the remaining two were USAF reserve officers. All served in an off-duty capacity and were paid for their participation. The average age of the pilots was 34.2 yr (ranging from 23 to 46 yr); half of them were over 35 yr and half were 30 yr or under. Their average flight experience was 2806 h (ranging from 207 to 5800 h), and the correlation between flight experience and age was almost perfect ($r = +0.96$). All pilots signed an informed consent document approved by the Brooks City-Base Institutional Review Board.

All pilots possessed at least 20/25 vision binocularly with or without correction, and they were allowed to wear contacts but not glasses because of the eye-tracking apparatus they wore throughout the experiment. All pilots had normal vestibular function as assessed by the Sharpened Romberg test and a negative clinical history of vestibular symptoms (dizziness, vertigo, disorientation). In addition, all pilots reported normal sleep patterns, and none had ever experienced a seizure of any sort. They were not permitted to be habitual smokers (i.e., more than one cigarette per day) or habitual caffeine drinkers (i.e., > 100 mg of caffeine per day) or currently taking any psychoactive medication (e.g., antihistamines, antidepressants, sleep aids, etc.). Each pilot completed a sleep log for the 7 d prior to the start of the experiment. All pilots refrained from caffeine, alcohol, and other mild stimulants or sedatives while monitored at home on the night before the sleep-deprivation period as well as during the 36 h of continuous wakefulness in the laboratory.

GSOS and Flight Profile

This study was conducted in the GSOS, a four-axis flight simulator with additional SD capabilities located within the confines of the Aviation Sustained Operations Laboratory at Brooks City-Base, TX. The GSOS possesses motion capabilities in pitch (up to ± 25 deg), roll (up to ± 25 deg), and continuous 360-deg yaw. The GSOS also features sub-threshold washout in pitch and roll as well as limited heave (up to ± 12 cm). It also has a three-channel, high-resolution, non-collimated out-the-window visual display, each channel of which subtends 28° vertically by 40° horizontally when viewed from the design-eye position (for a total field-of-view of ~28° by ~120°). The GSOS aeromodel replicates that of the T-6 aircraft, with which all of the pilots were familiar, and the reconfigurable instrument panel was also designed to depict that of the T-6 as closely as possible. The GSOS is operated and monitored from a control station in an adjacent room and is outfitted for full physiological recording. As part of the larger study, our pilots wore a head-mounted eye-tracker and a set of EEG electrodes during their flights.

Unlike a normal flight simulator, the GSOS allows the operator to program sustained and transient motions in concert with the motions generated by the aeromodel. For example, a pilot can experience a sustained pitch-up sensation during takeoff akin to the normal sensation provided by the shift of the gravitoinertial force, and sustained yawing can be provided during turning that can help to set up SD conflicts such as the Coriolis illusion (caused by cross-coupled head motion) and post-rotatory sensations (occurring following cessation of the sustained yawing). These additional motions, as well as visual illusions caused by sloping cloud decks, runway illusions, and varying visibility conditions, can be inserted into the normal simulator profile on a conditional basis. For example, a post-rotatory sensation complete with turning and banking sensations in the direction opposite to the original turn can be created by slowly ceasing the bank and yaw as the pilot's bank angle is reduced by a preset amount (e.g., 5° from the specified bank) during level-off at a new heading. In the GSOS flight profile to be described in the next section, the various visual and motion conflicts and the changes in weather (e.g., clouds) and time of day needed to set them up—along with a host of air traffic control commands and other communications—required a total of ~125 programmed events to seamlessly insert 7 SD conflicts/illusions in the context of a highly realistic flight scenario. The GSOS allows for operator intervention to occur if the pilot begins to fly a profile outside the windows permitted by the automation, which happened on less than 5% of flight segments overall in the present study due to the proficiency of the military pilots who participated.

