AM 66-10

EFFECTS OF DECOMPRESSION ON OPERATOR PERFORMANCE

William F. O'Connor, Ph. D.
George E. Pendergrass

Approved by

J. ROBERT DILLE, M.D.
CHIEF, CIVIL AEROMEDICAL INSTITUTE

Released by

P. V. SIEGEL, M.D.
FEDERAL AIR SURGEON

April 1966

FEDERAL AVIATION AGENCY

Office of Aviation Medicine

EFFECTS OF DECOMPRESSION ON OPERATOR PERFORMANCE*

I. Introduction.

Rapid decompression represents, even to the most experienced pilot, a highly demanding emergency situation that must be dealt with quickly and appropriately. With commercial passenger aircraft there is the additional problem of effecting a descent rapidly enough to avoid possible harm to the passengers. Evidence exists that even with instructions and demonstrations not all passengers will successfully don their masks.[1] It has been estimated that, following a decompression at the higher operational altitudes, a descent to 18,000 feet should be completely accomplished within 4 minutes to avoid permanent neurological injury to those who may be unprotected.[2]

Experienced and physiologically trained pilots have been observed to manifest greater variability and a degradation in the quality of their performance following decompression.[1,2,4] Taking into account these and other considerations, it has been recommended by Berry[5] and Hanks[2] that in high-altitude passenger-aircraft operations above 25,000 feet at least one pilot be on oxygen at all times. (Current FAA regulations call for one pilot to be on oxygen when at or above 41,000 feet.) In this manner, the immediate effects of the transition to oxygen and the time lost in mask donning would be avoided. Recent work[6] reports no significant psychomotor-performance degradation following rapid decompression to 60,000 feet while wearing a standard oxygen mask.

The present study was performed to provide more quantitative estimate of degradation of pilot performance following decompression and the extent to which a decompression with mask donning interrupts the task of piloting.

Mask-donning time is not equal to the total pilot-functioning time loss following decompression, and it, of course, does not reflect degradation of performance attributable to decompression. Pilot-functioning time loss is time that is taken away from the piloting task by mask-donning. This total time loss can be broken down into reaction time to the donning stimulus, actual time to don, and the time consumed reorienting to the interrupted task. Consideration of the total time loss becomes critical for flight safety, since rapid aircraft decompressions almost always call for immediate action on the part of the crew.[2] The distinction being made here is between the time needed for self-protection and the time consumed before functioning can resume.

A second consequence of decompression is its effects on the quality of performance. In addition to marked shifts in oxygen uptake and cardiac function, there is also expansion of gases in the abdomen and lungs.[7] All of these factors appear to contribute toward degradation of post-decompression task performance.

The present study is aimed at assessing under mask-donning conditions the task-interruption time (pilot-functioning time loss) associated with decompression and extent of performance decrement following decompression.

II. Procedure.

The objectives of the study called for a continuous task that would permit quantification of the subject's performance output. A modification of the Mashburn coordinator, the Scow complex coordinator shown in Figure 1, was employed as the performance task. This task requires the subject to match a pattern of four light stimuli by the concurrent positioning of four controls (two foot pedals and two hand-control levers). The four light stimuli are presented by a display that has four quadrants, each of the quadrants representing a control. Within a given quadrant, there are two vertical columns of five lights, the left column containing the stimulus lights and

* Opinions and conclusions drawn are those of the authors and are not to be construed as necessarily reflecting the policies or practices of the Office of Aviation Medicine or the Federal Aviation Agency.

