



NAVAL MEDICAL RESEARCH UNIT DAYTON

## **Effects of Various Types of Cockpit Workload on Incidence of Spatial Disorientation in Simulated Flight**

by Henry P. Williams<sup>1</sup>, Dain S. Horning<sup>1</sup>, Benton D. Lawson<sup>2,3</sup>, Charles R. Powell<sup>1,4</sup>,  
Frederick R. Patterson<sup>1,5</sup>

<sup>1</sup> Naval Medical Research Unit - Dayton

<sup>2</sup> Naval Submarine Medical Research Laboratory

<sup>3</sup> U.S. Army Aeromedical Research Laboratory

<sup>4</sup> Henry M. Jackson Foundation for the Advancement of Military Medicine

<sup>5</sup> Oak Ridge Institute for Science and Education

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The study protocol was approved by the Wright-Patterson Air Force Base Institutional Review Board in compliance with all applicable federal regulations governing the protection of human subjects.

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Henry P. Williams<sup>1</sup>, Dain S. Horning<sup>1</sup>,  
Benton D. Lawson<sup>2,3</sup>, Charles R. Powell<sup>1,4</sup>, and Frederick R. Patterson<sup>1,5</sup>

<sup>1</sup>Naval Medical Research Unit – Dayton

<sup>2</sup>Naval Submarine Medical Research Laboratory

<sup>3</sup>At the U.S. Army Aeromedical Research Laboratory  
for most of the duration of this work

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## Abstract

Spatial disorientation (SD) refers to a pilot's misperception of the attitude, position, or motion of his/her aircraft, and it is one of the leading causes of fatal mishaps in military and civilian aviation. While several studies have examined the effects of SD on cognition or have linked increased cockpit workload to SD, few specifically and systematically compared how various types of workload interfere with maintenance of spatial orientation. In the current study, 24 pilots flew simulated flights in four different workload conditions. The baseline condition presented no additional workload, while the other conditions added either a verbal working memory task, a spatial mental rotation task, or a spatial variable-following-distance task. The verbal working memory task condition resulted in a statistically significant threefold increase in the number of control reversal errors, while the mental rotation and variable-following-distance task conditions yielded significant increases in unusual attitudes. The results are discussed from attentional resource and task interference perspectives, and the importance of using different SD measures is emphasized.

## Introduction

Aviation spatial disorientation (SD) can be defined as a pilot's inaccurate perception of the attitude, position, or motion of his/her aircraft relative to gravitational vertical, the Earth's surface, or other points of reference, including other aircraft (Benson, 1999). SD typically occurs under some form of degraded visual environment (DVE) such as flight in instrument conditions or at night (Gibb, Gray, & Scharff, 2010). If not recognized and resolved quickly, this misperception can lead to controlled flight into terrain (CFIT), midair collision, entry into unusual attitudes, or inappropriate control inputs resulting in aircraft stall and/or loss of control inflight (LOC-I) (Patterson, Cacioppo, Gallimore, Hinman, & Nalepka, 1997). The prevalence of this problem has been well documented by mishap reports and surveys indicating that nearly all pilots experience some form of SD during their careers (Braithwaite, Durnford, Crowley, Rosado, & Albano, 1998; Singh & Navathe, 1994; Tormes & Guedry, 1975). Accident statistics help quantify the incidence and severity of this deadly threat to aviation safety. Poisson and Miller (2014) reviewed mishap data from the United States Air Force Safety Center's Air Force Safety Automated System. This extensive review covered the 21 year period from fiscal years 1993 through 2013, and it focused upon Class A mishaps, which by definition result in a loss of life, permanent disability, and/or more than \$2 million in property damage. The authors found a total of 601 Class A mishaps, and 72 (12%) of these included SD as a causal factor. Tragically, there were 101 lives lost in those 72 mishaps.

When fatality rates of non-SD and SD-related Class A's were compared, it was found that 16.1% of non-SD mishaps involved a fatality, but distressingly, 61.1% of the SD-related mishaps were fatal.

SD is certainly a problem for the Army and Navy as well. Regarding the U.S. Army, Braithwaite, DeRoche, Alvarez, and Reese (1997) reported that between 1987 and 1995 there were 970 Class A through C mishaps. Of these, 291 (30%) involved SD and claimed 110 lives. A more recent U.S. Army Combat Readiness Center/Safety Center review of fiscal 2002 through fiscal 2013 data shows DVE was responsible for 25% of Class A/B mishaps during that time, with DVE mishaps accounting for 46% of total fatalities (Edens & Higginbotham, 2014). Similarly, the U.S. Naval Safety Center indicates that SD was the #1 aeromedical causal factor of Class A mishaps occurring from 1990 – 2008 (Gibb, Ercoline, & Scharff, 2011).

In the general aviation (GA) community, SD has been cited as a causal factor in 11% to 16% of all fatal accidents (Collins & Dollar, 1996; Kirknum, Collins, Grape, Simpson, & Wallace, 1978). Furthermore, in GA accidents that were attributed to SD, the fatality rates were alarmingly high. Kirknum et al., (1978) reported that 90% of these were fatal accidents, while Mortimer (1995) found that number to be 92%.

Finally, a report from the Boeing company listed LOC-I and CFIT as the top two causes of fatalities in the worldwide commercial jet fleet (of any manufacture) in the period covered by 2004 through 2013 (Boeing, 2014). While SD was not explicitly listed as the cause of these mishaps, LOC-I and CFIT are strongly associated and frequently caused by SD (Veronneau & Evans, 2004; Lawson, Smith, Kass, Kennedy, & Muth, 2003). The total number of lives lost in the 16 LOC-I and 16 CFIT accidents was a staggering 2380.

Clearly, SD is a threat to safety in military, commercial, and general aviation. Traditional approaches to combatting SD have focused on training, ranging from simple demonstrations in a Bárány chair to sophisticated motion-base flight simulators, to training in actual aircraft under simulated instrument conditions. Other methods of reducing SD incidence have concentrated on novel cockpit instrument design. While these approaches certainly have merit, the fact that the SD mishap rate is not declining (Gibb et al., 2011) suggests that additional strategies are needed. One possible approach is to gain a better understanding of the root causes of and contributing factors to SD by conducting flight simulator research under controlled laboratory conditions. Knowledge gained from this type of research can help to develop and validate SD models that can simulate or predict SD during a wide variety of relevant stimulus situations known to occur in flight.