The flight profile, shown in **Fig. 1**, consisted of 1) takeoff at a heading of 360° and climb to 8000 ft; 2) a right climbing turn (30° of bank) to 10,000 ft and a heading of 235°; 3) a wings-level climb to 12,000 ft; 4) a right level turn (bank of 45°) to a heading of 180°; 5) a wings-level descent to 7500 ft; 6) a left descending turn (30° bank) to 4000 ft and a heading of 45°; and 7) visual approach and landing. There was one additional segment that involved a final approach turn to 360° and 3500 ft, but no commanded parameters were specified because this maneuver varied based on the pilot's course deviation. The flight, which required ~19 min to complete, simulated a transition from a dusk takeoff to a nighttime landing and was performed mostly in instrument meteorological conditions (IMC). The exceptions to IMC were during a brief period after takeoff, during a small section of the wings-level climb while pilots searched for traffic, and during the turn to final approach followed by the visual approach and landing. On each segment, except the turn to final approach, the pilot was commanded to maintain a set of two or three previously specified control or performance parameters, including airspeed (all segments), heading (Segments 1, 3, and 5), vertical velocity (Segments 2, 3, 5,

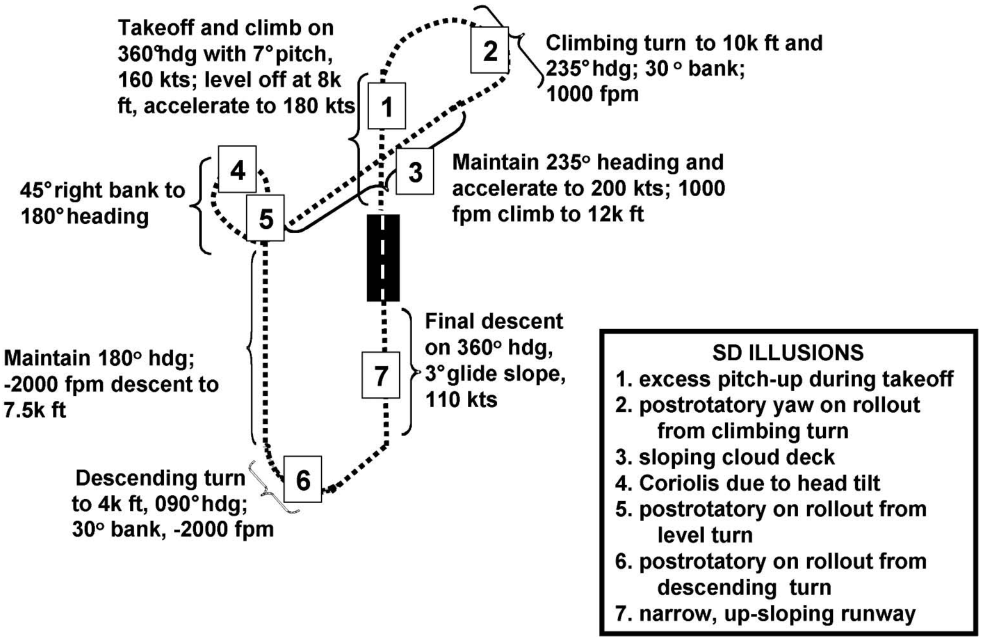

Fig. 1. The GSOS flight profile with the seven SD conflicts shown in boxes.

and 6), bank (Segments 2, 4, and 6), and longitudinal bearing and glide slope (Segment 7). On odd-numbered flights, the pilot flew as described above, while on even-numbered flights the pilot flew a mirror profile, beginning with a climb to the left to 125° rather than to the right to 235°.

On 4 of the 10 flights (flights 1, 4, 7, and 10), a set of 7 SD conflicts were inserted, as shown in Fig. 1 and in **Table I**. These conflicts simulated five well-known motion illusions and two well-known visual illusions (3,14). The five motion conflicts consisted of an excess pitch in Segment 1, post-rotatory sensations at the end of Segments 2, 4, and 6, and cross-coupled motion in Segment 4, which was responsible for the Coriolis illusion. The two visual conflicts were created by a sloping cloud deck in Segment 3 and a narrow, up-sloping runway in Segment 7. To ensure that pilots experienced the visual conflicts, they were required to search for traffic during the sloping cloud deck interval and to perform a visual approach and landing to the illusory runway without specific instrument glide path information. We interspersed the conflict flights with two non-

TABLE I. DESCRIPTION OF SEVEN CONFLICTS.