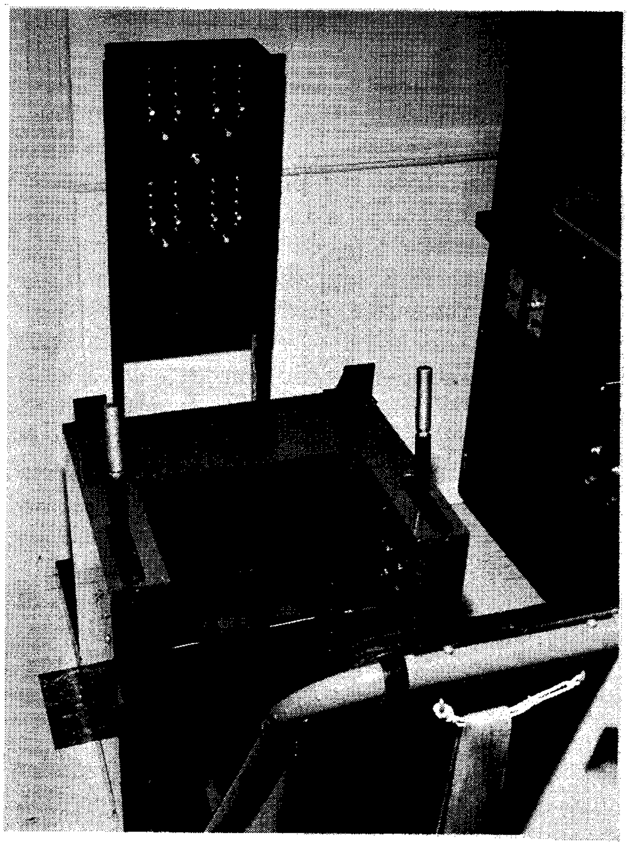


FIGURE 1. Scow complex coordinator.

the right column containing the response lights. The latter are illuminated singly by movement of the appropriate control. Successful completion of a trial occurs when the subject has concurrently positioned his controls to effect a match between stimulus and response lights for all four quadrants. This concurrent match must be held for approximately 0.5 second before the next set of stimuli are presented by a revolving programming drum. Stimuli for a given quadrant were presented in a random order, except for the restriction that the same stimulus light could not appear two trials in a row. The programming drum presented 25 sets of four stimuli patterns (trials), constituting a cycle. At the base of the display panel is an interval timer that can be preset any time up to 15 seconds. It resets when each problem is successfully completed. If the subject does not complete the problem in the preset time, there are two red lights on the coordinator forward of the hand controls that are lighted and remain on until the subject successfully completes the problem. The appearance of the red sweep hand at the vertical and the subsequent appearance of the red "overtime" lights provide the subject with feedback on his performance. During training, the latency of the red lights was progressively shortened as the subject improved, the settings being adjusted for a red-light frequency of occurrence of approximately one-third.

An Esterline Angus event recorder recorded response time for a correct solution to each of the four stimulus elements, the time to complete a trial, and the occurrence of the red "overtime" lights. Performance scores were the time to complete a cycle of 25 trials, which was measured in minutes and hundredths of minutes of the recorder.

The experiments were conducted in an altitude chamber equipped with an accumulator and a "butterfly"-type rapid-decompression valve. Each subject was briefed on the chamber-flight profile before each experimental run. The level-off altitudes following the decompression were 25,000, 27,000, 30,000, 35,000, and 41,000 feet. Each subject was decompressed to one of these altitudes. The predetermined starting altitude was calculated using 8.66 psi pressure differential. Decompression times were determined by a combination of the Haber-Clamman and Fliegner equations. Times varied from 10 to 47 seconds to simulate a partial and total pressure loss through a hole 266 sq in. in area; i.e., the approximate size of the current jet air-carrier window.

Each subject was fitted with a quick-donning mask of a type (Puritan Sweep-On) currently used aboard civil jet passenger aircraft. The subject was briefed and practiced mask donning until he and the experimenter were satisfied with his donning proficiency. The subject was instructed to start donning immediately after he detected the appearance of a red-stimulus signal light in the center of the coordinator display panel. This warning light was triggered by a mercuric barometer as soon as the chamber's simulated altitude reached 14,000 feet following decompression, comparable to the cabin-pressure warning-light system found in civil air carriers. Following the donning of his mask, the subject was instructed to resume the performance task as quickly as possible. A qualified altitude-chamber specialist accompanied the subject. At the outset of the decompression, an ear-sinus check was performed, followed by an ascent at 3,000 ft/min to the predecompression altitude.