Apart from surveys and analyses of mishap data, a number of studies have examined incidence of SD in simulators. A subset of these studies (Webb, Estrada & Kelley, 2012; Braithwaite, Durnford, Groh, Jones, Higdon, Estrada & Alvarez, 1998; Raj, Kass & Perry, 2000) looked at relationships between increased workload and various degrees of spatial orientation. Webb et al. (2012) evaluated how performance on two different secondary cockpit tasks was impacted by SD. One of the secondary tasks was a working memory task in which participants had to remember a string of up to nine single digit numbers. The other task also presented a string of single digit numbers but required subjects to add the two most recent numbers. The primary task was flying a helicopter simulator in various weather conditions and scenarios, some of which were designed to induce SD. The results showed that SD did significantly disrupt secondary task performance, but the study was not specifically designed to assess the converse: how does the workload imposed by a secondary task affect the probability of SD?

Braithwaite, Durnford, Groh et al. (1998) came closer to addressing this question. They tested pilots on instrument flight precision and unusual attitude recovery, comparing performance with and without a secondary task, which was a forced choice (High or Low) two-tone audio discrimination task. They also

compared standard cockpit instrumentation to a novel display. Generally the results showed that the secondary task negatively impacted IFR flight precision with the standard instrument display, while unusual attitude recovery, and presumably spatial orientation, were not significantly affected by that particular additional task.

Raj et al. (2000) also studied a secondary task's impact on spatial awareness, testing pilots' abilities to maintain a stable hover, with and without the additional task and with and without a vibrotactile stimulus designed to provide veridical drift cues. The secondary task required pilots to add a series of three-digit number pairs. While the impact of the math task on hover performance was not *statistically* significant, hover quality was degraded as measured by the number of drift excursions of more than ten feet from the designated hover point, when the vibrotactile cueing was not provided (A.K. Raj, personal communication, February 20, 2018). This ten foot limit is a standard operational pass/no pass criterion for hover proficiency.

While the three aforementioned studies examined various aspects of spatial awareness in the presence of certain secondary tasks, none specifically and directly compared how different types of secondary tasks, and their associated workload, affected the probability of SD. Performing that evaluation was the goal of the current research.

Three aviation-relevant secondary tasks were created to add workload to the primary task of flying a simulated formation flight. These secondary tasks were developed in-house and for the purposes of this experiment. The tasks were unique from each other and designed to induce different types of workload (e.g., verbal vs. spatial), with the intent of determining if various types of cognitive tasks relevant to piloting were more or less likely to lead to SD. The diversity of the tasks and their influence on incidence of SD should provide richer data than currently exists for subsequent SD model development.

## **Method**

### **Participants**

Participants in this study were 24 male pilots, ranging in age from 24 to 61 years, with a mean of 47.5 years. Twelve of the 24 held at least a civilian private pilot rating, 11 were current or former military pilots, and one was a civilian student pilot who had soloed. Sixteen held instrument ratings. Flight hours ranged from 40 to 5500, with a mean of 1708.3. Subjects were recruited via word of mouth, posted flyers, and e-mail contact, and they were not compensated.

### **Apparatus**

The experiment was conducted in a fixed-base (non-motion) flight simulator (see Figure 1) using X-Plane version 10.4 and a T-6 Texan II flight model developed in-house. Engine power was controlled with the left hand via a Thrustmaster Warthog throttle and pitch and roll were controlled with the right hand via a Thrustmaster Cougar joystick. Yaw was controlled with Flight Link adjustable rudder pedals. Participants sat in a SPARCO seat that was adjustable in height. The cockpit instrument panel was displayed on a 26 inch diagonal ELO 2639L monitor with a resolution of 1366 x 768 pixels. The out-the-window (OTW) scene was displayed on a 60 inch diagonal Samsung UN60H6350AF LED High Definition 1080p flat panel display which provided a 87° horizontal x 49° vertical field-of-view. Head and eye movements were tracked and recorded with an ISCAN AA-ETL-600 Head and Eye Tracking System.



*Figure 1.* NAMRU-D fixed-base flight simulator cockpit

## **Procedure**

The study protocol was approved by the Naval Medical Research Unit Dayton Institutional Review Board. When the participant arrived at the flight simulator lab the experimenter reviewed the informed consent document (ICD) with them, answered any questions, signed the ICD after the participant signed, and provided them with a copy.

The participant's flight task was to follow a pre-recorded lead aircraft through a series of turns, climbs, and descents. Each trial began with the aircraft in straight and level flight, at 9,500 feet above mean sea level (MSL). There was a level undercast (cloud deck) at 9000 feet MSL, and it provided a level and well-defined visual horizon. Visibility above the clouds was excellent and set to 25 statute miles. Participants were told to fly in trail formation and to stay close enough to easily see the lead aircraft's attitude. They were also told to fly at the same altitude as the lead.

Two lead aircraft flights (Flight A and Flight B) were recorded, each a mirror image of the other. In both flights the lead aircraft executed four right (R) and four left (L) turns, each with a 90° heading change and at a 45° angle of bank (AOB). In Flight A, the order of turns was L, L, R, R, L, R, L, R, and in Flight B turns were exactly opposite. For both flights, turns 1, 2, and 4 were level turns, turn 3 was climbing, and the last 4 turns were descending. At approximately 2 min 30 s into the flight, turn 6 brought the formation into the clouds, where it remained for the rest of the flight. While in the clouds, the lead aircraft remained visible but the horizon was completely obscured. Participants were told that while the flight was in the clouds the lead would disappear at some point, whereupon they should scan their flight instruments, level their wings and start a gentle climb. At approximately 3 min 30 s the lead disappeared while established in the eighth turn, in the clouds and with no visible horizon. The experimenter ended the trial shortly after the subject stabilized the aircraft in a wings-level gentle climb.

## **Workload Conditions**

Four workload conditions were created and are described below. Each subject flew six flights in each workload condition, three Flight A's and three Flight B's, in an alternating A, B pattern.

1) No Added Workload (NAW) - For this condition participants simply followed the lead aircraft with no added secondary task. Participants were told to fly in trail formation at the same altitude as the lead. They were told that the spacing between their aircraft and the lead aircraft was not critical, but that they should stay close enough to easily see the lead aircraft's attitude. They were instructed that when the lead disappeared they should look at their attitude indicator, level their wings, and start a gentle climb. The trial ended shortly after the climb was established. Since there were no additional tasks, this was considered to be the control condition.