Conflicts	Real-world Analogue	Description
Excess pitch-up on takeoff	Somatogravic illusion	+15° of excess pitch is added to aeromodel motion immediately following rotation from runway and after lifting of flaps to simulate backward tilt of gravitoinertial vector during takeoff; expected percept is of excessive upward pitching
Postrotatory after turn	Graveyard spin/spiral	$15° \cdot s^{-1}$ of sustained yaw and 1° of bank are gradually added (at $0.5° \cdot s^{-2}$, in the case of yaw) to simulator motion during Segment 2 turn; cessation of sustained turning and bank occurs upon rollout from turn; expected percept is of yawing or even leaning in direction opposite to turn
Sloping cloud deck	Visual leans	Slope of cloud deck tilted ±10° from 11,400 ft to 11,800 ft in Segment 3, with slope depending on direction of profile; pilot requested to "look for traffic" during sloping interval; expected percept is of leaning in response to visually depicted bank
Head pitch during turn	Coriolis	$24° \cdot s^{-1}$ of sustained yaw (at $0.5° \cdot s^{-2}$) and 1 ° of bank are added gradually to simulator motion during Segment 4 turn; pilot is instructed to change range on map button, located ~11° below attitude indicator; expected cross-coupled percept is of roll to right or left, depending on turn direction
Postrotatory after turn	Graveyard spin/spiral	$24° \cdot s^{-1}$ of sustained yaw (at $0.5° \cdot s^{-2}$) and 1° of bank are added gradually to simulator motion during Segment 4 turn; cessation of sustained turning and bank occurs upon rollout from turn; expected percept is of yawing or even leaning in direction opposite to turn
Postrotatory after turn	Graveyard spin/spiral	$15° \cdot s^{-1}$ of sustained yaw (at $0.5° \cdot s^{-2}$ and 1° of bank are gradually added to simulator motion during Segment 6 turn; cessation of sustained turning and bank occurs upon rollout from turn; expected percept is of yawing or even leaning in direction opposite to turn
Illusory runway	"Black hole" illusory approach	Nighttime runway shortened in width from 300 ft to 125 ft and up-sloped 2°; visual approach and landing required; expected sensation is of feeling too high, leading to steeper glide slope ("duck under")

conflict flights so that pilots would not be aware of when the conflicts would occur. It should be noted that no pilots reported either in advance or afterwards that they knew a specific flight to be a conflict or non-conflict one, so they evidently could not predict or anticipate the conflicts they encountered.

Spatial Disorientation Measures

Both subjective and objective measures of SD were recorded during the four conflict flights. The subjective measure consisted of conflict reports while the objective measure consisted of performance for a specific flight parameter such as bank or pitch. Pilots were instructed in terms of the perceptual measure to report any "unusual discrepancies" between their perceived motion and/or position vs. what was presented on the flight instruments. They were further instructed to be as timely and specific as possible (e.g., "feeling too high," "yawing to the right," etc.). They received this verbal instruction prior to each flight, just after takeoff, and toward the end of Segment 3. The perceptual measures recorded in this study were the number of conflict reports both for each conflict and for the seven conflicts altogether. Because there were four conflict flights, the maximum number of reports for each of the seven conflicts was four per pilot.

The objective flight measures recorded during the SD conflicts were: 1) average pitch in Segment 1 from the time pilots attained their command airspeed of 160 kn to level off at 8000 ft, during which 15° of extra pitch was added in the conflict flights; 2) amount of bank in Segment 3 during the period from 11,400 ft to 11,800 ft when the sloping cloud deck was visible in the conflict flights; 3) amount of bank for 10 s after the command to tilt the head in pitch in Segment 4, which should have led to an immediate rolling sensation because of the cross-coupled Coriolis motion caused by the $24° \cdot s^{-1}$ of imposed yaw during the conflict flights; and 4) glide slope during Segment 7, in which the visual approach was to a narrow, up-sloping runway in the conflict flights. We did not analyze performance during the transitional post-rotatory intervals because pilots were not required to level off with a specified bank and turn rate.