The decompression runs consisted of 10 cycles of performance on the coordinator, cycle 16 through 25 (cycles 1 through 15 being the training session). Decompression occurred immediately following the presentation of the stimulus lights for the 10th trial of the 22nd cycle. The subject was unaware as to when in the run the decompression would occur, nor was he aware of the total number of cycles in the run. Until the subject completed cycle 22, the chamber remained at the decompression altiude and then descended to ground level at 3,000 ft/min.

Decompression runs were filmed at 24 frames/sec with a camera driven by a synchronous motor. The camera view included the coordinator display panel, the altitude-warning light, a large sweep-hand timer, an altimeter, and a clear view of the subject's head, shoulders, and hands. By means of frame counting, a chronology accurate to 1/24 second was determined for the following events:

1. Onset of decompression.
2. Activation of the altitude-warning light.
3. Subject's hands leave controls.
4. Subject's hands return to controls.
5. Start of coordinator trial immediately preceding event #3.
6. Completion of coordinator trials following event #4.

III. Subjects.

The subjects for the study were 16 active male aircrewmen, 9 of whom were pilots, the remaining 7 being either navigators or flight engineers. Their mean age was 34.7 years, the range being from 26 to 47 years of age. The average flight time for the group was 3,633 hours, and the range was from 500 to 9,000 hours. All of the 16 subjects had received physiological training and were currently so qualified.

The subjects received training on the Scow coordinator, consisting of 15 cycles of 25 trials each. The performance times for the training cycles for each subject and the cycle means are presented in the Appendix. Figure 2 is a plot of mean performance time per cycle and is taken to indicate that by the eighth cycle the preponderance of improvement in performance time had occurred. These results are interpreted as indicating that the coordinator task was sufficiently learned in the training session to qualify it as an index of the performance effects of decompression. In instances where the training session and the decompression were run on the same day, a minimum of 1 hour separated the two.

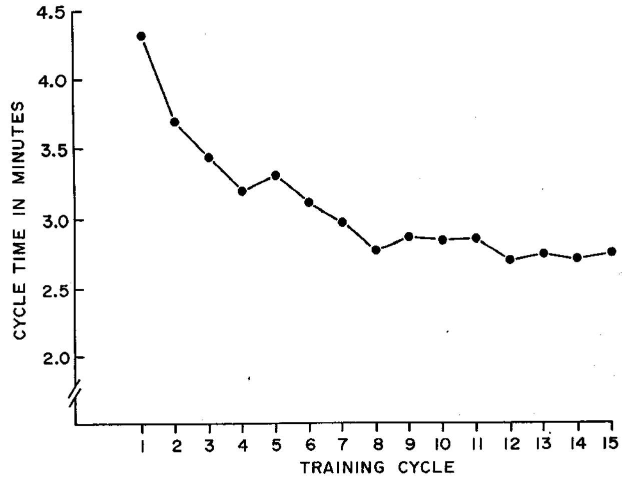


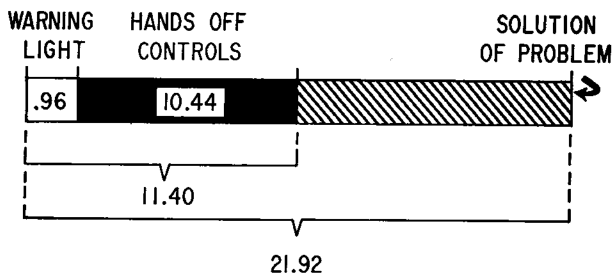
FIGURE 2. Mean time over 15 training cycles on Scow coordinator, 16 aircrewmen.