2) Working Memory Task (WMT) - This condition was the same as the NAW task above, but with a verbal working memory task (WMT) added. At the beginning of each flight, a set of 7 letters was presented on the OTW display for 10 seconds, and subjects were told to memorize this target letter set. In order to limit phonetic rehearsal the target letters were arranged to avoid forming pronounceable words (e.g., FVPGCQY). After the target set disappeared, a probe letter was shown on the OTW display and presented audibly every four seconds, and the participant pressed one of two buttons on the joystick to indicate whether or not the probe was a target letter. Of the 49 probe letters presented on each WMT flight, 15 (31%) were targets. The targets were randomly dispersed among the probes in a pre-recorded order. Six different memory set/probe set combinations were recorded, one for each of the six WMT flights. Subjects were told that if they forgot the memory set, they could ask for a "refresh", whereupon the letters would be redisplayed for another 10 s. Response time and percent correct were automatically recorded.

3) Direction Finding Task - This condition was the same as the NAW condition, but with an added secondary mental rotation task called the Direction Finding Task (DFT). The DFT presented a simulated sensor image of four orthogonally positioned storage tanks surrounding a building (see Figure 2). The storage tanks were located on the North, East, South, and West sides of the building. The sensor image was displayed on a small touchscreen tablet mounted adjacent to the lower left side of the cockpit instrument panel. The sensor image simulated a forward looking camera view that tracked the area of interest, and the image rotated as the aircraft turned. The rotation of the image always kept it "Track Up", aligned with the nose of the subject's aircraft. That is, "Up" on the DFT sensor screen was also the aircraft's current heading.

The sensor display prompted the subject with an audio tone, and with text instructing them to designate either the North, East, South, or West storage tank. In order to correctly perform the DFT, the subject had to look at the instrument panel to determine his/her aircraft's heading, then look at the sensor screen realizing that the top of that screen (or "Up") represented his/her aircraft's current heading. For example, in Figure 2, if the current aircraft heading was 225° (southwest), the correct storage tank (north) would be the one on the bottom right. The subject designated the tank with a finger tap on the touchscreen. A new DFT problem was presented in a pre-determined random order every 15 s, with a total of 14 DFT problems per flight. Response time and percent correct were automatically recorded.

4) Variable following-distance task (VFDT) - This condition was the same as the NAW condition, but with an added secondary task requiring subjects to follow the lead aircraft at various distances. A scale appeared on the simulator's OTW display indicating the requested or "command" following distance (in feet) as well as the actual following distance (see Figure 3). Command distances ranged between 400 and 1200 feet at 200 foot intervals. A new distance was presented in a predetermined random order every 40 s, with a total of 6 distances per flight. Following distance error (deviation from command distance) was automatically recorded throughout the flight.

Participants were told to treat all of the secondary tasks as "Critical Mission Tasks". They were instructed to do as well as they could both in flying the simulated aircraft, and on the critical mission



Figure 2. Screen shot of the Direction Finding Task.



Figure 3. Screen shot of the Variable Following-Distance Task (VFDT), with 400 feet as the requested following distance, and 345 feet as the actual distance.

tasks. While the secondary tasks were designed to impose different types of workload, pilot testing was used to adjust the amount of workload in an effort to make the tasks roughly equal in that dimension.

Before the simulator flights began, the eye tracker was fitted on the subject and calibrated. The experimenter explained the controls, displays, and operating characteristics of the simulator, and then the subject flew a full practice flight in each of the four workload conditions.

After the practice flights the participants flew six consecutive data collection flights in each workload condition. Subjects were provided a break after completing half of the 24 data collection flights.

## Experimental Design

This experiment used a repeated measures (within subjects) design with workload as the single factor. With four workload conditions there were 24 possible presentation orders, and these were fully counterbalanced across the 24 participants.

The main dependent variables were number of Control Reversal Errors (CREs) and the percentage of time participants reached or exceeded 65° AOB in the clouds. A CRE was defined as a lateral (roll) stick movement in the direction opposite to that required for a wings level recovery, where the errant stick input:

- had to be 15% or more of the maximum possible stick throw from the center/neutral position, and/or
- resulted in a 5° or more change in aircraft AOB in the wrong direction, steepening the bank angle rather than leveling the wings

For the purposes of this study the CRE period of interest was initiated by the lead aircraft disappearance, when the subject was to look at the attitude indicator, determine their aircraft direction of bank, and recover to a wings level attitude. In these flight conditions, the only reasonable explanation for moving the stick in the wrong direction and committing a CRE is that the pilot has misperceived the direction of bank, either by misinterpreting the attitude indicator or by feeling they are banked in the opposite direction. In either case, the pilot is spatially disoriented.

The 65° AOB threshold was chosen since it is a high bank angle for anything other than acrobatic flight, and it is an extremely high bank angle for flight in the clouds. Also, the FAA requires pilots and passengers to wear parachutes on flights where the intent is to exceed 60° AOB, and the threshold chosen here exceeds the FAA's. Percentage of time, rather than cumulative time, at or beyond 65° AOB was chosen since time in the clouds and trial length could vary slightly depending on pilot performance.

While these criteria are somewhat arbitrary, if exceeded they are good indicators that the pilot is uncertain of the aircraft's attitude. In the clouds it is very unlikely that a pilot would intentionally move the stick in the wrong direction or exceed 65° AOB, so these actions can be taken as signs of SD.

Another dependent variable of interest was altitude error, or altitude difference from the lead aircraft, since subjects were told to fly co-altitude with the lead. While performance here may not be a direct measure of spatial orientation, this task may be one that gets neglected or shed as workload increases and pilots strive to maintain orientation.

Secondary task performance, aircraft flight parameter data, and eye and head tracking information were also collected. The eye tracking information was used to confirm that, after the lead aircraft disappeared, subjects had transitioned to instruments before making any roll inputs to recover wings-level, and that

they were not still looking outside for the lead and perhaps unknowingly moving the stick. Verifying that they were looking at their instruments when an errant stick movement occurred helps classify the error as a CRE and not an unintentional movement made while searching outside.

