High Fidelity Simulations in the Evaluation of Environmental Stress: Acute CO_2 Exposure

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The usual laboratory evaluations of psychophysiologic responses to stress are based on measurements of uncertain relevance to operational effectiveness. This study examines the use of high fidelity simulations for such evaluations. Because of its importance in artificial environments, carbon dioxide (CO_2) was chosen as the stressor.

The test gas was 5% CO_2 in air (normoxic), delivered by mask. CO_2 and O_2 concentrations were continuously monitored. Each subject served as his own control with performance evaluations on air without mask, on air only with mask, and on CO_2 in air by mask. The first test involved image motion compensation in optically tracking a ground target from simulated orbit. The second involved the simulated horizontal landing of a reentry vehicle by jet qualified pilots. Exposure to 5% CO_2 in air for 15 minutes did not result in detectable decrements in image motion compensation. The horizontal landing simulations, however, revealed detectable degradation in the pilot's ability to control the final landing phase.

It is concluded that high fidelity simulations appear to be useful in confirming practical stress tolerance limits. In addition limited conclusions as to emergency limits for acute CO_2 exposure are made.

PSYCHOPHYSIOLOGIC RESPONSES to stress are usually evaluated with laboratory instruments, methods, and measurements which are of doubtful or unknown relevance to operational tasks. It is most difficult to relate, for example, changes in critical flicker fusion frequency, electroencephalographic changes or card sorting performance to landing an aircraft or conducting earth surveillance tasks. On the other hand, it is usually not feasible to investigate such effects in actual operations. Clearly, some compromise must be sought which allows application of results to practical mission operations.

High fidelity engineering simulators have been developed by the aerospace industry for a variety of design, test, and training applications. Test pilots find these simulators of real training value in practicing critical flight operations. This general pilot acceptance of the faithfulness of simulations led us to believe that these sophisticated systems could be applied to the evaluation of responses to environmental stress.

Because of a current advanced design problem, we decided to use acute CO_2 exposure as the stress and attempt to verify concepts of emergency tolerance limits we had developed. A parallel laboratory evaluation was also planned and is reported elsewhere.[7]

Emergency tolerance limits should be based on emergency performance criteria. Under these circumstances the fact that sensitive tests show an effect is not necessarily relevant to the requirements of the situation. Available information indicated that an upper limit of 40 mm. Hg CO_2 partial pressure (PI_{CO_2}) would not be unreasonable for rare, short term emergency, or operationally required exposures. Therefore, the purpose of this study was to evaluate high fidelity mission simulation as a tool in establishing an upper limit of CO_2 for acceptable performance. It was expected that such complex tests would possibly reveal even more subtle alterations in central nervous system function than revealed by electrophysiologic techniques, and at the same time reveal the practical significance of these alterations.

METHODS

The gas mixture selected was 5% CO_2 (P_{CO_2} 38 mm. Hg) in air at near sea level with O_2 adjusted to normoxic levels, ($P_{O_2} = 159$ mm. Hg). Physiologic monitoring in these studies was routine: a one-lead electrocardiogram and thermistor derived respiratory rate. All breathing mixtures were administered by mask (standard military MBU-5/P). O_2 and CO_2 were continuously monitored, using a Beckman Model E-2 (Rapid Response) oxygen analyzer and a Beckman IR-215 (0-10%) CO_2 analyzer. The McDonnell Douglas Astronautics (ED) Earth Orbital Simulator was used to evaluate environmental stress effects upon image motion compensation (IMC), a typical, albeit critical, crew orbital task. The system simulates the visual dynamics necessary to investigate the optical tracking of ground targets from an earth orbiting vehicle after initial target acquisition (Figure 1). The earth's surface, represented by a 1:10,400 scale 2-foot-square, photographic mosaic, was rotated to simulate an orbital flyby at 100 nautical miles. The image motion compensation task was accomplished by moving the mirror in two axes with a direct-rate, pencil-stick hand controller. The optics consisted of an 87 power, f/16 Questar telescope with an optically flat 12-inch mirror, gimballed in two axes. The photomosaic was viewed by reflection from the mirror. A low-level sinusoidal signal with a peak amplitude of 200 micro-radians per second and a frequency of 0.025 cycles per second was applied to the pitch servo to simulate extraneous spacecraft motion. Step disturbances simulating vehicle thruster firings were introduced in the pitch and roll axes through a servo signal to the mirror. The degree of image motion compensation achieved during each 40-second trial was indicated on a direct readout clock that cumulated time error whenever relative motion rates exceeded a high resolution photographic smear threshold (40 micro-radians per second, 24.3 ground feet per second). Following training to asymptote without mask on the IMC task, four McDonnell Douglas engineers received 50 test trials, 25 on each of two consecutive days. On one day, only air was administered by a face mask. On the alternate day, CO_2 was administered for 15 trials followed by 10 trials of air by mask. The four subjects were divided into two groups, with one group receiving CO_2 and air on the first day and only air on the second day. The other group received only air on the first day and CO_2 and air on the second day.

