Original Article

Mental Work Load Assessment during different Simulated Instrument Meteorological Conditions, in Clouds and During Dark Night

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Abstract

Denial of ambient visual cues and the conflicting sensory inputs from non-visual modalities is known to lead to spatial disorientation. Such perceptual conflicts during poor visibility conditions add to the stress the pilot faces. Mental workload assessment may help determine available cognitive resources in task performance during Instrument Meteorological Conditions (IMC). Hence, this study was undertaken to analyze pilots' mental workload, using psychophysiological and subjective measures, during simulated IMC, akin to inadvertent entry into clouds or flying on a dark night. 25 active male military pilots volunteered for this study. Pilot workload was evaluated using a Spatial Disorientation simulator. Continuous psychophysiological measures, viz. heart rate (HR), respiratory rate (RR) and galvanic skin response (GSR), were recorded using a proprietary physiological monitoring system. NASA TLX (task load index) was used to measure the subjective variable. HR, RR and GSR were found to be not significant, though mean values were found to be higher during test conditions as compared to control. The NASA TLX score was found to be strongly significant between control and test conditions. Correlation between psychophysiological measures and NASA TLX showed mostly moderate (0.3-0.5) and a few large (0.5-0.7) but negative correlation between HR and overall workload (and its sub-scales, except effort score) under test conditions. Evident correlation between HR and NASA TLX reinforced the importance of HR as the most useful psychophysiological variable to quantify workload. So also the significant difference between control and test conditions on the NASA TLX, suggested the perceived stress of flying during simulated IMC.

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Keywords. SD, IMC, psychophysiological measure, Coriolis, leans, black hole approach, pilot workload, mental workload

Introduction

Spatial Disorientation (SD) is one of the major causes of human error accidents in aviation, reportedly resulting in "at least 25-33% of all aircraft mishaps" [1, 2]. It is defined as "a variety of incidents occurring in flight in which pilot fails to sense correctly the position, motion or attitude of the aircraft or of himself within the fixed coordinate system provided by the surface of the Earth and the gravitational vertical. In addition, errors in perception by pilots of their position, motion or attitude with respect to their aircraft or of their own aircraft relative to other aircraft" [1].

SD mostly occurs when ambient visual cues are denied in flight. Conflicting inputs from non-visual sensory modalities deceive the pilot to believe what the body feels while he ignores what the instruments read. Flying, during bad weather or at night, adds to the mental workload. Such flights also increase pilots' susceptibility to SD. An assessment of in-flight workload may help determine the available cognitive resources in task performance [3]. In one such early work, Roman studied the cardio-respiratory response of three aviators to the in-flight environment of F-100 combat aircraft [4]. The subjects were found to have higher blood pressure (BP) and normal or near normal pulse and respiration rate (RR) during cross-country flights including sorties during marginal Visual Flight Rules (33%) and weather flights (22%) [4].

Cheung et al. investigated "whether there are

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consistent physiological changes" during false sensation of pitch in a simulator. After monitoring mean arterial pressure (MAP), heart rate (HR), Heart Rate Variability (HRV), respiration, Electrodermal Activity (EDA) and eye tracking, they reported changes in the cardiovascular responses such as MAP and HRV [5]. Another study on the influence of head position and eye state (open or close) on sympathetic activation during simulated type II SD found strong sympathetic outflow (increased HR and electrodermal response) on exposure to mild Coriolis illusion [6].

Lee et al. studied the pilot workload in a Boeing 747-400 flight simulator by comparing the physiological (heart rate) and the subjective measurement (NASA Task Load Index (NASA TLX) [7]. They found that the cardiac variables, incremental HR and HRV, besides NASA TLX, were sensitive indices for evaluating workload assessment during different phases of flight. They affirmed that NASA TLX is a practical tool for application in operational aviation environment. They also ascertained the usefulness of simulators to study cockpit workload [7].

An assessment of the mental workload, as a model of human-information processing, in the Instrument Meteorological Conditions (IMC), shall reflect the concurrent workload on the pilots during conditions conducive to disorientation. Therefore, an analysis of pilots' psychophysiological and subjective measures was undertaken as a surrogate to study the mental workload during simulated IMC akin to inadvertent entry into clouds or flying on a dark night.