Participants were asked to provide subjective workload ratings for each workload condition. The ten-point Bedford Pilot Workload Rating Scale (Roscoe & Ellis, 1990) was used to obtain these ratings. After flying each workload condition, participants were also asked to use a ten-point scale to provide ratings of any experience of SD. The anchor points on this scale were:

1 - "I did not feel spatially disoriented at all"

and

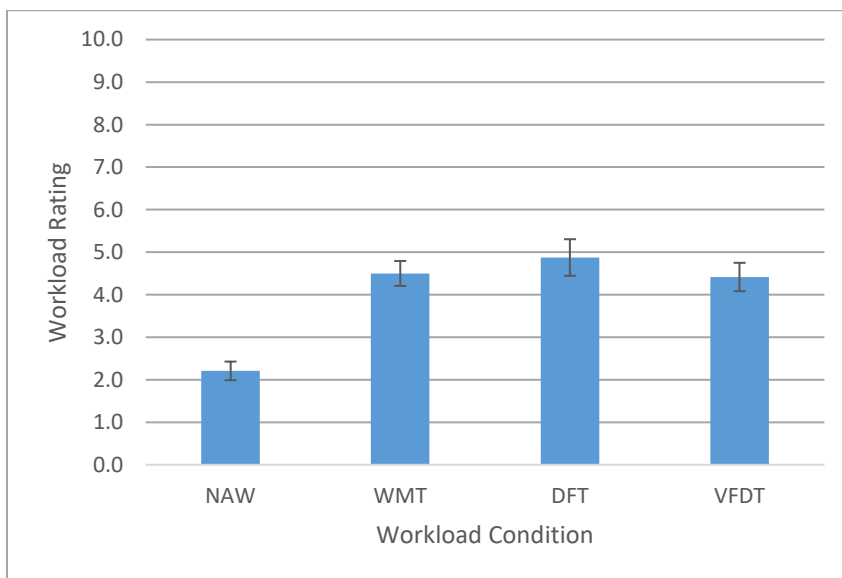
10 - "I felt severely spatially disoriented".

The workload and SD ratings were collected after the last flight in each workload condition.

## Results

### Subjective Ratings

Ratings of workload and SD are plotted in Figures 4 and 5, respectively. Given the subjective nature of the data, non-parametric analyses were applied.



*Figure 4.* Average Bedford workload ratings for the four workload conditions. NAW = No Added Workload, WMT = Working Memory Task, DFT = Direction Finding Task, and VFDT = Variable Following Distance Task.

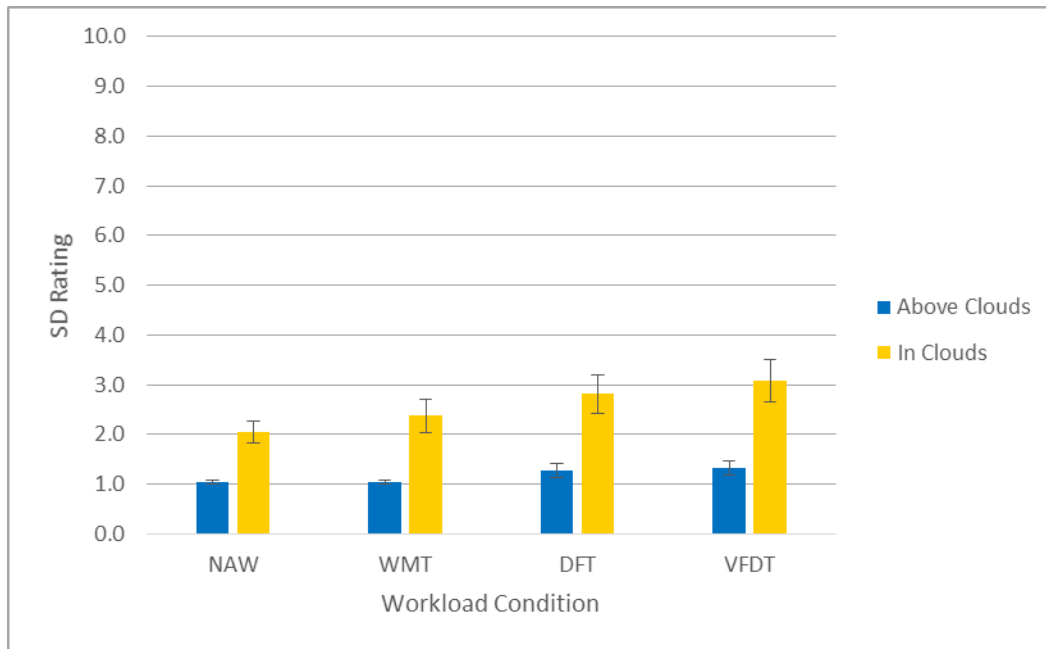


Figure 5. Average subjective SD ratings for the four workload conditions. NAW = No Added Workload, WMT = Working Memory Task, DFT = Direction Finding Task, and VFDT = Variable Following Distance Task.

A Friedman ANOVA conducted on the workload ratings showed a significant effect for workload condition ( $\chi^2(3, N = 24) = 37.26, p < .0001$ ). Post hoc Wilcoxon matched pairs tests were then run on all pairs. Familywise error was controlled at  $p < .05$  using stepwise Holm-Bonferroni corrections (Holm, 1979). These analyses revealed that the pilots rated the WMT, DFT, and VFDT conditions significantly higher than the NAW condition. There were no significant differences among the WMT, DFT, and VFDT conditions.

A similar approach was taken in analyzing the SD ratings data, with separate Friedman ANOVAs conducted for flight above and in the clouds. For flight above the clouds, the analysis did not reveal any significant differences among the four workload conditions ( $\chi^2(3, N = 24) = 6.79, p = .08$ ). The same pattern of results was found for flight in the clouds ( $\chi^2(3, N = 24) = 6.51, p = .09$ ). With no significant differences detected here, the data were collapsed across workload conditions to compare SD ratings for flight above the clouds ( $M = 1.17, SD = 0.30$ ) to those ratings in the clouds ( $M = 2.58, SD = 1.44$ ). A Wilcoxon Matched Pairs Test found that the SD ratings in the clouds were significantly higher than those above the clouds ( $Z = 3.94, p < .001$ ).

### CREs

With 24 subjects each flying 24 flights, a total of 576 flights were flown, each with an opportunity for a CRE. The actual total number of CREs was 32, or 5.6% of all trials. Thirteen of the 24 participants (54.2%) committed at least one CRE. Figure 6 shows the breakdown of CREs across the workload conditions.