IV. Results.

Mean interruption time (N = 13)*, which is the time elapsed from warning light through donning and the return of both hands to the control, was found to be 11.40 seconds. The mean time (N = 14)* that the operator's hands were off the controls was 10.44 seconds. The difference between these two values, 0.96 second, represents reaction time to the red warning light. It is well to note that our attention is not directed at mask donning itself, for, although donning is what necessitates the interruption, it is felt that the crucial time to be measured is the time taken away from the primary task. These values correspond to the findings of Bennett[8] in his experimental study of 42 in-flight aircraft decompressions. Bennett presents grouped data on the distribution of time to recognize depressurization and to complete mask donning grouped by 5-second intervals. A mean time for his data was calculated by the present authors, by using the interval midpoint, and was found to be 11.9 seconds for the 42 pilots. Although in most instances the mask was donned within 4 to 6 sec-

* Due to clouding of chamber and noise of decompression, some data were lost, and one subject anticipated the warning light and started donning early.

onds, from a time-and-motion point of view, this merely represents one element in a chain of events. The start of the chain is the warning stimulus, and its completion is the return of the operator's hands to the controls. As indicated above, the mean interruption time (11.40 seconds) is approximately double the time for mask donning itself. These data are presented schematically in Figure 3.



IMMEDIATE LOSS 21.92 − NORMAL AVE (6.64) = 15.28

FIGURE 3. Operator-response time in seconds to decompression.

For a two-operator crew, individual operator-interruption times will be less than crew-interruption times in instances where a coordinated crew response following depressurization is necessary. In such a case, the crew's return to the task will be a function of the slowest responding operator, as is illustrated in Figure 4. Thus, for all of the possible unique pairings of operator interruption times, the slowest time is treated as the time for the pair. The mean interruption time for such pairings for the data was found to be 14.22 seconds.

The above analysis does not take into account the immediate postdecompression effects upon the

PILOT	INDIVIDUAL INTERRUPTION TIME	A	B	C	D	
A	20	-	20	20	20	3 x 20 = 60
B	15	x	-	15	15	2 x 15 = 30
C	10	x	x	-	10	1 x 10 = 10
D	5	x	x	x	-	0 x 0 = 0
	4 | 50					6 | 100
MEAN INDIVIDUAL TIME	12.5				MEAN CREW TIME	16.7

FIGURE 4. Example illustrating derivation of two-operator team-response times.

operator's proficiency but merely indicates the magnitude of the gap in performance. There is a distinct slowing down in operator performance following decompression. In this group of subjects, the average time to complete a trial problem under normal conditions was 6.64 seconds, while the average time on the trial immediately following decompression was 10.52 seconds (this trial time is calculated from the moment the operator's hands return to the controls), or about 58% slower. The difference between normal and postdecompression response times (10.52 and 6.64 seconds), 3.88 seconds, when added to the mean interruption time of 11.40 seconds, yields an estimate of 15.28 seconds for the total time loss during the period immediately following decompression, as depicted in Figure 3.

The data represented in Figure 3 are average times, and it is felt that more emphasis should be placed on the distribution of interruption times or total time loss. Based on the present sample, Table 1 presents the cumulation proportion of operators for various lengths of total time loss.

TABLE 1. Distribution of operator total time loss following decompressions.

Percent operators	*Total time loss (seconds)*
10	9.9
25	13.0
50	16.6
75	20.1
90	23.3
95	25.1
99	28.6

These data indicate, for example, that an allowance of approximately 25 seconds loss from the operator's primary task will encompass 95% of the population of operators. This figure of 25 seconds represents the time loss due to donning and the slowing of performance immediately following decompression.

The performance-decrement effects of the decompression are not limited to the first 20 to 30 seconds but are found to persist over some 3 to 4 minutes. This time represents the approximate period required to complete the decompression block of trials, block 22, as shown in Figure 5. For some subjects, these effects persisted into block 23. The performance decrement observed on the postdecompression series of 25 trials for the five decompression altitudes of 25,000, 27,000, 30,000, 35,000, and 41,000 feet was calculated by dividing predecompression per-