Methods

This case-crossover study, after institutional ethical approval [8], participants from amongst the male military pilots reporting for medical evaluation at the Institute of Aerospace Medicine (IAM), Bangalore, India. Some pilots with medical disabilities, who were fit for aviation duties, also participated 25 instrument rated pilots volunteered for this study.

The Airfox® DISO simulator was used to simulate experimental flights. The 'free flight' mode allowed changing the environmental conditions, simulating clouds, changes in ambient light conditions, runway dimensions etc. [9]. This 'free flight' mode was used to conduct the experiments in this study.

Physiological monitoring of the subjects was done with a proprietary wireless physiological monitoring system: Nexus–10® physiological monitoring and feedback platform (Mind Media BV, Roermond-Herten, Netherlands). This system allowed acquisition of signals from 0 to 800 Hz, including raw EEG, ECG, EMG, EOG etc. The acquired signals were wirelessly transmitted, using Bluetooth® wireless communication, for online monitoring and data storage. Online graphics presentation of the physiological parameters and retrieval of database, data processing, trend reporting, digital filtering and statistical functions were provided by a compatible software (BioTrace+ software®, Mind Media BV, Roermond-Herten, The Netherlands). Three physiological parameters viz., HR (from ECG), RR and GSR were recorded for this study.

NASA-TLX, a multi-dimensional subjective measure of mental workload assessment evaluates mental workload on six dimensions viz., mental demands, physical demands, temporal demands, own performance, effort and frustration. The first three dimensions assess the demands of the task imposed on the subject, while the latter three assess the interaction of the subject with the task [10]. NASA-TLX was used to assess the subjective assessment of mental workload in this study.

Experimental Protocol

Each participant was briefed about the protocol a day prior to the experiment and a written informed consent was obtained [8]. The participants were advised not to consume alcohol the previous evening and abstain from smoking and caffeine consumption at least two hours prior to experiment (0800-1000h).

Each participant was briefed about the simulator. Once strapped he was given a 'free flight', for a duration of 8-10 minutes, to familiarize himself with its handling characteristics. This also included gentle maneuvers and aerobatics. After the familiarization, the participant was briefed about the experimental flight. Baseline physiological recording was commenced and continued till one minute after the end of the experiment. The experiment was conducted in two phases: Day-Clouds (Control) and Evening-Night (Test) on the same day. The control conditions were defined as 'Day-Clouds' since the flight was undertaken on a clear visibility day but the subject entered clouds to simulate intermittent IMC; unlike the test conditions of Evening-Night where the subject took off during dusk in poor visibility with advise to fly on instruments alone and the illusions were simulated on a completely dark night.

Half the subjects flew the control phase first and the other half flew the test phase first. Thereafter, each of them flew the reciprocal phase. The experiment lasted for about 110 – 120 minutes from stepping into the simulator till stepping out. The actual simulator flight during the control and the test phase lasted approximately 45 minutes each.

Control Phase

The pilot took off on a clear day at around noon time and climbed to 10,000'at a rate of 6000' /min and thereafter flew straight and level at 350 knots towards a designated airfield. Once the airfield was sighted, he went into clouds to be exposed to IMC, and subsequently, Coriolis [11]. After noon time visual meteorological conditions were restored, the subject turned back towards the base airfield. Once the base airfield was sighted, he once again went into clouds to simulate leans [11]. The flight was terminated 2 minutes after the completion of the leans. Finally, the subject had to execute a conventional landing from 8 nm inbound, aligned to the base runway, while descending from an altitude of about 3000'. The flight was terminated after touch down. After physiological monitoring was over for the first phase of the experiment, the participant undertook the NASA-TLX test on a notebook, computer.

Test Phase

The participants remained inside for the next 5 minutes (with an option to step out, if he so desired) awaiting commencement of the Test phase. During the test phase, the subject took-off at dusk with limited visibility. The rest of the flight profile was similar to the control conditions, except that Coriolis illusion and leans were simulated during dark night conditions and the landing was a Black Hole approach [11, 12] from 8 nm inbound.