Overall Procedure and Schedule

This experiment took place over 3 d, with pilots run in tandem. On the evening prior to the period of continuous wakefulness, pilots trained on the flight profile (two non-conflict runs each) and the various cognitive tasks. They then went to bed at either 22:00 or 23:00 and had a normal (8-h) night's sleep, monitored by a wristband activity monitor, either at home or at base quarters. The pilots returned at 07:30 or 08:30 (depending on whether they were the first or second pilot to be run) and received one more practice flight and additional cognitive training and were outfitted for physiological recording.

Actual flights began on the second day at 12:00 for the first pilot and at 13:00 for the second pilot and were performed at 3-h intervals thereafter (i.e., the second flights began at 15:00 and 16:00, respectively, for the first and second pilot and continued to stagger). The final flight was completed on Day 3 at either 15:00 or 16:00 after ~33 h of continuous wakefulness in the laboratory. Subjective fatigue measurements were made immediately after leaving the simulator, using two scales: 1) the Profile of Mood States (POMS), a 65-question survey (10) that scales on six dimensions (tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment); and 2) the Visual Analog Scale (VAS), a computerized scale involving ratings of various dimensions (alertness, anxiety, energy, confidence, irritability, jittery, sleepy, and talkative) with a line and pointer (13). The fatigue dimension on the POMS and the sleepy dimension on the VAS were considered the two most direct measures of subjective fatigue. Resting EEG measurements, cognitive tasks, and breaks filled the remaining interval between flights.

RESULTS

Subjective Fatigue Ratings

The ratings on the POMS fatigue dimension and the VAS sleepiness scales are shown in **Fig. 2**. As evidenced, the two measures paralleled each other fairly well, although their between-pilot correlation was somewhat modest ($r = +0.58$). Pilots reported little subjective fatigue/sleepiness over the first four flights, a large increase in fatigue/sleepiness over the next two flights (i.e., in the early morning hours), and continued high subjective fatigue over the final four flights. Using repeated-measures Analyses of Variance (ANOVAs) with Huyn-Feldt corrections for violations of sphericity, both the POMS fatigue and VAS sleepiness measures varied highly significantly across sessions: $F (1.49, 13.99) = 18.94$, $p < 0.001$ for POMS; $F (4.24, 38.16) = 27.84$, $p < 0.001$, for VAS. Because subjective fatigue, as well as flight error (see 16) increased markedly only after the fourth flight, we felt justified in collapsing conflict flights 1 and 4 as "early" ("rested") flights and flights 7 and 10 as "late" ("fatigued") flights in subsequent analyses.

Perceptual Measures

The percentages of flights in which particular conflicts were reported during the four conflict flights are shown in **Fig. 3**, broken down by individual conflict and age group of the pilots. On average, the motion conflicts were more frequently perceived than the visual conflicts (60.5% vs. 25.0%), with the runway illusion being the least reported (15%). Also, older (and more experienced) pilots generally recognized and reported more of the SD conflicts than did the younger pilots (62.9% vs. 37.9%, respectively), with only the runway illusion being reported more frequently by the younger pilots. The percentage of reports was greater in the last two fatigued conflict flights than for the two rested conflict flights, but this difference was very slight (53.5% vs. 47.1%).

A mixed ANOVA was run on the perceptual data, with two within-subject effects (conflict and early late)