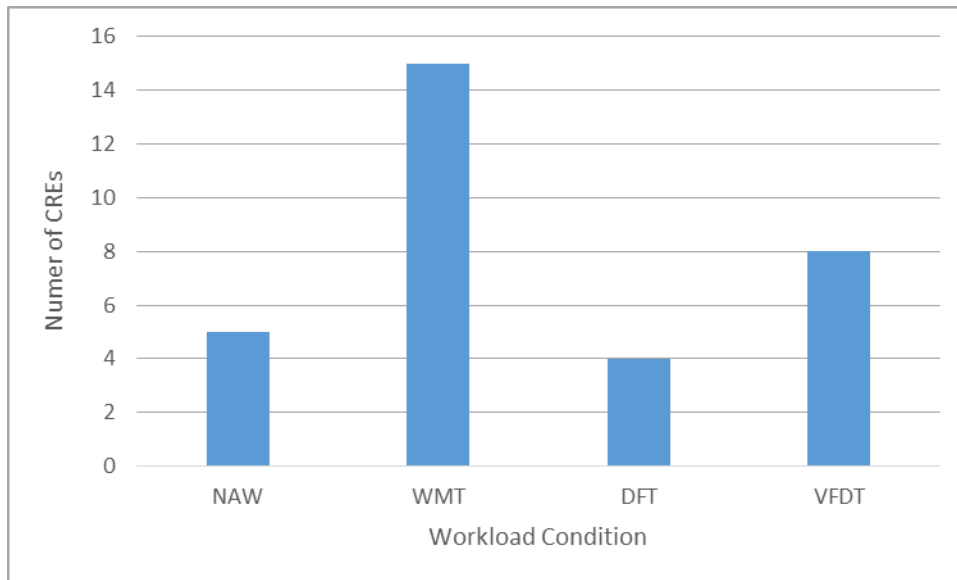


Figure 6. Number of CREs by workload condition.

There are two characteristics of CRE data that make them somewhat unique: CREs are rare events, and they are dichotomous (i.e., for each flight, a CRE either occurred, or it did not). These properties can make data poor candidates for traditional analyses such as ANOVA, so two less common but more appropriate approaches were considered: Poisson and Negative Binomial Regression. Initial inspection of the CRE data indicated they were somewhat over dispersed (the variances were greater than the means), and since the negative binomial model was formulated to handle this condition, that approach was chosen. The NAW condition was set as the baseline or reference workload condition for parameter estimates. The negative binomial regression found workload condition to be a significant predictor of CRE committal,  $\chi^2(3) = 11.01$ ,  $p = .012$ . Parameter estimates revealed that subjects were significantly more likely to commit a CRE only in the WMT condition,  $\chi^2(1) = 4.53$ ,  $p = .033$ . The exponentiated regression weight for WMT showed that subjects were 3 times as likely to commit a CRE compared to the NAW condition.

#### 65° AOB Exceedance

The percentage of time that subjects spent at or beyond 65° AOB in the clouds was calculated for each workload condition, and the results are plotted in Figure 7. Examination of the data for normality revealed that a square root transformation was required for correction. A one-way ANOVA across the four workload conditions was performed on the transformed data, and it detected a significant main effect  $F(3, 69) = 6.20$ ,  $p < .001$ . Post-hoc pairwise comparisons were conducted using stepwise Holm-Bonferroni corrections to limit familywise error to  $p < .05$ . These analyses showed that subjects spent more time at or beyond 65° AOB in the DFT ( $p = .004$ ) and VFDT ( $p < .001$ ) conditions as compared to the WMT condition. No other comparisons showed significant differences.

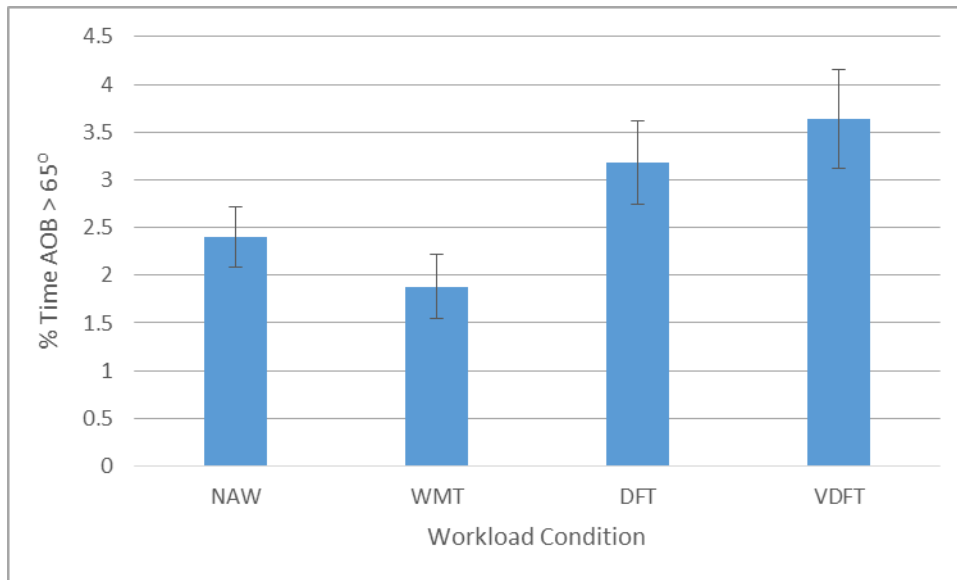


Figure 7. Average percent of time AOB was greater than or equal to 65° for the four workload conditions. NAW = No Added Workload, WMT = Working Memory Task, DFT = Direction Finding Task, and VFDT = Variable Following Distance Task.

Percentage of time was used in the calculations above since time in the clouds and trial length could vary slightly depending on pilot performance. To provide an idea of the average number of seconds per flight spent at or beyond 65° AOB in the clouds, Table 1 converts percentages to seconds.

Table 1

*Mean percentage of time and number of seconds spent at or beyond 65° AOB in the clouds*

	NAW	WMT	DFT	VFDT
% Time	2.40	1.88	3.18	3.64
Seconds	1.51	1.18	2.00	2.29

#### Altitude Error

Altitude Error was defined as the absolute value of the altitude difference between the lead and subject's aircraft. The data were divided into the two visibility conditions (above and in the clouds) and into the four workload conditions. The means are plotted in Figure 8. Examination of the data for normality indicated a natural log transformation was appropriate for correction, and a 2 x 4 ANOVA was performed on the transformed data. The main effect for visibility condition was significant ( $F(1, 23) = 11.41, p = .003$ ) with lower altitude error during flight in the clouds. The main effect for workload condition was also significant ( $F(3, 69) = 11.53, p < .001$ ). The Visibility by Workload condition interaction was not significant ( $F(3, 69) = 1.76, p = .16$ ).