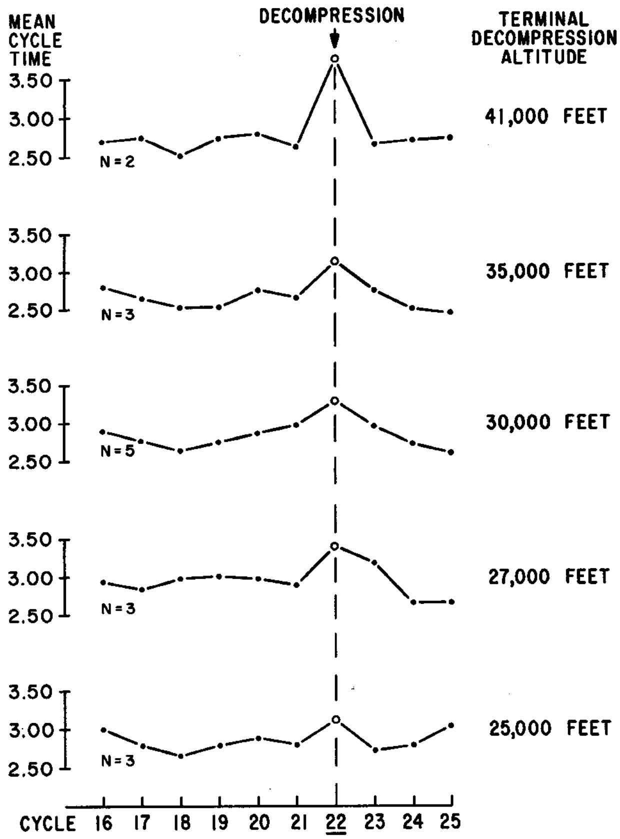


FIGURE 5. Cycle times before and after decompression for the five decompression altitudes.

formance to yield a percent of baseline figures—the higher the value, the slower the postdecompression performance. These figures are shown in Figure 6, with postdecompression altitude plotted against percent of performance decrement or amount of slowing. The number of

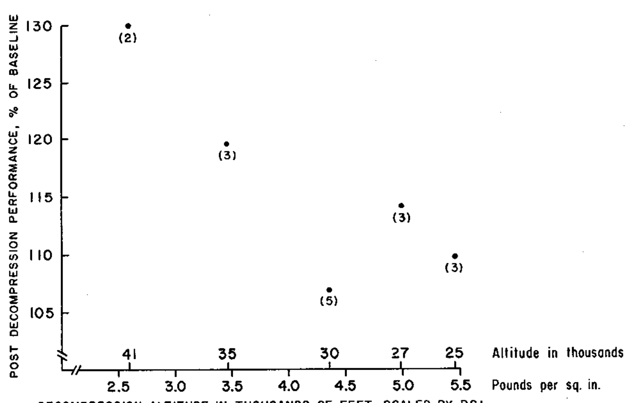


FIGURE 6. Performance decrement in percent of baseline time for 25 trials following decompression for the five decompression altitudes.

cases at each altitude does not permit establishing a relationship; however, the data indicate a trend toward greater performance decrement as decompression altitude rises.

A further analysis was performed to ascertain more precisely the temporal extent of the performance decrement. This analysis of the performance data utilized the methods of quality control, with the human operator representing a process, which is regarded as and is subject to perturbations causing output to vary. A certain range of variations is regarded as acceptable or within normal limits, but should the measure fall outside these the process is regarded as "out of control." In this instance of timed performance measures, only one side of the control limits may be regarded as crictical, the other or lower limit representing exceptionally rapid performance. Quality-control charts for each subject are presented in Figure 7, with the quality-control limits based on the 50 trials immediately prior to decompression. The operator was regarded as being "in control" if his mean of 5 successive trials fell within 3 standard deviations of his predecompression mean of 50 trials, which represented approximately the 0.01 level of confidence. The overall mean trial-completion time was 0.11 minute or about 6 seconds; therefore, each set of five trials represents behavior within approximately a 30-second interval.