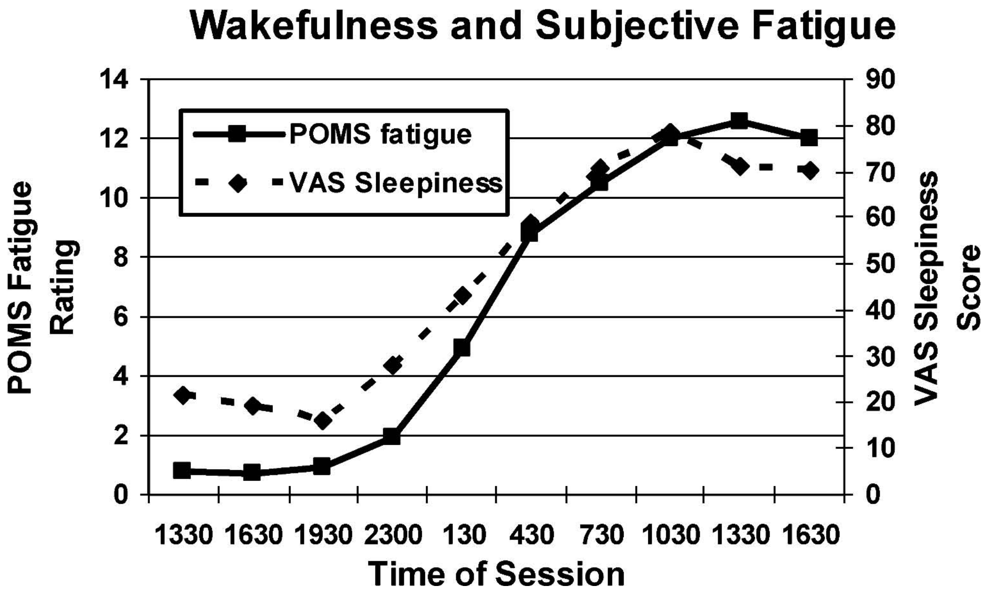

Fig. 2. Subjective fatigue across 10 flight sessions, as measured by the POMS fatigue scale and the VAS sleepy axis.

and one between-subjects effect (pilot age). Because violations of sphericity were non-significant for the conflict main effect (p = 0.10) and the conflict by early late interaction effect (p = 0.11) using Mauchly's test, no corrections to the ANOVA were performed. The within-subject analysis showed a highly significant effect of conflict type [F (6,48) = 4.68, p = 0.001]. Post hoc pair-wise comparisons showed that the percentage of reports for the runway conflict was significantly less ($p < 0.05$) than those for all other conflicts except the cloud-deck and Coriolis illusions, which differed from it at the 0.053 and 0.096 levels, respectively. The percentage of sloping cloud-deck reports was significantly less ($p < 0.05$) than for the pitch-up conflict and the post-rotatory conflict at the end of Segment 2, but did not differ from any other conflicts. By contrast, none of the motion-conflict reports differed even marginally from each other.

There was a marginally significant effect of age on the percentage of conflicts reported [F (1,8) = 5.09, p = 0.054]. The early/late comparison was not significant (p = 0.07), but the early/late by conflict interaction effect did prove significant [F (6,48) = 2.48, p = 0.036]. The latter effect was mainly due to the significant tendency for the pitch-up and sloping cloud-deck conflicts to be reported more frequently in the later two as compared with the early two conflict flights—75% vs. 55% for the pitch-up conflict and 50% vs. 20% for the sloping cloud-deck conflict (p = 0.037 and 0.024, respectively). No other main or interaction effects involving perceptual reports were significant.

Flight Performance Measures

The differences in performance during the conflict portions of Segments 1, 3, 4, and 7 are shown in **Tables II and III**. Table II shows the average pitch during the excess pitch conflict in Segment 1 along with glide slope during landing in Segment 7 (when pilots were instructed to maintain a 3° slope). Table III shows average bank while the sloping cloud deck was visible in Segment 3 (when pilots were supposed to maintain wings-level flight) and during the Coriolis head-pitch in the Segment 4 level turn (when pilots were supposed to maintain a 45° bank). The raw bank averages are shown for the Segment 3 portions in which pilots experienced either a leftward-rotated cloud deck (leading to a perceptual conflict of right bank and a left-bank control input, expressed in negative values), a rightward-rotated cloud deck (leading to a perceptual conflict of left bank and a right-bank control input, expressed in positive values), or no bank (in the non-conflict trials). In the segment 4 (Coriolis) data, the bank data from the rightward-turn flights (right-conflict), leftward-turn flights (left-conflict), and non-conflict flights (composed of an equal number rightward and leftward flights)