A fixed-based simulator was used to ascertain the effects of a high CO_2 environment on a pilot's ability to perform a horizontal landing utilizing a lifting body re-entry vehicle. The block diagram in Figure 2 illustrates the mechanization of the simulation. Six-degree-of-freedom equations of motion were solved for airframe response with one PACE 231R and two PACE 131R electronic analog computers. Control inputs to the computers were initiated by the pilots through an instrumented cockpit mock-up. The computer supplied the electronic signals through appropriate interface installations for the cockpit instruments, longitudinal feel system, and the television transport system. A television camera and optical system was mounted on a transport to provide three translational and three rotational degrees-of-freedom representing airframe response. A three-dimensional model of a landing site and the surrounding terrain was attached to a vertical frame next to the transport system tracks. The terrain model, 45 feet long and 25 feet wide, represents an area approximately 8.5 by 4.5 statute miles (1:1000 scale). The transport system's limits of motion are 40 feet of longitudinal and 10 feet of lateral translation. The runway is 10,000 feet long and 200 feet wide. The 60-degree image viewed by the television optical system was transmitted by closed circuit to a rear view video projector. The projector displayed the terrain image on a screen, located approximately 5 feet in front of the cockpit, to provide the pilot with the visual scene during the approach and landing maneuver.

Following extended practice without mask, two McDonnel Douglas jet fighter pilots flew 30 test trials with mask, the trial sequence being 10 on air, 10 on 5% CO_2 in air, and 10 trials on air. The NASA high-energy approach and landing technique was employed by the pilots during the simulation. This technique involves a straight in, unpowered approach, consisting of three segments. The first segment is the pre-flare approach during which a constant-speed glide is maintained with the vehicle aimed at a point about one mile short of the runway. The second segment is the landing flare which is initiated at a predetermined altitude during the final approach. The final segment of the maneuver is the deceleration to touchdown. During this last phase, the pilot slowly rotates the aircraft up to maintain a constant flight path angle until ground contact is experienced. The specific lifting body reentry vehicle simulated during the study, representative of current state-of-the-art technology achieved a maximum subsonic lift-to-drag ratio of 3.0 at an angle-of-attack of 12 degrees. The vehicle was positioned 25,000 feet short and 2500 feet to the left of the runway at an altitude of 8500 feet. The approach velocity was 325 knots calibrated air-speed, which corresponds to an approach flight path angle of -22 degrees. The pilots were instructed to flare at 1400 feet with touchdown to be accomplished at 210 knots at a 12-degree angle-of-attack. A constant load factor was sought during the flare and was maintained until a flight path of approximately -3 degrees was attained, at which time the load factor was reduced to one "g". Two eight-channel strip chart recorders documented time histories of simulation and performance parameters.

RESULTS

Image Motion Compensation—The results failed to show a significant difference between a 5% CO_2 at-

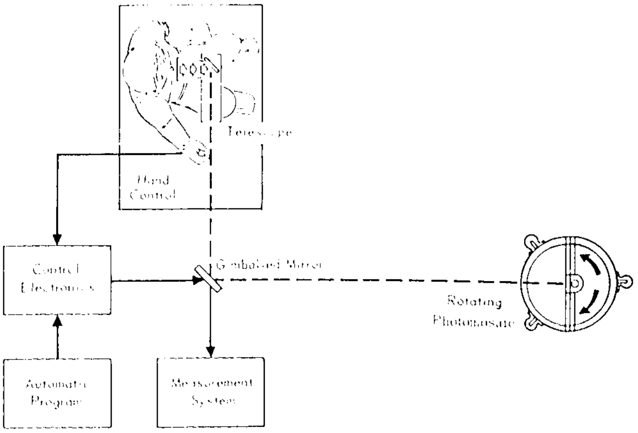

Fig. 1. Earth orbital simulator.