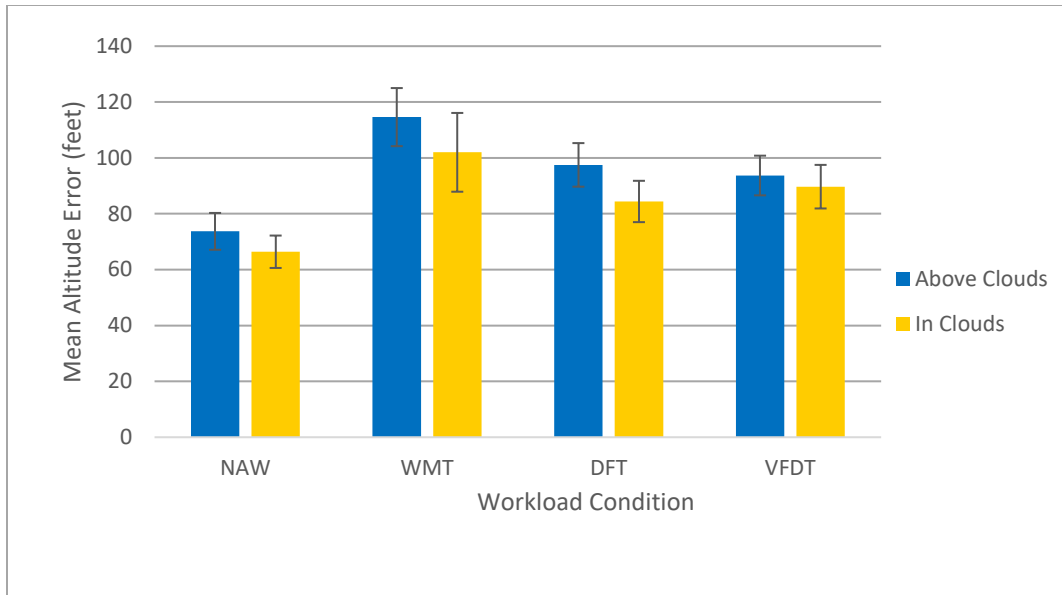


Figure 8. Mean error from lead aircraft’s altitude.

Pilot performance under conditions conducive to SD, such as flight in the clouds with secondary tasks, was of the most interest in this study. Therefore a separate one-way ANOVA was conducted on the altitude error data during flight in the clouds, and the main effect for workload was again significant ( $F(3, 69) = 6.75, p < .0001$ ). Post hoc pairwise comparisons between the NAW condition and each of the three added workload conditions (WMT, DFT, and VFDT) showed significantly greater altitude error for each of those added workload conditions, with  $p < .003$  in all cases. There were no significant differences among the added workload conditions.

### Secondary Task Performance

Summary statistics for secondary task performance data are presented in Table 2, and the data are again broken down by visibility condition.

Table 2

*Summary statistics for secondary task performance*

		WMT		DFT		VFDT	
		Above Clouds	In Clouds	Above Clouds	In Clouds	Above Clouds	In Clouds
% Correct	<i>M</i> ( <i>SD</i> )	88.7 (8.8)	88.0 (10.4)	80.4 (17.0)	83.7 (16.5)	N/A	N/A
Response Time (ms)	<i>M</i> ( <i>SD</i> )	1603 (254)	1581 (254)	4549 (1106)	4147 (985)	N/A	N/A
Error (feet)	<i>M</i> ( <i>SD</i> )	N/A	N/A	N/A	N/A	310 (139)	259 (151)

The three tasks were designed to be different from each other so comparing performance (e.g., response time) on one task versus another would not be meaningful. However, comparing performance within each task across the visibility conditions is potentially informative, so paired samples t-tests (2-tailed) were conducted to compare performance above and in the clouds. For the WMT, neither percent correct nor response time differed significantly between visibility conditions ( $t(23) = .80, p = .43$  and  $t(23) = .78, p = .44$ , respectively). For this task participants were told that if they forgot the memory set, they could ask for a refresh and the letters would be shown again for 10 s. There was a total of 144 WMT flights, and on 29 of these (20.1%), 11 participants asked for at least one refresh. The remaining 13 subjects never asked for a refresh on any of the flights.

For the DFT, percent correct was significantly higher ( $t(23) = 2.27, p = .03$ ) and RT was significantly faster ( $t(23) = 4.73, p < .001$ ) in the clouds as compared to above the clouds. Finally, for the VFDT, the difference in following distance error between the two visibility conditions was not significant ( $t(23) = 1.91, p = .07$ ).

## Discussion

The main goal of this research was to examine how different types of workload, as imposed by secondary cockpit tasks, affected the incidence of SD, as measured by several different dependent variables. It is first important to establish that workload was indeed successfully manipulated, and at least two of the analyses indicated that it was. First, the subjective workload ratings for the three secondary tasks were all significantly higher than the NAW condition (see Figure 4). The mean ratings for the secondary tasks all fell near the middle of the workload scale, between “4” and “5”, which corresponded to “Insufficient spare capacity for easy attention to additional tasks” and “Reduced spare capacity: additional tasks cannot be given the desired amount of attention”, respectively. For comparison, the mean rating for the NAW condition was 2.0, corresponding to “Workload low”. Also, the workload ratings for the secondary tasks did not differ significantly from each other, indicating that they were generally similar in terms of the amount of workload imposed, as intended.

The second indication that workload was successfully manipulated was the increase in altitude error with the introduction of the secondary tasks, as compared to the baseline NAW condition (see Figure 8). This result suggests that the higher workload associated with the added tasks consumed pilot attentional resources that would otherwise have been applied to maintain co-altitude flight with the lead aircraft, as participants were instructed to do. Consistent with the workload ratings, there were no significant differences in altitude error among the three different secondary tasks while flying in the clouds, another indication that workload levels were generally similar across the secondary tasks.

Altitude error above the clouds was significantly higher than error in the clouds. This effect is probably due to the fact that it was easier to lose sight of the lead aircraft in the clouds, and subjects therefore provided themselves with more of a buffer by trying to keep the lead better centered in their field of view while in the clouds, which would also keep them closer to the lead’s altitude.