Each phase of the experiment was divided into stages viz. pre-run baseline, cruise (2 min), pre Coriolis, Coriolis (360° turn till straight and level), post Coriolis, pre leans , leans (120° turn till straight and level), post leans, approach till landing (from commencing descent till touch down), post landing and post-run baseline. Each recording lasted for duration of one minute except where specified.

Descriptive statistical analysis was carried out in this study. Results on continuous measurements are presented as Mean and Standard deviation (SD). Significance was assessed at the 5% level of significance. Student't' test (two tailed, independent) was applied to find the significance of study parameters on continuous scale between the two groups (inter-group analysis). Pearson's correlation coefficient was applied to measure the degree of relationship between the two independent measures. Statistical tool used for analysis was SPSS 15.0®.

Results

The results were available for 21 of the 25 subjects. The mean age of the subjects (n=21) was 33.09 (±6.09) years. Their mean flying experience was 1775.33 Hours (±1297.38). Figure 1 presents the comparison of HR between the Day-Clouds (Control) and Evening-Night (Test) conditions. Evidently, the mean HR during the test conditions was higher, though not significantly, than the control (Table 1).

Figure 2 presents the comparison of mean RR between the Day-Clouds (Control) and Evening-Night (Test) conditions. RR was found to be not significantly different both during control and test conditions (Table 2).

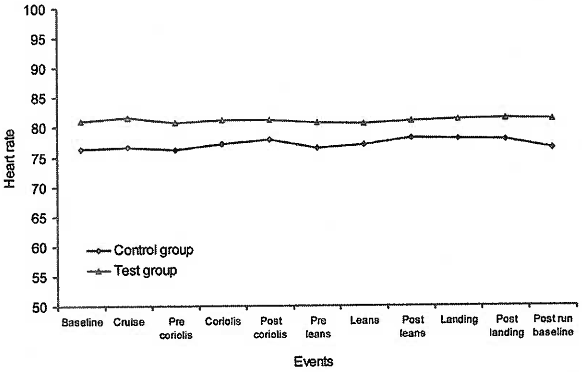

Figure 1: Comparison of Heart rate between the Day-Clouds (Control) and Evening-Night (Test) conditions

Figure 3 presents the comparison of mean GSR between the Day-Clouds (Control) and Evening-Night (Test) conditions. GSR was found to be not significantly different both during control and test conditions (Table 3).

Table 4 presents the comparison of NASA-TLX between the Day-Clouds (Control) and

Table 1: Comparison of Heart Rate between the Day-Clouds (Control) and Evening-Night (Test) conditions

Events	Day-Clouds (Control) Mean ± SD (per min)	Evening-Night (Test) Mean ± SD (per min)	p value
Pre-run Baseline	76.34±11.40	81.00±10.74	0.117
Cruise	76.59±10.36	81.64±10.33	0.108
	Coriolis Illusion		
Pre Coriolis	76.15±10.43	80.78±9.57	0.118
Coriolis	77.22±11.12	81.19±10.73	0.186
Post Coriolis	77.99±12.39	81.13±11.77	0.371
Leans			
Pre leans	76.47±11.09	80.73±10.65	0.163
Leans	77.06±10.93	80.67±10.52	0.261
Post leans	78.20±13.54	81.10±10.67	0.422
	Approach and Landing		
	Normal Day	Dark Night	
Approach to Land	78.06±11.42	81.34±10.59	0.275
Post landing	77.91±12.46	81.42±10.59	0.367
Post-run baseline	76.43±11.29	81.30±9.86	0.162

Table 2: Comparison of Respiration Rate between the Day-Clouds (Control) and Evening-Night (Test) conditions

Events	Day-Clouds (Control) Mean ± SD (per min)	Evening-Night (Test) Mean ± SD (per min)	p value
Baseline	21.77±6.44	22.31±5.74	0.462
Cruise	21.23±4.31	22.49±5.64	0.166
	Coriolis Illusion		
Pre coriolis	21.44±4.55	21.48±4.49	0.942
Coriolis	21.68±4.32	21.73±4.25	0.903
Post coriolis	22.62±5.88	21.49±4.14	0.077
Leans			
Pre leans	20.49±4.26	20.73±3.77	0.727
Leans	21.87±4.94	21.71±4.40	0.569
Post leans	21.65±5.15	20.66±4.14	0.089
	Approach and Landing		
	Normal Day	Dark Night	
Approach to Land	22.54±4.76	22.40±4.37	0.795
Post landing	20.63±5.69	21.67±5.28	0.418
Post-run baseline	21.34±4.49	21.20±3.89	0.552

