Eye Tracking, Point of Gaze, and Performance Degradation During Disorientation

BOB CHEUNG AND KEVIN HOFER

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Background: The cognitive cockpit concept has been proposed as a potential disorientation countermeasure. It involves monitoring the pilot's physiological, behavioral and subjective responses during disorientation. This data is combined to provide a real time model of pilot state, which is used as a basis for optimizing pilot performance. This study attempts to investigate whether there are consistent behavioral or physiological "markers" that can be monitored during a specific disorientation scenario. ***Methods:*** An Integrated Physiological Trainer with interactive aircraft controls and an eye-tracking device was employed Fourteen subjects proficient in maintaining straight-and-level flight and who have acquired the skills in changing attitude participated in the study. They were exposed to a flight profile consisting of straight-and-level flying and change in attitude without exposure to a head roll (control condition) and a profile with exposure to a head roll (experimental conditions) during constant yaw rotation Flight performance parameters and subjects' eye movements and point of gaze behavior were monitored continuously ***Results:*** Immediately on the return to upright head position, all subjects reported a strong apparent pitch displacement that lasted ≤ 20 s and a lesser sensation of lateral movement Significant differences ($p < 0.01$) were noted on a number of scanning behaviors between the control and the experimental conditions. The appearance of nystagmus was apparent as indicated by the number of involuntary saccades during disorientation. Flight performance decrement in the experimental conditions was reflected by a significant deviation in maintaining airspeed ($p < 0.01$) ***Conclusion:*** It appears that the pitch illusion consistently affects visual scanning behavior and is responsible for the decrement in flight performance observed in the simulator.

Keywords: disorientation, Coriolis, flight performance, eye tracking, cognitive cockpit.

SPATIAL DISORIENTATION (SD) in flight occurs when a pilot fails to sense, or senses incorrectly, the position, motion, and attitude of the aircraft or of himself/herself within the fixed coordinate system provided by the surface of the Earth and the gravitational vertical (3). It remains a major cause of mishaps resulting in the loss of aircraft and personnel (14). For the past 50 yr, efforts have been made to understand some of the fundamental mechanisms of orientation, and initiatives have been made to educate aircrew. For example, considerable progress has been made in understanding the roles played by the visual, vestibular, and somatosensory systems in spatial orientation. This has led to the understanding of some of the visual and vestibular illusions that pilots may experience. While SD is a proven "killer," its greatest effect is its degradation of pilot performance, which has not been thoroughly investigated (6). It is suspected that non-mishap SD events could negatively affect aircrew performance and reduce mission effectiveness.

One of the proposed SD countermeasures involves the cognitive cockpit safety net concept (18). This proposed concept focuses on helping the pilot through the coupling of adaptive automation and decision support concepts with technologies that monitor pilot behavior and their physiological responses for detection of performance degradation and incapacitation. Ideally, the broad objective is to provide a system for task management that retains the pilot's executive control of critical system functions while utilizing the computer for other tasks during high workload or stressful situations. Alternatively, the system can automatically assume control until the pilot is able to regain full control of the system. One of the essential requirements of this concept is the monitoring of physiological and/or behavioral "markers" that are consistently displayed during the period of disorientation. To our knowledge, investigations into the possible physiological and behavioral "markers" corresponding to the instances when the subject experienced disorientation have not been carried out. We have formulated a research program investigating the above issues. The first objective of this study is to investigate whether there are consistent behavioral and physiological responses at the onset and throughout the duration of the disorientation period in a simulator. Specifically, eye movements, pupil diameter, and point of gaze behavior are addressed in this paper. The second objective is to investigate the immediate effect of disorientation on flight performance in the simulator and its possible correlation with the observed responses. The third objective is to develop a ground-based SD demonstration strategy that will focus on the effect of SD on task performance and to provide immediate feedback to the trainee beyond the

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From the Defence R&D Canada–Toronto, Toronto, Ont., Canada.

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Address reprint requests to Bob Cheung, Ph D , Senior Defence Scientist and Project Leader for Disorientation Countermeasures and Vestibular Studies a the Defence Research and Development Canada–Toronto (DRDC-Toronto), 1133 Sheppard Ave. W, P O Box 2000, Toronto, Ont., Canada M3M 3B9; bob.cheung@drdc-rddc gc.ca.

experience of subjective sensation of disorientation and unpleasant symptoms of motion sickness.

METHODS

Subjects

There were 14 healthy subjects (3 women, 11 men) between the ages of 20 and 48 who participated in this study. Approval for this study was obtained from the DRDC-Toronto Human Ethics Committee. Subjects gave informed consent and completed a medical history questionnaire. They had no known history of ophthalmologic, oculomotor, or vestibular disorders. All subjects were instructed to strictly abstain from over-the-counter cold and flu medication and abstain from alcohol for at least 36 h prior to each experimental session. All subjects had no previous flight simulator experience. These subjects were trained (for up to 3 h) to be proficient in maintaining straight-and-level (S&L) flight and in the procedures for changing attitude. The minimum proficiency required included the ability to control the aircraft while reaching a given target attitude within a given time and maintaining this attitude (flying S&L) for a period of 3 min within acceptable deviations of ± 100 ft in altitude and ± 5° in heading. In addition, the subjects were trained to perform a standardized procedure of visual crosscheck on the instrument displays. They were trained to actively monitor attitude direction indicator, altitude, heading, airspeed, and engine torque in a systematic manner. This training was to ensure that all subjects could demonstrate a basic level of eye-hand coordination proficiency in flying the simulator and to familiarize them with the experimental procedures. Only subjects who could attain the proficiency stated above as indicated by a simulated flight test were allowed to participate in the study.

Motion Stimulus

An Integrated Physiological Trainer (GYRO-IPT, ETC, Southampton, PA) provided all the necessary visual and motion flight simulation required in this study. It has a three-axis (roll ± 30°, pitch ± 15°, and yaw 360°) motion base and out-of-the-window visual scene. A one-way visual and a two-way audio communication system allow the subject to interact with the investigator, and allow the investigator to continuously monitor the subject. The simulator is equipped with a data acquisition system so that flight data in real-time from the subject's flight profile status are readily recorded for analysis. The closed loop control capability creates an interactive environment so that the subject can maintain control of the simulator while being exposed to a number of somatogyral and some visual illusions. For ease of experimental design in inducing the desirable disorientation scenario, the GYRO-IPT motion base can also be programmed to change its position independent of the subject's control (stick) inputs.