Subjects provided ratings of any incident of SD, and did so separately for flight above the clouds and in the clouds (see Figure 5). For flight above the clouds the mean SD rating across the four workload conditions was 1.17, barely above the minimum rating of 1.0 which corresponded to “I did not feel spatially disoriented at all”. This low rating is not surprising for two reasons. First, visibility was excellent above the level cloud deck, providing a clear horizon and a strong visual cue for maintaining orientation (see Figure 3). Second, the experiment was conducted in a non-motion simulator and in a stable 1-G environment, so participants were not subjected to the truly disorienting acceleration effects common in actual flight. Under these conditions, anything *but* low SD ratings would be surprising.

When overall SD ratings above the clouds were compared to those in the clouds where no horizon was visible, the ratings increased from 1.17 to 2.5. While this increase was not extremely large given the 1 – 10 rating scale, it was statistically significant and more than double that of the SD ratings for flight above the clouds. This result speaks to the power and value of having a well-defined visual horizon when it comes to maintaining spatial orientation.

Unlike the workload ratings, SD ratings did not increase with the introduction of the secondary tasks above the clouds. It is likely that the clear and level horizon visible while flying above the clouds allowed pilots to maintain spatial orientation, with or without the added workload of the secondary tasks. For flight in the clouds, the pattern of results was statistically the same: the addition of the secondary tasks did not significantly increase SD ratings. Examination of Figure 5 shows that although there was a tendency for the SD ratings to increase with the secondary tasks, especially with the DFT and VFDT (two spatial tasks), the increase was not statistically significant by conventional standards.

The overall CRE rate in this study was 5.6%, and over half of the participants committed at least one CRE. These results are consistent with previous studies (see Williams, Littman, Folga & Patterson, 2014; Ercoline, Weintstein, DeVilbiss & Bitton, 1994; Lincoln, Palmer, & Wempe, 1972). Analysis of the CREs in the present study showed that they happened most often in the WMT condition, where they were three times more likely to occur as compared to the NAW condition (see Figure 6). Neither of the other two workload conditions differed significantly from the NAW with respect to the number of CREs. The increase in CREs in the WMT condition is somewhat surprising since it is a verbal task, not a spatial task like the DFT or VFDT. The DFT requires mental rotation and knowledge of ownship heading, whereas the VFDT requires variable distance-keeping and tracking in three dimensions. Wickens' (1984) multiple resource theory might predict that these two spatial tasks should have produced the greatest amount of disorientation and CREs since they likely compete for the same spatial resources as orientation maintenance does.

There are several possible explanations for the results found here. First, the DFT and VFDT may not have demanded enough spatial resources to cause significant interference with orientation maintenance, at least as measured by CREs. This reasoning is supported by these tasks' workload ratings which hovered near the middle of the scale, not toward the upper end. A question then arises as to why the WMT, with similar workload ratings, did seem to interfere as evidenced by the increased number of CREs. A second explanation here for the CRE results may lie in the continuous nature of the WMT. In order to successfully perform the task, subjects had to keep the letter set in memory for the entire flight, likely by constantly repeating the letter set to themselves. In fact, it was not uncommon to hear subjects whispering the memory set repeatedly. The DFT was more intermittent or episodic in nature, with a new problem occurring every 15 s and an average response time of approximately 4.5 s. This meant that on average subjects had a 10 s "break" between problems. While the flights were designed to have the lead aircraft disappear during a DFT problem, delaying or shedding the task for just one DFT presentation in order to reduce the likelihood of a CRE was probably an acceptable tradeoff for these pilots. However, shedding verbal rehearsal of the letter set could lead to forgetting it entirely, requiring a refresh display of the letters, something the subjects were generally reluctant to request. Also, the WMT flights continued for an average of 6.6 s after the lead disappeared, and since a probe letter was presented every 4 s, at least one more letter was presented before the flight ended. It may be that the combination of the continuous and frequent nature of the WMT and the desire not to abandon it when faced with the lead aircraft disappearance interfered with correct interpretation of the attitude indicator, and/or the correct motor response to it, resulting in the increased number of CREs.

A third possible explanation for the increased number of CREs in the WMT condition is hemispheric lateralization of the brain. The left hemisphere is largely responsible for and more efficient at processing verbal information, while the right hemisphere is better with spatial information (see Harris, 1999 for an

historical review). In general, performance on two simultaneous tasks suffers more when the tasks are controlled by the same hemisphere. Ballesteros, Manga, & Coello (1989) and Kinsbourne & Cook (1971) demonstrated that dual task performance declined more when a verbal task was paired with a right-handed manual task versus a left-handed task. Indeed, the WMT condition in the current study paired a verbal task with a right-handed manual task. Being a verbal task, the WMT was a left hemisphere processing task, and roll inputs were executed with the right hand, also controlled by the left hemisphere. It may be that the type of interference observed by Ballesteros et al. (1989) and Kinsbourne & Cook (1971) was also operating in the current study, increasing the likelihood of CREs. The DFT and VFDT were both spatial tasks controlled by the right hemisphere, so interference with the left hemisphere manual task was not as likely, resulting in no increase in CREs.

Like the DFT, the VFDT was more episodic than the WMT in that a new following distance was only presented every 40 s, and although establishing the new distance was challenging, once established it was relatively easy to maintain. Also the command distance and actual distance were constantly displayed so there were no memory requirements as with the WMT. Finally, by definition, the VFDT ended when the lead aircraft disappeared, so all attentional resources could then be focused on rolling wings-level in the proper direction and avoiding a CRE. Therefore CREs may not have been a good index of SD for the VFDT workload condition.

While this study and others have found that CREs are relatively rare, it is worth pointing out that their consequences can be disastrous in actual flight. Bramble (2008) describes two fatal airliner mishaps where flight data recorders and cockpit voice recorders provided evidence that the pilots were spatially disoriented and subsequent CREs worsened the situations. A third fatal airline mishap where CREs were again implicated is described in a Flight Safety Foundation article (Lacagnina, 2010). Sadly, the total number of fatalities across these three very preventable tragedies was 364.

Finally, regarding CREs, and as mentioned earlier, the current study was conducted in a fixed-base simulator without the often-disorienting acceleration cues that pilots contend with in actual flight. The scenarios used here also provided ample altitude, and therefore time, for pilots to complete proper wings-level recoveries. Since a simulator was used, pilots were not exposed to anxiety provoking real world risks. Considering these factors it would not be unreasonable to expect CRE rates in actual flight scenarios to be somewhat higher than found here.