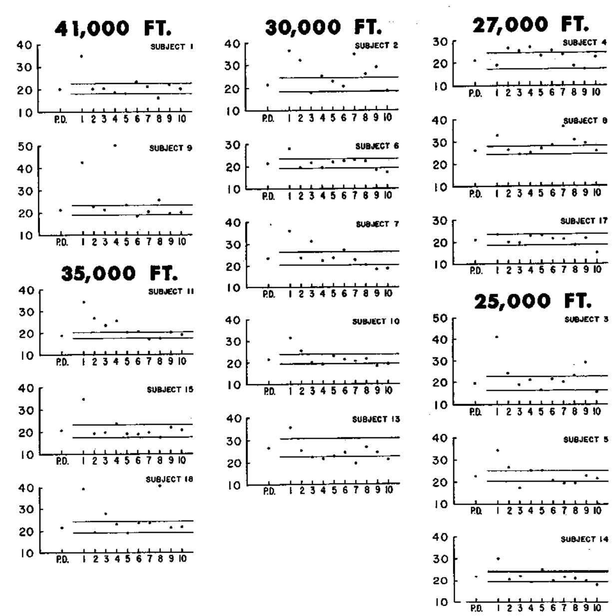


FIGURE 7. Quality-control limit charts, limits equal 3 standard deviations of baseline mean of 50 trials.

TABLE 2. Incidence of performance deviations following decompression outside control limits during 10 sets of five trials each, 16 aircrewmen operators where + = slow deviation and − = fast deviation

Altitude	Subject No.	Set No. 1	2	3	4	5	6	7	8	9	10
41,000	9	+			+		−		+		
	1	+					+		−		
35,000	18	+		+					+		
	15	+			+				−		
	11	+	+	+	+	+	+	−		+	
30,000	13	+		−	−			−			−
	10	+	+		−					−	−
	7	+		+			+			−	−
	6	+								−	−
	2	+	+	−	+			+	+	+	
27,000	4		+	+	+		+				
	8	+					+	+	+	+	
	17	+							−		−
25,000	14	+			−	+					−
	5	+	+	−	+	+		−	−		
	3	+	+						+	+	−
	Totals +	15	6	4	6	3	5	2	5	4	0
	−	0	0	3	3	0	1	3	4	3	7

Table 2 presents the data for all subjects, indicating when, on a basis of indivdualized norm or process data, their postdecompression performance was outside the three standard deviations of the mean limits. For the first set of five trials, 15 of 16 are abnormally slow, and for the first five sets of five trials, 31 of the 37 are outside the limits and represent slower times. On the other hand, the sets 6 through 10 split closely, 16 slow and 18 fast. Testing this difference between the first five sets and second five sets yields a χ^2 of 12.06 (1.d.f, P = 0.001). Thus, it would appear that operator performance is significantly slowed through the first 25 trials (five sets) following decompression, or for approximately 2-½ minutes. There are insufficient data here to draw conclusions concerning differences that may be associated with the various terminal decompression altitudes.

IV. Discussion and Conclusions.

The various analyses indicate impairment of the operator's rate of performance for 2 to 4 minutes following rapid decompression with some suggestion that the severity of effects increases with increase in decompression altitude. The operator's total time lost from his primary task, at the point of decompression where donning is required, has a mean value of some 16 seconds, while the 95th percentile falls at about 25 seconds.

Application of these results to the environment of the commercial air carrier involves a number of extrapolations. For one, the task involved is not piloting, but rather a continuous self-paced serial-coordination problem. This possesses the advantage of permitting a degree of quantification of performance not feasible with an actual aircraft or aircraft simulator. On the other hand, the subjects employed were all current with respect to physiological training, whereas no requirement exists for such training for air-carrier pilots, though many have had previous exposure as military pilots. Hence, it is felt that this study presents evidence that the effects on performance are much more extended than merely the 5 to 6 seconds consumed by mask donning.

Further work suggested by this study includes obtaining control data on performance following decompression with mask on throughout.