Eye Tracking/Point of Gaze Monitoring

An eye tracking monitoring system (Vision 2000, El-Mar Inc, Toronto, Canada) mounted onto the GYRO-IPT was used to monitor the subjects' point of gaze behavior and eye movements in real-time. Monocular horizontal and vertical eye position estimates are derived from the relative positions of two corneal and pupil center reflections generated by illumination with infrared light emitting diodes (LEDs) mounted on the eye-tracker. The recording unit uses adaptive real-time image processing to obtain accurate measurements of eye position. A video image of the subject's forward view from the visual scene camera is recorded simultaneously. The visual scene camera attached to the head-mounted frame can be adjusted so that four given reference targets are balanced within the field of view during calibration and analysis. The merged eye position and visual scene image output provides the operator with an image of the subject's point of gaze. The resolution of the video eye tracking system is less than 0.1° with a range of ± 40° and ± 30° in the horizontal and vertical directions, respectively. Typical noise in eye velocity records during pursuit tasks was greater than that of the search coil and was approximately 4–5° $\cdot$ s^{-1}. During active head movement, the standard deviation of the point of gaze estimate was typically less than 1.63 mm (0.42° at 222 cm) and an average deviation of 1 cm (0.69° at 82 cm). There is excellent agreement between the video eye tracking system estimates and data collected using the search coil method (the so-called "gold-standard" in eye tracking technology). Further technical details regarding accuracy and resolution can be found in Allison et al. (1).

Design and Procedure

At the beginning of each trial, subjects were given 5–10 min of "free-flight" to become re-acquainted with the simulator and the pressure on the control stick. Subjects with eyes opened were exposed to 120° $\cdot$ s^{-1} yaw rotation during simulated flight at a prescribed attitude. The out-of-the window visual scene was set at nighttime. Some stars and city lights were visible but the visual horizon was ambiguous. After the initial sensation of rotation subsided (60 s from the initial acceleration) with their head maintaining erect, subjects were instructed to change their flight path to a new altitude and heading. At the prescribed power setting, rates of climb and bank, the transition took approximately 30 s to reach the new attitude. This 30 s transition in the profile served as the control condition (**Fig. 1**). After maintaining S&L flight for another 120 s at the new attitude, they were instructed to voluntarily make a head roll (either right or left) to 35 ± 2° from vertical (head erect position) within 0.5 s, and to maintain the head tilt for 20 s. The subjects were randomly assigned so that half of them rolled their head to the right and the other half rolled their head to the left only. During this period, they were asked to stare straight ahead and the operator at the console maintained S&L flight. On the return to upright head position, subjects were instructed to initiate either an ascent or descent to another prescribed altitude and heading, which took another 30 s. This portion of the profile served as the experimental conditions (Fig. 1).

The combined action of head roll and simultaneous

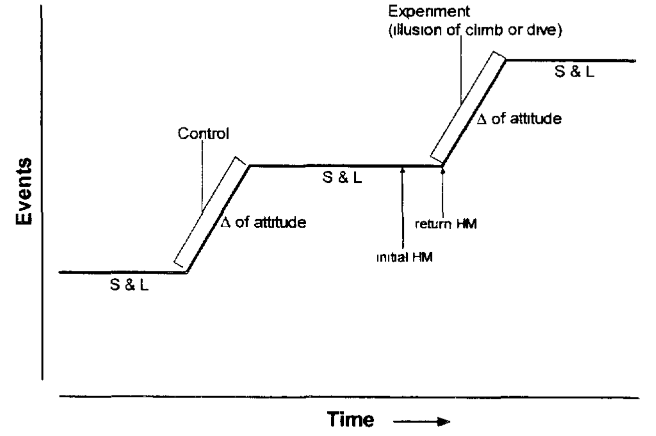

Fig. 1. The timeline of the experimental design and the timeline for objective data analysis (S&L = straight and level, Δ of attitude = change of attitude, Return HM = Return head movement).

constant velocity rotation induces the classic Coriolis vestibular cross-coupling effect. To control the possible bias of the direction of rotation and direction of head movements, we used different directions of yaw motion and head roll to achieve the pitch up (ascent) and pitch down (descent) sensation (**Fig. 2**). For each trial, there were two different tasks with the subject either ascending or descending 2000 ft to a new altitude accompanied by a 60° change in heading (which requires banking either to the right or left). Therefore, each of the subjects was exposed to 8 test trials (4 disorientation profiles × 2 assigned tasks). The order of these trials was randomized across the subjects and each of the trials was separated by at least 1 wk. During each trial subjects were asked to concentrate on the flying task and follow the instruction of the pre-recorded announcement on when to change attitude and initiate head roll. At the end of the trial, subjects were invited to describe in writing their sensation of motion and any perceived difficulty in their performance.

Data Analysis

MANOVA with $\alpha = 0.05$ was employed with three repeating factors: conditions (control vs. experimental), flight tasks (ascent or descent), directions of yaw rotation (right vs. left), and time interval (three consecutive 5-s intervals). As identical Coriolis sensation was elicited between different directions of head roll (4), these data were combined for the final analysis. All post hoc analyses were completed using Tukey's HSD (Statistica by Statsoft, Tulsa, OK). An automated fixation analysis program (FAST, El-Mar Inc) was used to quantify information regarding the subject's point of gaze. In this study the objects of interest included five basic flight instruments: air speed indicator (ASI), attitude indicator (ADI), directional gyroscope (DG, heading), altimeter (ALT), and engine torque as indicated by pounds per square inch (PSI). During data analysis the video images of the reference points were continuously tracked and the position of the objects of interest was continuously redefined for each video frame. Using eye position information and the calculated coordinates of the objects of interest, the program provided the duration of the time spent (or fixation duration) and frequency of fixation on each object of interest, over a pre-set time interval. In addition, it also provided the total number of saccadic eye movements, pupil diameter, number of eye blinks, horizontal and vertical eye positions within the head. Finally, the latency to fixate on an object of interest immediately after the return to upright head position was also derived from the eye tracking data. Due to technical complications inherent with the eye tracker design, such as slippage of the head assembly (less than 1%), insecure electrical connections for signal transmission (eight trials from one subject), and artifacts caused by excessive blinking (two trials from two separate subjects), the final eye tracking and flight performance analyses were based on 12 and 13 subjects, respectively. One subject did not complete the series and these data were not included in the analysis.