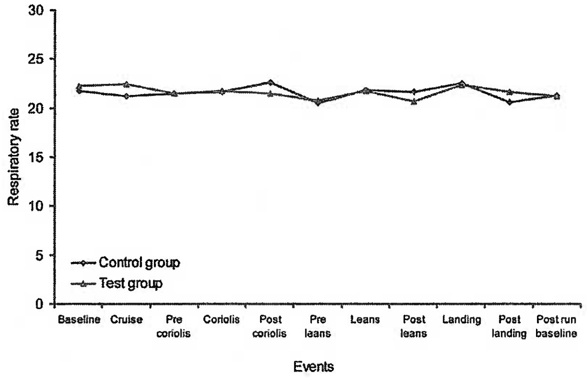

Figure 2: Comparison of respiration rate between the Day-Clouds (Control) and Evening-Night (Test) conditions

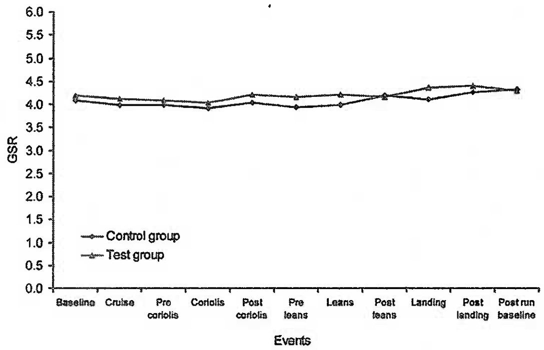

Figure 3: Comparison of galvanic skin response between the Day-Clouds (Control) and Evening-Night (Test) conditions

Evening-Night (Test) conditions. The subjective work load was found to be strongly significantly different between control and test conditions.

The correlation between psychophysiological measures and NASA TLX - Total workload during the Day-Clouds (Control) and Evening-Night (Test) conditions is presented at table V. HR showed mostly negative moderate correlation (0.3-0.5) to overall workload (and all the sub-scales, except effort score), during the test conditions. For the purpose of brevity, the correlation between psychophysiological measures and NASA TLX's six sub-scales is not presented.

Discussion

An evaluation of the pilots' mental workload during simulated IMC was undertaken in this study. The psychophysiological measures: HR, RR and

Table 3: Comparison of galvanic skin response between the Day-Clouds (Control) and Evening-Night (Test) conditions

Events	Day-Clouds (Control) Mean ± SD (per min)	Evening-Night (Test) Mean ± SD (per min)	p value
Baseline	4.08±2.71	4.18±2.63	0.694
Cruise	3.98±2.75	4.12±2.64	0.493
Coriolis Illusion			
Pre Coriolis	3.99±2.78	4.08±2.67	0.718
Coriolis	3.92±2.68	4.04±2.55	0.553
Post Coriolis	4.03±2.57	4.21±2.74	0.398
Leans			
Pre leans	3.94±2.45	4.16±2.72	0.329
Leans	3.98±2.84	4.20±2.77	0.522
Post leans	4.18±2.7	4.16±2.68	0.841
Approach and Landing			
	Normal Day	Dark Night	
Approach to Land	4.10±2.74	4.36±2.91	0.245
Post landing	4.26±2.97	4.39±2.93	0.480
Post-run baseline	4.33±2.79	4.29±2.81	0.512

Table 4: Comparison of NASA Task Load Index between the Day-Clouds (Control) and Evening-Night (Test) conditions

NASA-TLX	Day-Clouds (Control)	Evening-Night(Test)	p value
Mental Demand	55.48 ± 20.18	74.52 ± 18.23	<0.001**
Physical Demand	41.43 ± 18.17	54.52 ± 19.29	<0.001**
Temporal Demand	49.29 ± 17.13	65.23 ± 19.20	0.001**
Performance	37.14 ± 20.53	51.67 ± 21.41	0.011*
Effort	51.19 ± 20.85	71.43 ± 17.08	<0.001**
Frustration	30.24 ± 22.16	46.43 ± 24.61	0.002**
Total work load	47.65 ± 16.72	65.39 ± 15.68	<0.001**

GSR, were found to be not significantly different between control and test conditions (Table 1, 2, 3 & Figures 1, 2, 3).