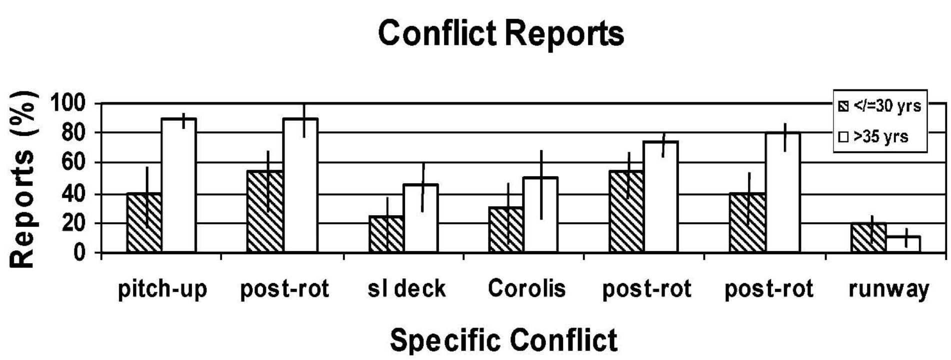

Fig. 3. The percentage of conflict reports for each SD conflict and pilot age group. Thin bars represent standard errors.

TABLE II. PITCH AND GLIDE SLOPE IN EARLY AND LATE CONFLICT AND NON-CONFLICT FLIGHTS (IN DEGREES).

Measure	Early Conflict	Late conflict	Early Non-conflict	Late Non-conflict
Pitch (Segment 1)	+9.54	+9.53	+9.61	+9.53
Glide Slope (Segment 7)	−4.56	−4.41	−3.77	−3.34

were all converted to absolute values because we were merely interested in whether bank increased or decreased due to the presumed illusion of roll generated by the head-pitch movement. Mixed ANOVAs with two repeated factors (conflict and early/late) and one between factor (pilot age) were conducted.

The pitch means during the takeoff segment were highly similar for the early and late non-conflict and conflict flights, varying by less than 1% (from +9.53° to +9.91°). There was no significant conflict vs. non-conflict, early vs. late, or pilot age effects on Segment 1 pitch (all $p > 0.10$). However, glide slope in Segment 7 did differ among conditions, especially between conflict flights (slope of −4.49°) and non-conflict flights (slope of −3.56°). The difference between the conflict and non-conflict glide slopes was highly significant [$F(1,8) = 31.94$, $p < 0.001$]. Glide slope was also reduced for the later relative to earlier flights, as indicated by a significant difference between the early and late glide slope means [$F(1,8) = 6.11$, $p = 0.039$]. However, the differences between the early and late mean glide slopes were small and mostly confined to the non-conflict flights (0.43°) as opposed to conflict flights (0.15°), consistent with a marginally significant early/late by conflict interaction effect [$F(1,8) = 4.85$, $p = 0.059$]. There was no main effect of pilot age ($p = 0.59$), nor did age significantly interact with either the conflict or early/late effects ($p > 0.60$ in both cases).

The two conflicts expected to create bank errors had varying effects. The Coriolis illusion resulting from the head tilt in Segment 4, which was perceived on less than half of all occasions, had little effect on bank control. Accordingly, the ANOVA revealed no significant differences ($p > 0.10$) between conflict and non-conflict flights or between early and late flights, nor was there a significant interaction between these two variables. By contrast, the sloping cloud deck in Segment 3 produced distinctly different bank errors, depending on the slope of the bank. Cloud decks depicting a left bank resulted in a rightward bank error of 0.45°, cloud decks depicting a right bank resulted in a leftward bank error of −0.6°, and very little bank deviation (+0.15°) was found when there was no slope to the deck (Table III). These differences were reflected in a significant effect of conflict [$F(2,16) = 7.41$, $p = 0.005$] in the mixed ANOVA. Although the difference between the right and left conflict flights was greater for late as compared with early flights (1.51° vs. 0.59°) and for older vs. younger pilots (1.86° vs. 0.24°, not shown in Table III), only the age by conflict interaction effect even approached significance [$F(2,16) = 3.37$, $p = 0.06$].