The duration of the subjective Coriolis vestibular cross-coupling reaction can be predicted on the basis of the effective Coriolis cross-coupling on the semicircular canals (9). Using the second differential equation that describes the canal dynamics and the long time constants for the respective semicircular canals, the duration of the sensation of pitching following the initial head roll and following the return head movement can be estimated to be within 10 and 20 s, respectively. In a separate study, we measured the duration of the pitch illusion by subjective indication. Illusion of pitch after the return to upright head position lasted about twice as long as the initial head roll, with a range of 15–18 s and 7–9 s, respectively As a result, three consecutive 5-s intervals (0–5 s, 6–10 s, and 11–15 s) were chosen for analysis starting immediately after the subject completed the return head movement. Flight performance data acquired through the on-board data acquisition system were subjected to identical statistical analysis described above. Deviations from the target flight parameters, the RMSE (root mean square error) of airspeed, and the latency to the controlled input of power setting were compared across all test conditions.

RESULTS

A four-way (condition, flight task, yaw direction, and time interval) MANOVA was applied to saccadic re-

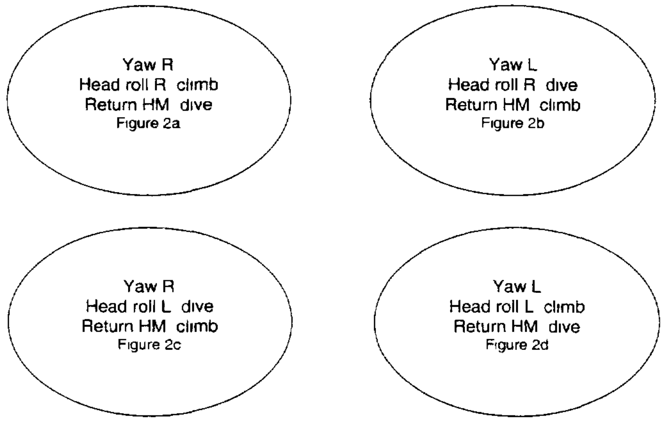

Fig. 2. Different combinations of yaw rotation direction and head roll direction used to achieve the Coriolis vestibular cross coupling induced illusions of climb or dive (R = right; L = left; HM = head movement).

TABLE I. MULTIVARIATE RESULTS FOR THE CONDITION × TIME INTERVAL INTERACTION

MANOVA performed on	Wilks' Lamda	Rao R	(df 1, 2)	p-Value
Saccades, pupil diameter & time away from designated display instruments	0.172646	4.79218	6, 6	0.039054
Fixation duration on designated display instruments	0.136534	8.85385	5, 7	*0.006169
	0.002664	74.86401	10, 2	0.013251
Frequency of fixations on designated display instruments	0.009179	21.58807	10, 2	0.045062
Flight performance (rms) (IAS, PSI)				
Condition	0.352809	10.08919	2, 11	0.003247
Interval	0.22360	13.11675	10, 3	0.028590
Interaction	0.036624	7.80246	10, 3	0.058797

* Main effect for Condition.

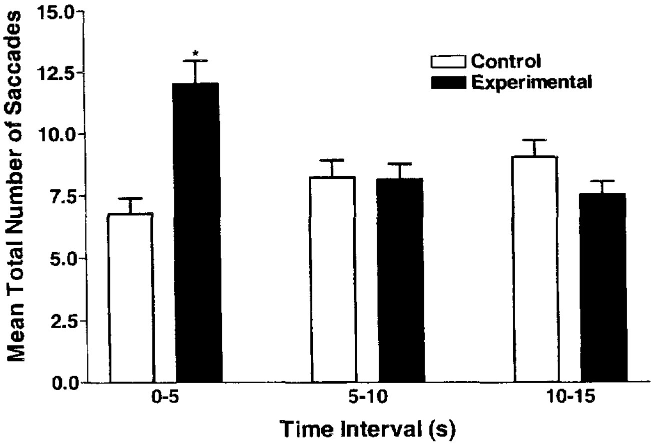

Fig. 3. The analysis of the mean total number of saccades across the three designated time intervals during transition to the prescribed attitude *Significant difference between the experimental and control conditions The mean total number of saccades was significantly greater, $p < 0.0002$ in the experimental conditions during the first 5 s after the return head movement.

sponse, pupil diameter, time spent away from the designated instrument displays, and flight performance (indicated airspeed and PSI). Similarly, a four-way MANOVA with five dependent variables was applied to the frequency of fixation and time spent on objects of interests such as PSI, ASI, ADI, ALT, and DG. Multivariate followed by univariate results showing statistical significance are summarized in **Table I and II** and are described as follows.

Saccadic Responses and Pupil Diameter

Significant interaction between conditions and intervals is illustrated in **Fig. 3**; the mean total number of saccades was greater in the experimental vs. control conditions during the first interval ($p = 0.0002$). On examination of the horizontal and vertical eye position during the same time interval, it was apparent that the saccadic eye movements during the first 5 s on the return head movement were affected by the quick phase of the involuntary nystagmus that was induced, as opposed to voluntary change of gaze. Within the control condition there was no significant difference in the mean total number of saccades across the time intervals. However, within the experimental conditions the mean total number of saccades decreased significantly in the second ($p = 0.005$) and the third ($p < 0.001$) intervals. In general, pupil diameter is larger