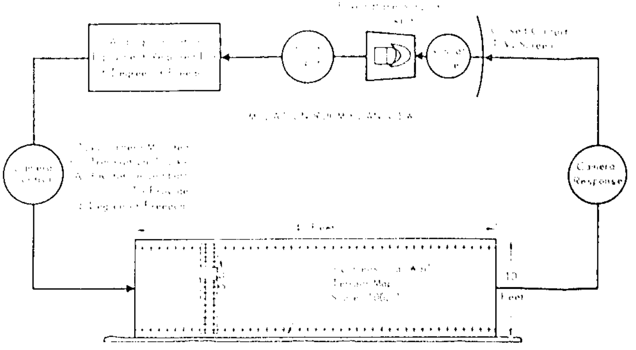

Fig. 2. Horizontal landing simulation.

mosphere and a normal air atmosphere on IMC performance. The only term to achieve significance was the Gas x Subjects interaction term presented graphically in Figure 3. As can be seen, three of the four subjects experienced a decrease in time below criterion when going from an air atmosphere to a 5% CO_2 atmosphere. One subject showed exactly the opposite effect. Additional analysis indicated no effect on performance for the period following CO_2 exposure.

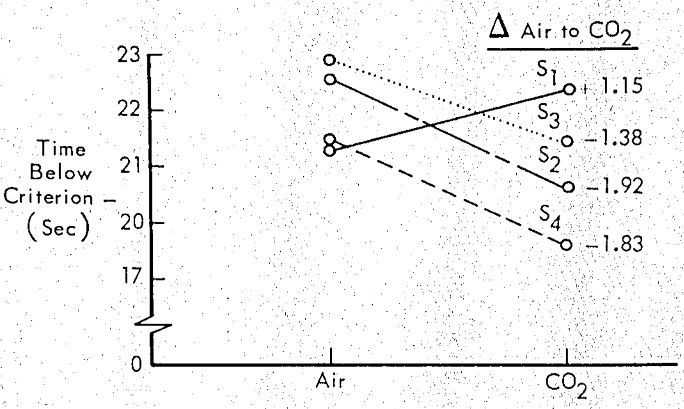

Fig. 3. Effect of CO_2 on image motion compensation. The gas x subjects interaction is significant, however, the performance changes for each individual are not significant.

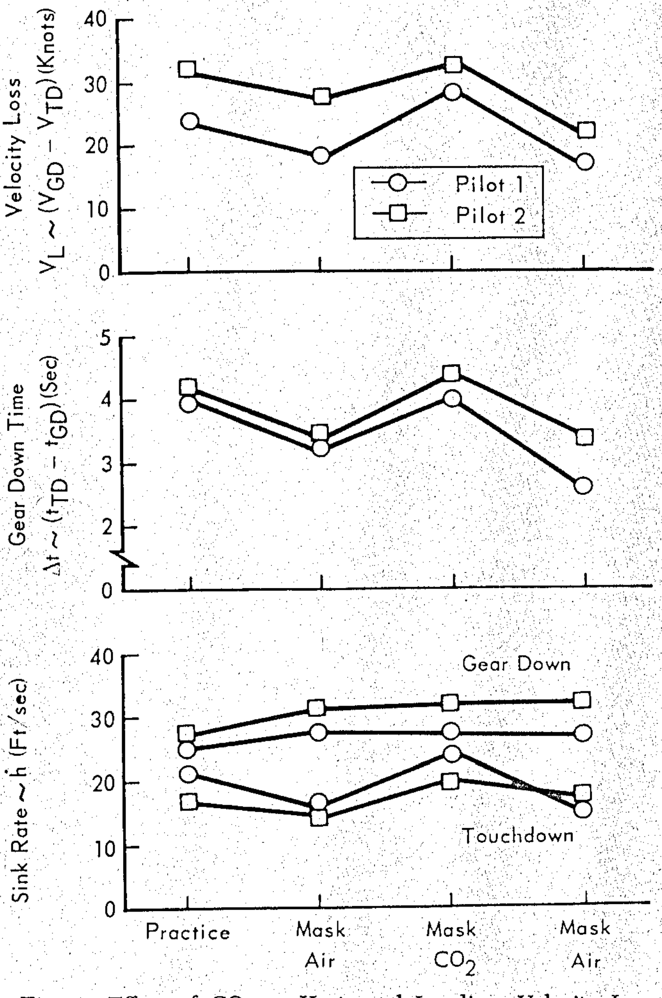

Fig. 4. Effect of CO_2 on Horizontal Landing; Velocity Loss (V_L) from Gear Down (G_D) to Touch Down (T_D), Gear Down Time (flight time with gear extended) and Sink Rate at touch down and gear down.