DISCUSSION

The results of this study document that the SD conflicts employed in this study were recognizable to varying degrees and did, in some cases, influence performance. Overall, the effects of these conflicts on perception (e.g., Type II SD) and performance were not altered by fatigue, although fatigue did slightly affect the perception of some individual conflicts/illusions. The two conflicts that were the least reported—the sloping cloud deck and the narrow, up-sloping runway—were the only ones to yield significant effects on performance, which demonstrates that simulator conflicts can induce Type I (unrecognized) SD. The effect of pilot age/experience on SD in the GSOS was somewhat complex in that older, more experienced pilots were marginally more likely to recognize the SD conflicts, but at least in the case of the sloping cloud deck, tended to be slightly more influenced by it in terms of their bank deviation.

The results of this study clearly demonstrate that, with the proper device, embedding physiologically appropriate spatial disorientation conflicts in a relatively unobtrusive manner can be achieved during a normal flight simulation, along with the measurement of their effects on perception and performance. Prior to this study, the notion of embedding SD conflicts in an ongoing flight profile faced many potential hurdles. For one, extraneous motion was required to set up many of the conflicts; for example, continuous yawing was necessary to produce the cross-coupled Coriolis illusion, and the cessation of the continuous yawing produced the various post-rotatory sensations. We were concerned that pilots would report this motion as readily as the intended conflicts, but this did not prove to be the case as false alarms were reported on < 2% of all segments and, by using slower ramp accelerations, might be reduced still further in the future. We were also concerned that pilots might deviate so far from the designated route or parameters that the timing of the conditional events associated with the various conflicts would be upset, as happened repeatedly with less experienced pilots in preliminary data-collection flights. However, very few interventions of the GSOS operator were required due to the excellent flying proficiency of

TABLE III. BANK FOR EARLY AND LATE RIGHT CONFLICT, LEFT CONFLICT, AND NON-CONFLICT FLIGHTS (IN DEGREES).

Measure	Early Right conflict	Late Right conflict	Early Left conflict	Late Left conflict	Early Non-conflict	Late Non-conflict
Bank (Segment 3)	−0.34	0.86	+0.25	+0.65	+0.10	+0.20
Bank (Segment 4)	40.94	43.35	41.13*	42.34*	42.73**	41.66**

*Converted to absolute values.
**Average of left and right non-conflict flights after converting left non-conflict values to absolute values.

our trained military pilots, and no pilot-induced crashes or other breakdowns of the profile occurred. Moreover, the GSOS itself performed well, in that it failed on only 1 of the 100 flights due to a computer glitch.

On average, the various conflicts were reported about 50% of the time. We could have, in retrospect, designed the conflicts to be more frequently perceived, but that was not our goal since the 50% level of recognition allowed for other effects (e.g., age and sleep deprivation) to be manifested in the data. In the case of the motion conflicts, we could have added even more sustained yaw motion during the turns by more gradually ramping up the yaw velocity, and we could have demanded a larger head tilt in the case of the Coriolis illusion. The sloping cloud-deck illusion could have been enhanced by requiring the pilot to look out the window for a longer period of time (either by breaking the cloud deck sooner or by delaying the appearance of the outside traffic) and perhaps by adding more realism to the clouds. It is not clear what more we could have done (or should have done) in the case of the illusory runway, since it had a highly significant effect on glide slope even though it was very rarely recognized.

Indeed, the illusory runway and, to a lesser extent, the sloping deck were able to significantly produce Type I SD, which is a very valuable didactic demonstration and to the best of our knowledge has not been systematically measured before during a realistic flight simulation. During the period in which they were visible, the left and right versions of the sloping cloud deck produced average bank deviations of $-0.6°$ and $0.45°$, respectively. The black-hole runway illusion proved even more powerful and increased glide slope by an average of $\sim 1°$. This led pilots on average to reach the landing decision height (100 ft above ground, when we stopped calculating glide slope) over 1 mi ($\sim$5600 ft) from the edge of the runway. While this dangerous "duck-under" tendency did not cause any actual crashes because pilots were aware of the runway altitude, it could very well have done so had elevated terrain existed leading up to the runway rather than the level terrain that was actually present in our database. One possible reason why the visual illusions had a larger effect on flight performance is that pilots spent more time fixating out-the-window (and away from their instruments) during them.