TABLE II UNIVARIATE RESULTS FOR THE CONDITION × TIME INTERVAL INTERACTION

Dependent Variable	Mean Sqr Effect	Mean Sqr. Error	(df 1, 2)	F	p-Level
Saccades, pupil diameter, and time away from designated display instruments					
Total number of saccades	303.0423	18.83646	2, 22	16.08807	0.000050
Pupil diameter	0.1935	0.28592	2, 22	0.67678	0.518522
Time spent on designated display instrument	6.3626	0.55260	2, 22	11.51393	0.000379
PSI Gaze latency	85.11012	6.807417	1, 11	12.50256	*0.00466
PSI Response delay	252.3773	11.21579	1, 12	22.50196	*0.00047
Time spent on designated display instrument					
PSI	14.35817	1.117179	2, 22	12.85217	0.000201
IAS	0.62154	0.149665	2, 22	4.15289	0.029503
ADI	12.2351	1.591394	2, 22	7.68848	0.002938
ALT	2.97516	0.248657	2, 22	11.96492	0.000305
DG	0.23202	0.172625	2, 22	1.34409	0.281354
Frequency of fixations on designated display instrument					
PSI	4.837067	0.305562	2, 22	15.83009	0.000555
IAS	0.926312	0.134973	2, 22	6.86293	0.004829
ADI	1.079601	0.453745	2, 22	2.37812	0.116138
ALT	4.048404	0.326099	2, 22	12.41463	0.000246
DG	0.173873	0.305562	2, 22	0.57302	0.572015
Flight performance (RMS)					
IAS	30.4591	12.04780	5, 60	2.52819	0.03837
PSI	1498.940	16.91788	5, 60	88.60097	**0.00000
	5.59295	13.88447	5, 60	0.402821	0.844985

* Main effect for Condition.
** Main effect for Interval.

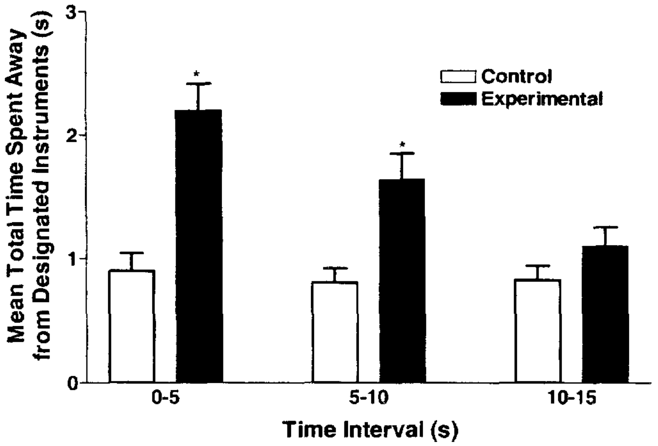

Fig. 4. The mean total time spent away from the designated instrument displays, which was higher during the experimental conditions and was statistically significant at the first ($p < 0.0002$) and the second ($p < 0.001$) interval.

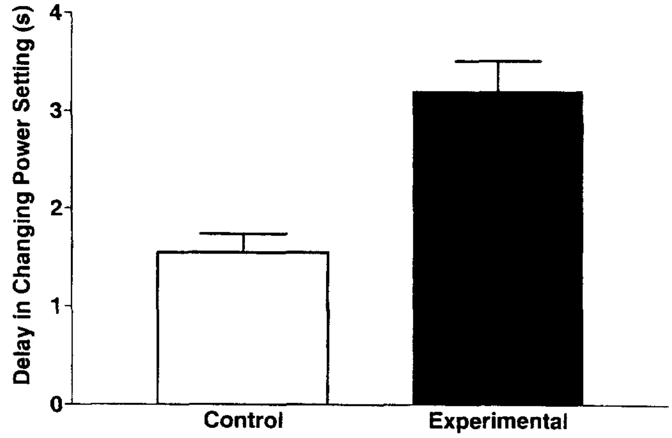

Fig. 6. The significant delay in directing gaze toward the torque indicator as reflected by the significant ($p < 0.004$) delay in adjusting the throttle to the appropriate position for the prescribed profile on the return head movement.

during the experimental conditions than the control, ($p = 0.03$). Within each condition, the pupil diameter decreased across the 15-s transition period to new attitude.

Time Spent Away from Designated Instrument Displays

Fig. 4 illustrates that the time spent away from designated instrument displays was significantly greater in the experimental vs. the control condition in the first ($p = 0.0002$) and second ($p = 0.001$) intervals. Within the control, there was virtually no difference across the three intervals; whereas in the experimental conditions, the time spent away from designated targets was greater in the first time interval compared with the second ($p = 0.017$), and the second compared with the third ($p = 0.026$), and also significantly greater in the first when compared with third interval ($p = 0.0002$).

Engine Torque (PSI)

The mean latency to direct gaze in the control and experimental conditions were 0.34 ± 0.11 s and 2.22 ± 0.44 s, respectively (**Fig. 5**). It suggests that subjects had a significant delay in directing their gaze toward the engine torque in response to Coriolis cross-coupling stimulation. This latency in directing gaze on the torque indicator was consistent with the physical delay observed in changing the power setting (**Fig. 6**). It took significantly longer for the subjects to react in the experimental vs. the control condition ($p < 0.004$). **Fig. 7a**

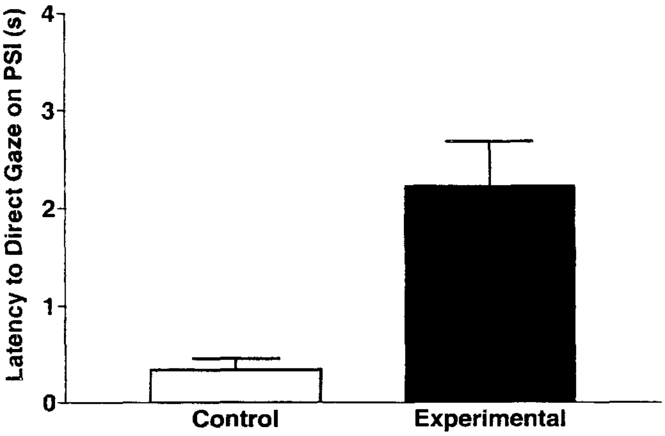

Fig. 5. The significant ($p < 0.005$) delay in directing gaze toward the torque indicator in the experimental conditions.