Horizontal Landing—Under both air and CO_2 exposure, the pilots were able to consistently perform most portions of the flight, such as maintaining the proper approach velocity and flight path angle, eliminating lateral displacement before touchdown, successfully negotiating the flare maneuver, controlling vehicle roll orientation, and consistently acquiring the runway threshold with the necessary energy level. Average touchdown velocities were found to be in an acceptable region, fluctuating around the desired value of 210 knots.

The effects of CO_2 are seen in the pilot's ability to negotiate the flight path from geardown to touchdown. Administration of CO_2 resulted in detectable variations in several of the recorded flight parameters. For example, Figure 4 reveals that when exposed to CO_2, both pilots remained airborne longer and touchdown occurred at significantly increased sink rates.

Physiologic Monitoring—Routine physiologic monitoring of heart and respiratory rates failed to reveal any changes which might have signalled an atmosphere stress to an observer. In CO_2 exposures, episodes of breath-holding were not noted although such episodes were frequent on air under the same performance stress. This observation was substantiated by respiratory tracings but would probably be missed by an observer unaware of the CO_2 exposure.

DISCUSSION

Glatte and Welch[9] and Glatte, Motsay and Welch[8] have reviewed the literature concerning performance degradation in CO_2 exposures. It was apparent to them that there was ". . . a paucity of performance studies to review. . ." Certainly, this is true if performance, as such, is separated from electrophysiologic responses and sensory changes. White[17] observed performance of card sorting at $P_{I_{CO_2}}$ 36 mm. Hg (16-minute exposure), and while subjective symptoms were reported (headache, "fatigue", dyspnea, odd tastes or smells), the task was not influenced, and all the pilot subjects felt they could safely operate an aircraft. In longer duration tests, Schaefer[14] saw attitude changes in submarine crews exposed to more than 21 mm. Hg PI_{CO_2}. Finally, based on their identification of data gaps, Welch's group undertook CO_2 tolerance studies at PI_{CO_2} of 21 to 31 mm. Hg. Performance testing has been reported only for the 21 mm. Hg exposure (5 days), and at no time was degradation noted. These findings substantiated an earlier report of exposure to the same level of CO_2 at reduced pressure in an O_2-rich atmosphere.[3]

In the realm of electrophysiology and sensory perception, a few studies stand out in respect to intermediate ranges of CO_2 exposure (i.e. 21 to 40 mm. Hg $P_{I_{CO_2}}$). Gellhorn and Spiesman[5,6] demonstrated effects of 19 to 64 mm. Hg on the hearing threshold and visual after-image persistence. The first slight change in auditory threshold was seen at about 27 mm. Hg with definite changes in both auditory threshold and in visual after-image persistence at 30 mm. Hg for 6 to 10 minutes. These studies involved a small number of subjects but were well controlled. Schaefer and Carey[15] studied the effect of CO_2 on critical flicker fusion frequency and EEG alpha blocking. Significant changes were found at 38 mm. Hg PI_{CO_2} for flicker fusion frequency and at 41 mm. Hg for alpha blocking time. Increased respiratory effort with alveolar CO_2 controlled did not result in changes. The changes reported by Schaefer and Carey and by Gellhorn and Spiesman imply depressive alterations in central corticosensory function beginning in a range of 25 to 40 mm. Hg P_{ICO_2}. This range was also substantiated by Harter[11,12] who described a threshold for alpha depression and increased reaction time between 3.5 and 7.0% CO_2 with an average of about 5.5%.

In establishing criteria for exposure to any environmental stress, consideration must be given to the combination of length of the exposure and the degree of change compatible with a particular mission. For long-term exposure to CO_2, Schaefer[13] described a concept of "triple tolerance limits." For long term, continuous exposure, his limiting criteria were "no significant physiologic, psychologic, or adaptive changes." At that time, he thought this to be in the range of P_{ICO_2} of 3.5 to 6.0 mm. Hg (0.5-0.8%); but, in fact, there probably is no allowable exposure meeting such restrictive criteria. In missions, however, which are concerned with investigating the biochemical and physiologic reactions to the space environment, this consideration probably overrides others in the NASA limit of 8 mm. Hg[1] and makes more sense than concern over adaptive processes being pathologic in themselves or causing pathologic consequences.