Psychophysiological measures are indicators of the autonomic response to stress and the current level of alertness [5]. During simulated Coriolis cross coupling, Westmoreland et al. reported significant rise in HR and electrodermal response, but respiratory changes were non-significant [6]. Kallus et al. too reported marked increase in HR during BHA [13]. Similarly, Cheung et al. reported regular paced breathing rate of 12-15/min but a significant difference in mean HR (and MAP, HRV) and GSR between the control and experimental conditions, on exposure to simulated pitch illusion, with decrement in the flight performance [5]. The findings of this study are at variance with earlier

Table 5: Correlation between NASA TLX Overall Workload Score and Psychophysiological measures (n = 21)

Correlations		Control			Test		
		HR	RR	GSR	HR	RR	GSR
Baseline	Pearson Correlation	0.146	0.455	0.229	-0.389	0.438	0.225
	P (2-tailed)	0.527	0.038	0.318	0.081	0.047	0.328
Cruise	Pearson Correlation	0.188	0.221	0.201	-0.446	0.321	0.215
	P (2-tailed)	0.413	0.336	0.383	0.043	0.156	0.350
			Coriolis Illusion				
Pre Coriolis	Pearson Correlation	0.181	0.171	0.208	-0.450	0.068	0.227
	P (2-tailed)	0.431	0.458	0.367	0.041	0.771	0.322
Coriolis	Pearson Correlation	0.136	0.207	0.222	-0.457	0.098	0.225
	P (2-tailed)	0.558	0.368	0.333	0.037	0.673	0.328
Post Coriolis	Pearson Correlation	0.095	0.077	0.268	-0.487	0.057	0.206
	P (2-tailed)	0.699	0.753	0.267	0.025	0.807	0.371
			Leans				
Pre leans	Pearson Correlation	0.129	0.211	0.231	-0.447	0.006	0.224
	P (2-tailed)	0.576	0.358	0.313	0.042	0.979	0.329
Leans	Pearson Correlation	0.143	0.094	0.187	-0.426	0.152	0.222
	P (2-tailed)	0.547	0.694	0.430	0.054	0.510	0.333
Post leans	Pearson Correlation	0.029	0.074	0.257	-0.459	-0.008	0.224
	P (2-tailed)	0.905	0.763	0.289	0.036	0.971	0.329
			Approach and Landing				
Approach to Land	Pearson Correlation	0.229	0.139	0.210	-0.452	0.000	0.201
	P (2-tailed)	0.319	0.548	0.360	0.040	0.999	0.382
Post landing	Pearson Correlation	0.111	0.106	0.248	-0.489	0.241	0.202
	P (2-tailed)	0.650	0.666	0.306	0.024	0.293	0.380
Post-run baseline	Pearson Correlation	0.146	0.165	0.300	-0.445	0.125	0.199
	P (2-tailed)	0.550	0.499	0.213	0.043	0.590	0.388

Note: Level of Significance (P) ≤ 5%

studies, which could be due to variation in stimuli and collection methodologies [6], particularly the choice of simulated conditions of comparing IMC at night as test conditions to the control conditions of intermittent IMC in clouds except during approach and landing.

Interestingly, Cheung stated that the results of HR measurement in Coriolis are controversial, with "very small, variable, or inconsistent changes" being reported [11]. But Lee et al. found HR to be the "most useful single variable for quantifying workload", among the three variables studied viz., HR, HRV and skin conductance, during simulated landings [7]. It is known that the sinus arrhythmia of the respiratory cycle and phasic changes due to muscle tension and activity influence the cardiovascular system [5]. Thus the chosen variables in this study, especially HR, could have reflected changes in the respiration and striate muscle tension, if any, under the experimental conditions.