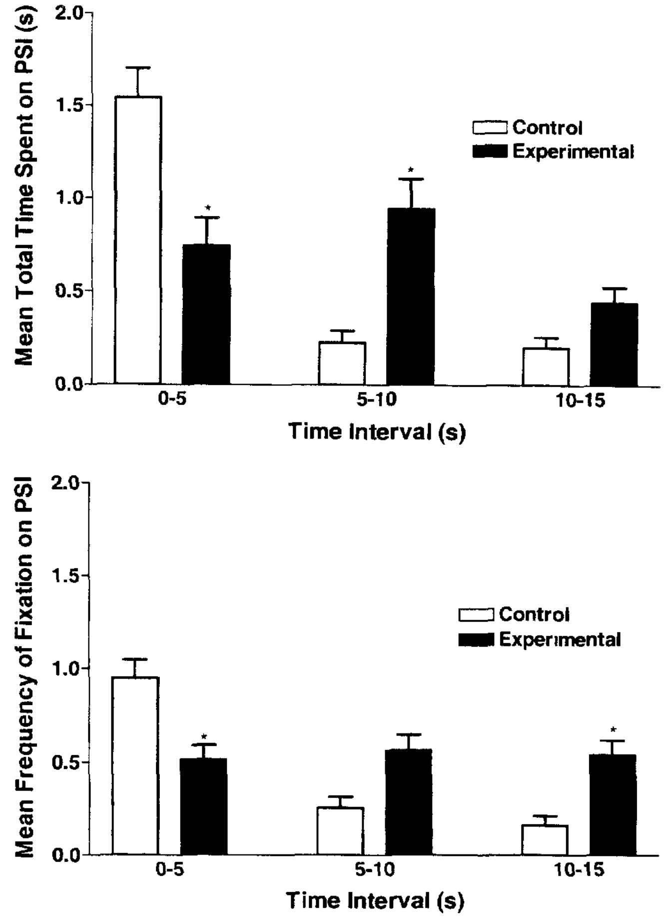

Fig. 7a and 7b. The mean total time spent (a) and mean frequency of fixation (b) on the torque indicator respectively (PSI = pounds per square inch, unit measurement of the engine torque) *Significant difference between the experimental and control conditions.

illustrates the significant differences between the total time spent on the PSI in the control and the experimental conditions at both the 0–5 s (control > experimental, p = 0.018) and 6–10 s (experimental > control, p = 0.04) intervals. Within the control condition, time spent on PSI was significantly greater in the first interval than in the second (p < 0.0002) and third (p = 0.0002) intervals. In the first interval, subjects spent significantly less time (p = 0.018) on the torque indicator during the experimental conditions which is consistent with the finding (Fig. 5) that there was a significant delay in directing gaze at the torque indicator. During the second interval, the findings appeared to be the reverse of the first interval. Subjects spent more time on the torque indicator, perhaps in an attempt to correct for the error made during the initial delay in directing gaze toward the torque indicator. There was no difference over the three intervals in the experimental conditions. **Fig. 7b** illustrates that significant differences were found between the frequency of fixation on the PSI in the control and the experimental conditions at the first (control > experimental, p = 0.011) and third (experimental > control, p = 0.029) time intervals. Within the control condition, the mean frequency of fixation was significantly greater in the first interval than in the second (p = 0.0001) or third (p = 0.0001) intervals. The mean frequency of fixation on the torque indicator shows similar pattern to that in Fig 7a. There was no significant difference across all three intervals in the experimental conditions.

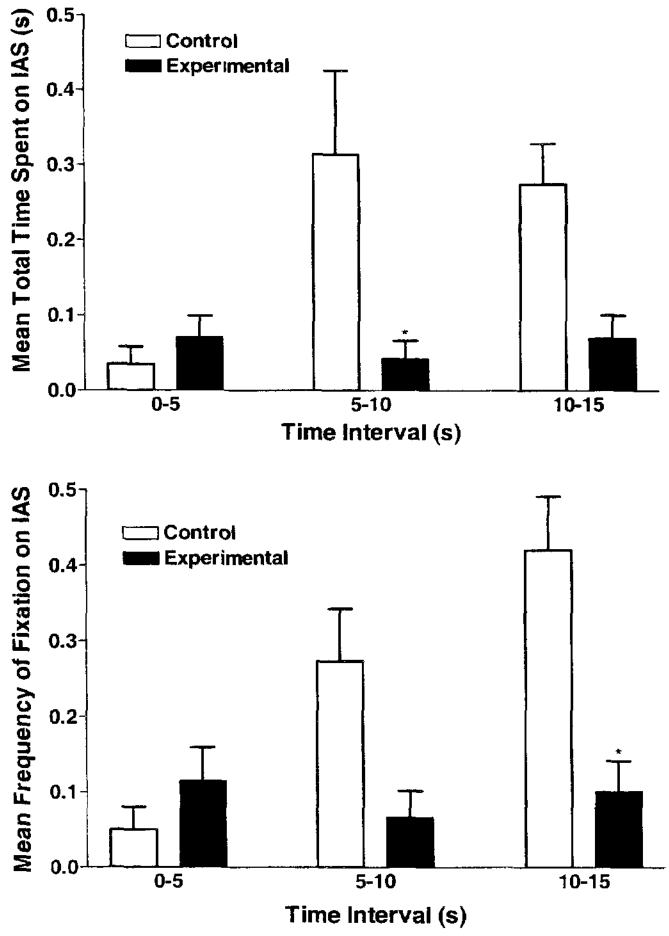

Fig. 8a and 8b. Mean total time spent (a) and mean frequency of fixation (b) on the airspeed indicator between the control and experimental conditions (IAS = indicated airspeed) *Significant difference between the experimental and control conditions