Despite a slightly greater tendency to report the two visual conflicts in the later flights, there were overall no significant effects of sleep deprivation (i.e., early vs. late flights) in our data for either the conflict reports or the specific performance parameters. This was somewhat surprising in that sleep deprivation was previously shown to delay the ability to detect and/or recover from visual SD conflicts in a rotary simulator (9) and also because flying precision was significantly impaired in our own study in the later flights (16). It appears that our fixed-wing pilots were as experienced as the rotary-winged pilots in the U.S. Army study (9) and they were similarly fatigued, with both sets of pilots reporting a POMS fatigue score of $\sim$12 in the later flights. However, the tasks in the two studies were very different, in that LeDuc et al. (9) measured the time required to both detect and recover from an SD conflict, whereas we measured the recognition of conflicts and their continuous effect on specific flight parameters during specific maneuvers. Indeed, the times required to recover from the perturbations in Leduc et al.'s study ranged from $\sim$60 s in the case of pitch and roll to $>$ 128 s in the case of drift, whereas our measurements were made in a much shorter time-frame.

The results of this study should not be used to argue that sleep deprivation has no effect on susceptibility to SD. There is no doubt that our pilots were highly fatigued by the sixth flight (the first of the later ones), and indeed a total of six visually confirmed micro-sleeps (from three pilots) were recorded at or beyond this point. However, by the seventh flight—the first of the late conflict ones—all of our pilots had already flown the flight profile a total of nine times (including the three practice flights) and were highly trained on it. One possible reason that perception and performance during SD conflicts were not more greatly altered by sleep deprivation in our study was that instrument scanning, also measured in the current study and reported by Previc et al. (16), was largely unaffected by our sleep deprivation conditions. Indeed, the amount of time spent on the 5 major flight instruments (the electronic attitude direction indicator, airspeed indicator, altimeter, heading indicator, and vertical velocity indicator) never varied from the early to late flights by more than 12% in any our pilots, and only 2 of the 10 transitional probabilities among the 5 instruments did so (16). It has long been held that a proper and unbroken instrument crosscheck is important in avoiding Type I SD (15). Had our pilots flown a novel and more difficult profile while fatigued, their instrument scan may not have been as solidly maintained and the susceptibility to Type I SD in particular would have been increased.

Finally, the marginally significant effect of age suggests that younger pilots may not be as adept as older pilots at recognizing conflicts between their perceptions and their instrument readings. At least one study has demonstrated that experienced pilots are more likely to report episodes of SD events (7), but experience level is less likely to predict actual SD mishaps (1,4). It is possible that older pilots are more sensitive to the extraneous motion used to set up the conflicts, in that they reported a total of 10 false alarms as compared with only 1 for the younger pilots. Interestingly, experienced pilots in our study who were better able to recognize the conflicts were not any less susceptible to being influenced by them in terms of their bank or glide slope performance. However, because Type II or recognized SD much more infrequently leads to aircraft mishaps than does Type I SD, it has long been held that it is important to avoid Type I SD by maintaining good awareness of any conflict situations (15). The results of this study suggest that SD training in the GSOS or some similar device might benefit younger pilots, who, despite their good flying proficiency, have yet to experience many of the most prominent SD illusions in flight and may be less aware of the propensity for such conflicts to occur. If the simulator-based SD training is not included as part of the physiological curriculum in undergraduate pilot training, then it should, at the very least, be included early in the pilot's operational flying career.

In conclusion, the effect of sleep deprivation on SD was mostly non-significant, both in terms of Type I (recognized) and Type II (unrecognized) SD. The lack of SD effects occurred despite large increases in subjective fatigue as well as overall decrements in flight performance (16). Because many different events occur during sleep deprivation that could influence perception and performance during SD conflicts, it is somewhat surprising that the SD effects were so little influenced by the increased fatigue. By contrast, the age of the pilot did affect the ability to detect SD conflicts, presumably because of the older pilots' greater experience with similar conflicts during their flying careers.

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