Beyond CREs, another indicator of SD in this study was percentage of time spent at or beyond 65° AOB while in the clouds. An AOB of 65° in the clouds is very steep, and a spatially oriented pilot would certainly avoid such an attitude when there is no visible horizon. Accordingly, higher scores on this measure indicate a greater likelihood of SD. Also, since the lead aircraft performed its turns using a maximum bank angle of approximately 45° there was no need for participants to maneuver much beyond that. Analyses of the bank angle data showed that subjects spent more time at or beyond 65° AOB in the two spatial workload conditions, DFT and VFDT, when compared to the WMT condition, which actually had the lowest score on this measure (see Figure 7). This latter observation is somewhat surprising since it was the NAW, not the WMT, condition that received the lowest workload ratings and presented no additional tasks to interfere with maintaining safe bank angles. No simple explanation presents itself here. Nevertheless, the fact that the two spatial workload conditions did show the greatest tendency to induce unusual attitudes, and by inference SD, is consistent with spatial resource competition (Wickens, 1984). It is likely that the spatial resource demands of the DFT and VFDT competed for and interfered with the same spatial resources required to continuously maintain safe and proper bank angles. Pilots know that a 65° AOB in the clouds is a dangerous aircraft attitude. Since the flights did not require severe bank angles and there was no other motivation to venture to those extremes, it is reasonable to conclude that the pilots had misperceived their aircraft's attitude and were spatially disoriented. Indeed, inaccurate perception of aircraft attitude is a core part of Benson's (1999) well-accepted definition of SD.

## Secondary Tasks

Performance on the secondary tasks was good, indicating that the subjects put effort into them and took them seriously. Percent correct on the WMT and DFT ranged between 80% – 89%, depending on the task (see Table 2). The overall average error for the VDFT flights was approximately 300 ft. Every 40 s on these flights, the command distance changed by at least 200 ft, and as much as 800 ft, so even if the subject had zero error at the change, error jumped to at least 200 ft after the change. Given these dynamics, an average error of 300 ft can be considered good.

When performance above the clouds was compared to that in the clouds for the WMT, no differences were found, so participants were able to maintain speed and accuracy on the WMT when faced with flying in the clouds, a more difficult flight condition (Braithwaite, Durnford, Groh et al., 1998). Subjects were asked to differentiate SD ratings (but not workload ratings) by visibility condition. SD ratings were significantly higher in the clouds, so it is somewhat surprising that for the DFT, both speed and accuracy actually improved in the clouds. A possible explanation is that since all of the flights always progressed from above the clouds to in the clouds, participants were more practiced at the secondary tasks during the latter portion of the flights, which may account for the maintenance or improvement of performance. Performance on the VFDT was consistent with this explanation, since there was a slight but non-significant improvement in following distance error (see Table 2). As with the WMT, it can at least be said that performance was maintained.

When the results of the various subjective and objective measures are considered together, several important observations emerge. First, subjective ratings can play an important role in the interpretation of results. The workload ratings provided evidence that the secondary tasks indeed elevated cockpit workload, and that the increase was roughly equal across the three added-workload conditions. This latter point is important here since it helped explain that any increase in objective measures of SD, such as the elevated CREs in the WMT condition, was not simply due to that condition being particularly more difficult than the other conditions. Rather, the increase was due to the nature of the WMT condition itself.

A second observation is that it is useful to incorporate several different types of dependent measures of SD. As noted above, the CRE rate (but not the unusual attitude rate) increased in the WMT condition. A CRE is a binary and rare event in trained aviators, so an absence of a CRE does not necessarily indicate an absence of SD since even a disoriented pilot has a 50/50 chance of moving the stick in the correct direction and avoiding the error. However as others have noted, if a CRE does occur it is a strong indicator that the pilot is disoriented (see Liggett and Gallimore, 2002; Braithwaite, Durnford, Groh et al., 1998). There is no reason that an oriented pilot would deliberately move the stick in the wrong direction, in IFR conditions, even in a simulator. Because the WMT is a non-spatial task, spatial resource competition would not be a mechanism for the increase in CREs seen here. Rather it is likely that the continuous need to keep the letter set in working memory imposed a sustained distraction that interfered with correctly processing the information provided by the attitude indicator, and hemispheric lateralization may have further contributed to the execution of improper motor responses. General distractions and task loadings have indeed been frequently cited as contributing factors to SD (Durnford & Crowley, 1995; Gallimore, 2003; Gibb et al., 2011; Braithwaite, Durnford, Groh et al., 1998; Webb et al., 2012; Durnford, DeRoche, Harper, & Trudeau, 1996). Accordingly, a third observation here is that the CRE results indicate that the distraction need not be spatial in nature to disrupt the maintenance of spatial orientation.

Finally, although the percentage of time spent in an unusual attitude was not affected by the WMT condition, it was increased by the DFT and VFDT conditions. While in the clouds, the average amount of

time spent in an unusual attitude for the DFT and VFDT conditions was 2.00 s and 2.29 s per flight, respectively. At first glance these numbers might seem small, but when viewed as the amount of time exposed to the risks of IMC unusual attitudes (e.g., unrecoverable LOC-I, airframe overstress and in-flight breakup), the magnitude of these numbers becomes more formidable. The fact that the unusual attitude exposure time in the VFDT was almost twice that of the WMT is also notable, and emphasizes that a variety of metrics, such as continuous AOB measures or discrete CRE counts may be needed to detect the incidence of SD.

#### Future Direction

This study incorporated a diverse set of independent and dependent variables to measure workload effects on SD in a scenario that was flight-relevant, with one notable exception: There was no actual motion component in the simulation, and this very likely limited the amount of SD experienced by the subjects, as reflected by the low SD ratings. This shortcoming does not discredit the results, but it certainly does limit the generalizability to actual flight. To address this limitation plans have been made to conduct a similar study in the Naval Aerospace Medical Research Lab's Disorientation Research Device, a.k.a. the "Kraken". The Kraken is a six degree-of-freedom motion device that can replicate the forces of flight with up to 3 G of sustained acceleration. Repeating the study in a motion device will provide the vestibular and somatosensory cues that were missing in the current study, and will probably elicit more SD. These additions will improve the research in two ways. First, it will increase the generalizability to real world flight. Second, it will enable comparison between motion and non-motion scenarios. This will allow the evaluation and quantification of the roles that the visual, vestibular, and somatosensory systems play in maintaining orientation. The new information can be used to improve SD models that could be used to identify and predict SD inducing flight conditions, as well as improve SD countermeasures and training. Ultimately, this work should improve aviation safety by reducing the deadly threat of SD.

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