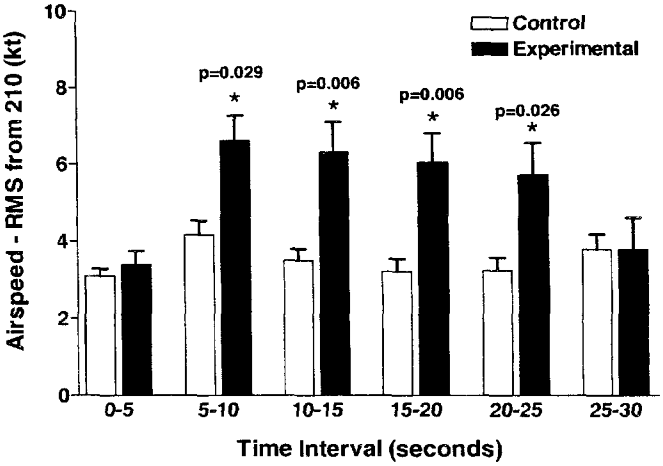

Fig. 9. Comparison of the flight performance during transition to prescribed attitude between the control and experimental conditions There were no significant differences between the control and experimental conditions 30 s after the prescribed attitude was attained (not illustrated in this diagram)

Time Spent on Indicated Airspeed (IAS)

In general, after an initial delay, the total time spent on the IAS was greater in the control (0.207 ± 0.043) than the experimental (0.061 ± 0.015) condition (**Fig. 8a**). Time spent on IAS was greater during the second (p = 0.025) and third (p = 0.14) intervals in the control vs. the experimental conditions. As illustrated in **Fig. 8b**, the frequency of fixation on the IAS was greater in the control vs. experimental conditions during the third (p = 0.007) intervals compared with the first. In addition, within the control condition, the frequency was significantly greater in the third than the first interval (p = 0.002), there was no difference within the experimental conditions.

Performance in Maintaining Airspeed

Fig. 9 illustrates that subjects were able to maintain airspeed significantly better during the control than the experimental conditions. Specifically, the performance in maintaining airspeed was significantly better (p ≤ 0.01) during the second to the fifth interval. The ability to maintain airspeed between the two conditions was comparable toward the end of the transition period to new attitude. There were no significant differences between the two conditions during the last 5-s interval of the transition phase to prescribed attitude.

Attitude Direction Indicator (ADI)

Fig. 10a illustrates that fixation on the ADI was significantly higher in the control than the experimental conditions with p < 0.001 and p < 0.0003 in the first and second interval respectively. Across the time intervals there was no difference in fixation duration during the

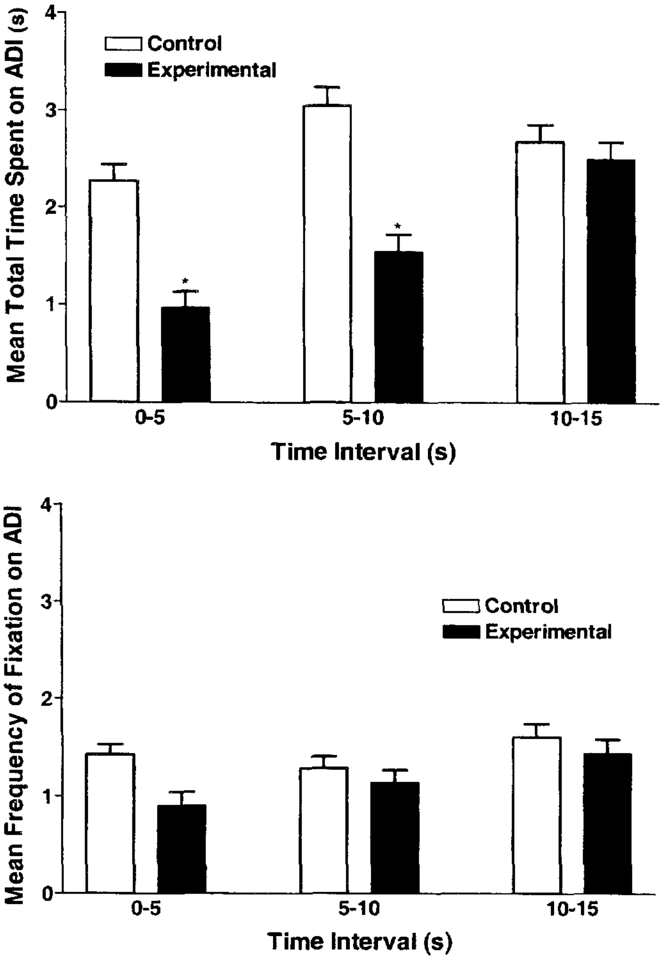

Fig. 10a and 10b. Mean total time spent (a) and mean frequency of fixation (b) on the Attitude Direction Indicator (ADI) between the control and experimental conditions.*Significant difference between the experimental and control conditions

control; but an increase from the first to the last interval ($p = 0.0003$) in the experimental conditions was observed. There was no significant difference in the mean frequency of fixation between the control and experimental conditions (**Fig. 10b**).

Altitude (ALT) and Heading (DG)

During the first interval, mean total time spent on ALT was significantly less in the control vs. experimental conditions ($p = 0.003$); in the second interval there was no difference, and during the third interval, though not significant, fixation duration on ALT was greater in the control than experimental ($p = 0.253$) condition (**Fig. 11a**). In addition, within the control condition, time spent on the ALT in the first interval was significantly less compared with the third interval ($p = 0.009$); whereas within the experimental conditions, time spent on the ALT was almost the reverse, subjects spent longer on the ALT during the first than the second ($p = 0.03$) and third ($p = 0.08$) interval.

In the first interval (**Fig. 11b**), the frequency of fixation was significantly less in the control vs. the experimental conditions ($p = 0.002$). In the second interval there was no difference; and in the third interval, though not significant, frequency of fixation was greater in the control vs. the experimental conditions ($p = 0.12$). Within the control conditions the frequency of fixation on the ALT in the first interval was significantly less than during the third interval ($p = 0.001$); whereas in the experimental conditions, frequency of fixation on the ALT in the first interval was greater than during the second and third interval, but they did not reach significance. The significant increase in mean total time spent and frequency of fixation on the ALT in the experimental condition during the first 5 s interval might have been contributed by the sudden apparent illusion of pitch on the return head movement.