It is also known that "novel, unexpected, significant or aversive stimuli" elicit a specific or event-related skin conductance response [5]. Thus as “an indicator of psychological state or process of interest”, skin conductance (GSR/EDA) is considered as a direct representation of sympathetic activity [5]. One need not accept such indicators as ideal autonomic responses, since there is likely dissociation in the autonomic responses as per environmental emotional challenges, nature of the stimuli, and the perception of the individual about the extent and, thereby, subject’s response to the external situations faced [5]. Yet, such variables are useful for evolving an understanding about the pilot’s performance, including under IMC, as in the present study.

Strong significance was found between control and test conditions on NASA-TLX scores. This reflected the perceived difficulty of experimental conditions of flying at dusk and executing maneuvers at night, including ‘Black Hole approach’. Even though the subjects were on instruments during simulated IMC phase of flight, denial of external visual cues may have resulted in perceived difficulty of the task. In an experiment on steep approaches in low-visibility conditions, Boehm-Davis et al. reported an increase in subjective workload ratings (using Modified Cooper-Harper scale) with increasing difficulty associated with landing. Though not consistently significant in their experiment, they suggested that additional demands of steeper approaches and lowered ceiling gave rise to an increase in perceived workload [14].

Negative significant correlation between NASA TLX scores and HR during test conditions reflects that the subjects found the simulated test conditions to be severe as compared to the control conditions. It is conjectured that the negatively correlated changes in HR reflected the coping psychophysiological ability to the perceived workload. In this particular instance, both the psychophysiological and the subjective measure viz., HR and NASA-TLX are but two different measures of the mental workload, and there is no cause and effect relationship between the two [15]. On one hand, HR is an objective, real-time measure, which varies as per the task or phase of the flight. On the other hand, NASA-TLX provides the post-run subjective evaluation by the subject for the overall task performed. In addition, such a discrepancy could also be explained on the basis of the different mechanisms underlying the two responses – HR response to the varying workload throughout the experiment as compared to end-of-the-experiment feedback for the complete situation under evaluation. However, as compared to the subjective measures, the psychophysiological measures provide useful instantaneous and overall information [16].

The significant negative correlation between HR and NASA TLX highlights the importance of HR, as a single vital psychophysiological measure. This reinforces the assertion by Lindholm et al. that simulator based studies were useful to study cockpit workload, and that the HR was the “most useful single variable for quantifying workload” [17]. HR changes are parasympathetic manifestations of motor and perceptual preparatory responses and information processing activity. Thus cardiac activity is a useful measure of cortical activity to study cognitive processes [5]. Hence, while primary performance measure in aviation may not be easy to record without compromising the safety of the flight, psychophysiological measures, particularly HR provides a safe, non-intrusive, objective workload measure. Such psychophysiological variables also reflect moment to moment fluctuations in workload, without being affected by the subject’s judgement.

In comparison, subjective measures like NASA TLX may be affected by the subjects’ biases and retrospective ability to assess their own workload [18]. Yet, it is advocated that a combination of measures [19] must be utilized to study the mental workload, it being multi-dimensional for a single measure to adequately capture [20]. In addition, as Skinner et al. suggested, while addressing workload challenges in transition to 2-pilot tactical military airlift, that the psychophysiological measures can be gainfully used as debriefing tools to pinpoint episodes of significant workload [18]. This may have implications for ensuring aviation safety.

Limitations of the study

The small sample size for the study might have affected the outcome of this study as compared to others due to the variation in stimuli and collection methodologies [6]. Another limitation was non availability of HRV data for analysis, despite recording, due to limitations of the software. This denied the investigators a vital opportunity to study more variables than the ones reported in this study.

Conclusion

Twenty one male military pilots participated in this study to further an understanding about the mental workload during simulated SD susceptible in-flight conditions, using psychophysiological and subjective measures. The outcome of psychophysiological measures in isolation were not significant, though the subjective measures revealed the significant workload under test conditions during simulated IMC flight, akin to inadvertent entry into clouds or flying on a dark night. Significant negative correlation between HR and NASA TLX reinforced the importance of HR, as the most useful psychophysiological variable to quantify workload.

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