APPENDIX

Performance Time per Subject per Training Cycle.
Scow Coordinator

Subject	Cycle Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
D. M.	4.83	4.41	4.02	3.56	4.24	3.73	3.64	3.12	3.37	3.34	3.41	3.07	3.19	3.13	3.17
R. T.	4.65	3.88	3.23	3.07	3.12	2.82	2.84	2.72	2.90	2.82	2.85	2.41	2.71	2.70	2.77
G. H.	4.70	3.93	3.75	3.35	3.65	3.16	3.17	3.07	3.15	3.29	2.84	3.05	3.10	3.07	2.95
C. C. P.	4.00	3.49	3.16	3.21	3.96	3.84	2.75	2.73	2.74	2.56	2.48	2.71	2.59	2.52	2.70
J. D. B.	5.23	3.99	3.32	2.86	3.08	2.71	2.78	2.50	2.57	2.53	2.82	2.60	2.63	2.41	2.32
S. H. G.	4.64	3.14	3.40	3.24	2.77	2.73	2.58	2.65	2.82	2.55	3.05	2.87	2.67	2.69	2.64
R. L. B.	3.92	4.15	3.39	3.08	4.03	3.15	3.13	2.54	2.97	3.12	2.90	2.84	2.92	2.53	3.23
B. M.	4.47	3.51	3.36	3.27	3.04	2.88	2.46	2.44	2.57	2.44	2.51	2.30	2.23	2.51	2.37
C. H.	4.08	3.50	3.22	3.14	2.90	2.70	2.82	2.75	2.70	2.75	2.71	2.66	2.75	2.76	2.49
R. P.	--*	3.24	3.25	2.89	3.20	3.17	3.16	2.90	2.87	2.83	3.20	2.94	2.66	2.98	2.56
R. L.	4.22	3.22	3.11	2.95	3.00	3.04	2.60	2.70	2.79	2.77	2.48	2.46	2.67	2.75	2.70
J. S.	3.45	3.71	3.39	2.96	3.11	3.33	3.39	2.85	2.96	3.05	2.64	2.54	2.92	2.70	2.54
W. O.	3.48	3.32	3.39	2.76	3.08	3.02	3.05	3.17	3.22	3.12	2.88	2.53	2.66	2.58	2.61
W. P. W.	4.06	3.57	3.74	3.96	3.11	3.25	2.76	2.47	2.71	2.83	3.17	2.75	2.76	2.85	3.25
H. A.	4.91	4.08	3.64	3.54	3.37	3.20	3.57	2.82	2.50	2.75	2.72	2.83	2.75	2.78	2.72
L. M.	4.24	4.11	3.69	3.28	3.38	3.15	2.95	3.04	3.08	2.88	3.02	2.62	2.71	2.54	2.77
Mean (N = 16)	4.32	3.70	3.44	3.20	3.32	3.12	2.98	2.78	2.87	2.85	2.86	2.70	2.74	2.72	2.75

* Recording system malfunction.

REFERENCES

1. BARRON, C. I,, and COOK, T. J.: Effects of variable decompressions to 45,000 feet. *Aerospace Med.*, 36: 425-430, 1965.
2. HANKS, T. G.: Human factors related to jet aircraft, in SELLS, S. B., and BERRY, C. A., eds., Human Factors in Jet and Space Travel. Ronald Press, N.Y., 1961.
3. BARRON, C. I., COLLIER, D. I., and COOK, T. J.: Observations on simulated 12 second decompressions to 32,000 feet. *J. Avia. Med.*, 29: 564-574, 1958.
4. BRYAN, A. C.: Rapid decompression in transport aircraft. RCAP Rept. IAM 58/3, *Instit. Aviat. Med.*, RCAF, Toronto, Canada, 1958.
5. BERRY, C. A.: Human qualifications for and reactions to jet flight, in SELLS, S. B., and BERRY, C. A., eds., Human Factors in Jet and Space Travel. Ronald Press, N.Y., 1961.
6. BANCROFT, R. W., and SIMMONS, J. G.: Rapid decompression up to 60,000 feet wearing the standard oxygen mask. *Aerospace Med.*, 35: 203-211, 1964.
7. FRYER, D. I.: Consequences of loss of cabin pressure, in collected papers on Aviation Medicine, AGARD, NATO, Butterworth, London, 1955.
8. BENNETT, G.: Reactions and performance of pilots following decompression. *Aerospace Med.*, 32: 134-136, 1960.