The results of the DG analysis for fixation duration revealed no significant interaction at the $\alpha = 0.05$ level. However, it is noteworthy to report the trends for both condition ($F(1,11) = 7.96$, $p = 0.016$). In general, the fixation duration on the DG was less during control vs. experimental conditions throughout the three time intervals, although not statistically significant. Similarly, analysis for frequency of fixation on the DG revealed no significant effects.

Subjective Sensation of Disorientation

On the return to upright head position, subjects experienced disorientation and difficulty in focusing on

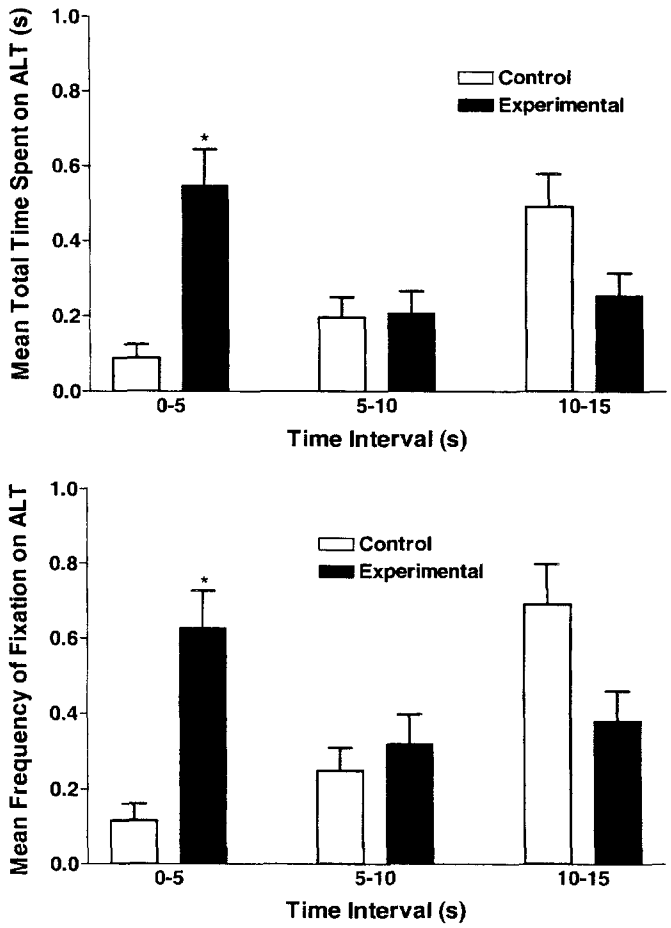

Fig. 11a and 11b. Mean total time spent (a) and mean frequency of fixation (b) on the altitude indicator (ALT) between the control and experimental conditions. *Significant difference between the experimental and control conditions.

the instrument display. Some subjects reported dizziness and slight but brief nausea; however, there were no lasting symptoms of motion sickness. All of the subjects described the disorientation sensation as "tumbling backward or forward" or that the cockpit and himself/herself were "rising up, similar to a climbing maneuver in an aircraft" or "falling down, similar to a diving maneuver in an aircraft." The direction of the false sensation of pitch also depended on the direction of yaw rotation and direction of head roll as predicted in Fig. 2. During yaw rotation to the right, head roll to the right produced sensations of apparent backward displacement (sensation of climb) accompanied by lateral displacement to the right. The return to upright head position resulted in sensations of apparent forward displacement (sensation of dive) with a lateral displacement to the right (Fig. 2a). The subjects reported similar sensations during yaw rotation to the left, with initial head roll to the left (Fig. 2d). During yaw rotation to the left, initial head roll to the right elicited a sensation of dive and the return to upright head position elicited a sensation of climb with a lateral displacement to the left (Fig. 2b). The subjects reported similar sensations during yaw rotation to the right and initial head roll to the left (Fig. 2c). However, not all of the subjects reported the apparent lateral displacement in each of the above stimulus conditions. Some subjects consistently rated the apparent pitch down sensations as stronger and more disturbing than the apparent sensation of pitch up, regardless of whether it was induced by the initial head roll or return to upright head position.

DISCUSSION

In this study we employed classic Coriolis vestibular cross-coupling stimulation to generate a disorientation scenario (an unexpected perceived change in body/aircraft orientation) during simulated flight. Although there have been numerous studies on Coriolis vestibular reaction, most studies have been concerned with motion sickness symptoms, subjective sensations, attitude perception (4,17), and vestibular nystagmus (7,9,15) with limited attention to performance during the period of disorientation (13). It is often inferred that Coriolis acceleration can adversely affect pilot's efficiency (12); however, direct evidence of how the combination of these adverse effects may degrade flight performance is unavailable.

Our analysis suggests that the false sensation of pitch as induced by Coriolis cross-coupling significantly affected visual scanning behavior and flight performance independent of the direction of yaw and direction of head roll or whether their assigned task was to ascend or descend. The increase in the number of saccades on the return to upright head positions was affected by the quick phase of the involuntary vestibular nystagmus both in the vertical and horizontal plane. The magnitude and direction of the Coriolis-induced nystagmus were predictable from analysis of the kinematics of the vestibular end-organs. This has been reviewed extensively by Guedry (8). The peak slow phase eye velocity among our subjects was $\leq 3° \cdot s^{-1}$. Although visual acuity was not measured, the majority of the subjects reported that they had trouble reading the instruments, or that the images of the instrument display were moving rapidly. However, the duration of this visual disturbance was brief and was confirmed by the disappearance of the nystagmic (saw-tooth) pattern within the first 5-s interval on the return to upright head position. The much shorter duration of the vestibular nystagmus observed was probably attributed to the visual suppression mechanism as the subjects were instructed to fixate on certain instruments while disoriented in the lighted cockpit.

Task-evoked pupillary response (changes in pupil diameter) has been shown to be a reliable index of cognitive processing. It was reported that pupil dilation is correlated more strongly with demanding task (2), whether judged behaviorally, subjectively, or by an analysis of task requirements. In contrast, the results obtained by Dunham (5) suggest that changes in pupil diameter reflect the actual amount of processing accomplished rather than the processing load imposed. Our results indicated that subjects' pupil diameter increased substantially (significant at the 0.05 level) during disorientation when compared with the control condition. Whether this increase in pupil diameter is due to cognitive demands, anxiety or arousal, requires further investigation during which pupillary responses as well as heart rate and skin conductance activity can be measured simultaneously.