In operational systems or for short-term (hours to days) exposures of operational necessity, Schaefer's second level of CO_2 tolerance seems reasonable (11 to 21 mm. Hg P_{ICO_2}) since no performance alterations of any kind have been seen at these levels in spite of obvious biochemical and metabolic changes[10,13,14,16] and in spite of the possibility of pathologic changes.[14]

These two ranges correspond essentially to a "Threshold Limiting Value" (TLV) and a "Maximum Allowable Concentration" (MAC) as these terms are defined by the American Conference of Government Industrial Hygienists and the American Standards Association respectively. A MAC of 21 mm. Hg PI_{CO_2} is a level which may not be exceeded and below which all other exposures should fluctuate; a TLV of around 8 mm. Hg P_{ICO_2} is an average of time-weighted concentrations during the exposure period. These standards might then be applicable to long-term exposures if biochemical and adaptive changes are acceptable in the mission. In this context it must also be realized that exposure for hours or days to any level of CO_2 will probably result in adaptive changes.[2,10,14]

On the basis of our literature review, we had considered an inspired P_{CO_2} of around 40 mm. Hg to be operationally tolerable even without adaptation, i.e. for short exposures. The results of our preliminary investigations using high fidelity mission simulators seems to substantiate this opinion with certain reservations. During exposure to this single stress, less demanding operations were not affected (IMC and landing approach), but complex critical tasks (final landing phase) showed degradation. With the limited data available to us at this time, we have been unable to dissect the exact mechanism for the degradation in landing performance, but it seems to be related to an inability to compensate adequately for the dynamic changes caused by gear extension. Landing gear deployment, which occurs a few seconds prior to touchdown, increases the piloting task by introducing a nose down pitching moment and by reducing the vehicle's lift-to-drag ratio. These effects require immediate pilot compensation in order to avoid a large increase in vehicle sink rate. Parallel laboratory studies[7] have revealed a complex discrimination reaction time degradation in some subjects. It may be, quite simply, that the number of discrete tasks involved in the final phase of landing represented an overload to a minimally depressed central nervous system.

It must be emphasized that CO_2 exposure as a single environmental stress would be unusual in operational situations. The combined effects of exercise, heat, and CO_2 stress may be overwhelming long before any single one influences function. These interacting effects require extensive study with the purpose of delineating tolerance limits for various stress combinations. It is also possible that the exposure time in this study was too short to reveal total acute effects. The true time-dose relationship in exposures up to a limit of around 60 minutes should also be investigated. We expect, on the basis of the work of Bradley et al.[1] that maximum effects should be seen in about thirty minutes, the point at which cerebrospinal fluid P_{CO_2} reaches equilibrium. At this point adaptive CSF changes make further exposure "chronic" rather than "acute." Performance observations through this time range (0-60 minutes) crossing over the equilibrium point should be most interesting.

Landing simulations display some distinct characteristics which must be considered when attempting to apply simulation performance to the reach task. These characteristics manifest themselves in two distinct areas:

(a) As the altitude decreases to 100 feet or less, the visual image presented in simulation decreases in resolution while the opposite is observed in flight. In simulated touchdowns, pilots tend to fly the visual display down to gear extension and then revert to instruments for the touchdown control (altitude and sink rate). This procedure is never followed in flight. Thus, landing simulation may create a false task below approximately 100 feet, and pilot performance in this region must be cautiously evaluated.

(b) The other problem deals with the psychological behavior of a subject in flight versus simulation. Simulations do not stimulate a pilot to the high level of human operator gain created in actual landing. Postflare control surface inputs are typically much more evident in flight histories than in simulations. Flight recordings show control inputs increasing in frequency and rate as touchdown approaches; therefore, there is need for caution in interpreting simulated landings in the post-flare region because of the human factor variations between simulation and flight.

These observations are based on personal communications (WFB) with aerospace research test pilots (Edwards Air Force Base, 1969). The criticisms do not negate the value of engineering simulations in general but are particularly directed at the fidelity of the last phases of landing.

It is, nevertheless, our opinion that engineering simulators can be quite useful in the evaluation of the operational significance of stress effects and in corroborating or reinforcing laboratory studies. While direct transfer of the results of simulator tests to operational tasks may not be valid in all cases, we feel that the results are much more easily and believably related to operational requirements for performance.

It was of some interest to confirm the fact that routine biomedical monitoring (ECG, heart rate, respiratory rate) was essentially useless in detecting CO_2 exposure. This observation was pursued in more depth in our parallel study and will be reported elsewhere.[7]

SUMMARY

A feasibility study of the use of high fidelity engineering simulators for the evaluation of the effects of performance of exposure to 38 mm. Hg PI_{CO_2} was conducted. There was no evidence of performance degradation except in the most complex and demanding tasks. It is our conclusion that these simulators can be quite useful in relating laboratory measurements to operational requirements.

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