The initial visual disturbance described above may have contributed in part to the significant delay in directing gaze and the delay in appropriately adjusting the throttle for the climb or dive maneuver. The delay is also reflected by the significantly less fixation duration and less frequent visits to the torque indicator during the first 5 s. In changing altitude, the power setting as reflected by the engine torque measured in PSI, is the first control parameter that requires adjustment. During training, the subjects were instructed to adjust the throttle prior to setting the pitch and bank angle for the respective maneuvering task. Therefore, the torque indicator should be the first instrument to be fixated on. Our results suggest that during the period of disorientation flight performance in preparation for the intended maneuvers decreased.

In general, our data suggest that subjects paid less attention to the ASI and the ADI while disoriented. Indicated airspeed is a reflection of control inputs to other flight parameters, such as power setting, rate of climb or dive, and the rate of banking. Therefore, we chose the airspeed RMSE from 210 kt, as a measurement of flight performance between the control and experimental conditions. Our results demonstrate that subjects' ability in maintaining airspeed was significantly decreased within the period of subjective sensation of disorientation as estimated by the subjects (approximately 20–25 s after the return head movement). It is interesting that during the first 5-s interval, no significant difference was observed between the two conditions, which could be due to the inherent delay within the simulator. The ADI, being a key instrument providing information about the degree of pitch and roll, is essential for carrying out proper changes in attitude. The overall results suggest that subjects spent the most time on the ADI and had the most frequent fixations on the ADI. In particular during the control condition, subjects were able to maintain about equal length of time on the ADI across the time intervals whereas the subjects spent significantly less time during the first two intervals while disoriented.

Analysis of the ALT data demonstrates that there is an inverse pattern between the control and the experimental conditions for both duration and frequency of fixation on the ALT. The duration and frequency of fixation on the ALT were significantly higher on the return head movement. In the control condition there was a gradual increase in time spent on the ALT. Similarly subjects also spent significantly more time on the DG (heading) in the experimental conditions, although the frequency of fixation on the DG did not reach significance at the 0.01 level. These observations could be attributed to the fact that the subjects were adversely affected by the strong apparent sensation of pitch and lateral displacement and, as a result, paid more attention to the ALT and DG indicators during this period.

At a constant rate of yaw rotation, the relative intensity of disorientation induced by one head movement as opposed to another depended on the direction of head movement. In this study, the subjective sensations reported during disorientation were virtually consistent with previous studies on the quantitative evaluation of the Coriolis vestibular cross-coupling reaction. With eyes open, our subjects experienced a visually reinforced sensation of displacement in that the out-of-the window visual scene appeared to simply move with the instrument displays and the window frame of the cockpit, eliciting a strong apparent sensation of pitch and a less distinct lateral displacement. Comments from the subjects include: "when I bring my head back it seems everything is out of focus, blurry vision and it seemed to last for 30 s;" "the plane was going down, the instrument reading told me otherwise, banked the wrong way;" and "maneuvers seemed harder after the head movement."

The much stronger sensation of disorientation experienced by the majority of our subjects on the perceived pitch down illusion is consistent with previous findings (3,8). The reason(s) behind this response asymmetry have not been satisfactorily explained. It has been attributed to the fact that the relative stimulation of the several canals is different for the initial head tilt and return head movements producing vestibular reactions in different planes while the otoliths (gravity sensors) respond more or less the same regardless of the yaw rotation (8). Further investigation dealing exclusively with the subjective aspects of the reaction and its asymmetry is warranted.

Previous studies have suggested that there is a general deterioration of cognitive performance as reflected by a significant increase in reaction time in typing a three-digit number on announcement at the end of vestibular cross-coupling stimulation (10) and attention as measured by digital symbol substitution and letter cancellation tests (15). Despite the performance decrement as demonstrated by the increased error in maintaining airspeed, all of the subjects were able to eventually reach and maintain the prescribed attitude within the allotted time. Comparison between the control and experimental conditions for the 30-s period after the subjects had reached the new attitude did not reveal significant differences in any of the parameters that were measured.

The Coriolis illusion is one of the most frequently demonstrated SD illusions, as it is easy to reproduce. These demonstrations prove to aircrew that under certain circumstances our sensory organs are inadequate. Unfortunately, most trainees recall only the unpleasant sensation of nausea and other motion sickness symptoms. It has also been suggested that the sustained turn rate of aircraft is not often of sufficient magnitude to generate a strong cross-coupled stimulus to the semicircular canals during head movements, and that some disorientation incidents previously attributed to the Coriolis effect were probably engendered by the G-excess effect. Nevertheless, accelerative forces in flight are complex, and some combinations may yield strong disorienting effects with head movements. We acknowledge that our study employed a ground-based artificial situation and that our subjects were not pilots. Measurements of oculometric variables have been done under highly constrained conditions. There is at least suggestive evidence that when these constraints are removed, the system is found to operate somewhat differently. Therefore, observational skills are required to augment conclusions drawn from laboratory-based studies.

The procedure described in this paper may serve as an effective means of disorientation demonstration when combined with eye tracking and the monitoring of flight performance. This could be beneficial to undergraduate pilot training or refresher training where the candidates can observe the direct effect of disorientation on their ability to control simulated flight. Furthermore, this type of training may reduce their tendency to underestimate disorientation, and to provide them with a more realistic understanding of the effects of disorientation in a safe environment. In conclusion, our results extend the behavioral and physiological response to operational relevance. It appears that the observed eye tracking behavior is affected by the induced illusion and is reflected by performance decrement in maintaining airspeed. Our findings provide impetus to continue further research using eye tracking in other disorienting scenarios and for in-flight studies. Our second study will focus on the correlation between eye-tracking, other physiological responses such as electrodermal impedance, heart rate variability, and performance during disorientation in an attempt to investigate further on the feasibility of cognitive cockpit as a potential disorientation countermeasure.

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DISCLAIMER

We also acknowledge that we have no commercial interest in any apparatus and equipment that were used in this study nor do we necessarily endorse these products by using them.

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