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Cognitive and emotional changes during a simulated 686-m deep dive

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Logue PE, Schmitt FA, Rogers HE, Strong GB. Cognitive and emotional changes during a simulated 686-m deep dive. Undersea Biomed Res 1986; 13(2):225–235.—Three experienced divers were subjected simultaneously to world record hyperbaric pressures using an oxygen-helium-10% nitrogen breathing mixture. The simulated depth reached by these divers was 686 m (2250 ft). Cognitive and emotional state measures were obtained predive, during compression, decompression, and postdive. Although the divers showed no overt signs of nitrogen narcosis or HPNS, declines in memory, adaptive, and spatial functions were seen at 670 m. These performance deficits were reversed when the divers returned to surface pressures. The observed declines in performance are discussed in light of their implications for future dives.

adaptive function	memory
affect	neuropsychology
compression	performance
emotional state	pressure
HPNS	trimix

Diving below 100–200 ft of sea water (fsw) (30–61 m) produces major cognitive and physiological effects known as "rapture of the depths" or nitrogen narcosis. This effect is described as being similar to significant alcohol intoxication, yet without an awareness of the decline. Lipowski (1) describes the nitrogen narcosis syndrome as one of the general delirium states brought about by metabolic changes. Replacing nitrogen with helium in divers' breathing mixtures counteracts nitrogen narcosis to depths of 400–500 ft (122–152 m). Beyond this depth, even with helium replacement, divers may begin to experience HPNS, a syndrome consisting of disorientation, tremors, nausea, microsleep, and increased EEG slow wave activity (2, 3). These symptoms of HPNS tend to become more severe with increases in depth and compression rate (2, 4), and are sufficiently debilitating to preclude useful safe work at depths exceeding 500 ft (5, 6).

Over the past decade, helium-oxygen atmosphere dive simulation studies have demonstrated changes in mental performance as a function of depth. These cognitive changes may reflect subtle changes in CNS functioning even in the absence of overt symptoms of HPNS or nitrogen narcosis. Changes of this type may also be influenced by factors inherent to the dive such as compression rate, gas mixture, and individual differences (7). Impaired perceptual speed, spatial orientation, and flexibility of closure were reported by O'Reilly (8) when divers' performances were compared at surface and at a depth of 152 m. Poorer associative memory performance has been reported for depths of 163 and 152 m (8, 9). However, not all cognitive abilities are negatively affected at these depths. Carter (10) reported impaired perceptual speed and number facility but improved associative memory in comparing the performance of 6 divers at 427 m and at sea level. No changes or performance differences across various cognitive tasks have been reported for divers at a depth of 366 m (11) or between divers at 305 m and a control group (12).

Lewis and Baddeley (13), across a series of 5 dives, reported significant cognitive impairment in divers at maximum depths ranging from 300 to 540 m. These declines were observed on measures of short-term memory, perceptual speed, arithmetic, spatial abilities, and semantic processing but not on tasks assessing word-number associative memory or grammatical reasoning. Rostain et al. (7), in a series of dives utilizing a somewhat limited battery of psychological tests (including manual dexterity, visual choice reaction time, number orientation, and double-single signal barring), found that declines in cognitive functioning appear to be a stable individual characteristic which represented a reliable response in subsequent dives. Therefore, absolute values at the surface could be used to predict performance, at least at 450 m. In addition to the somewhat limited psychological tests given, these investigators were attempting to compare both trimix and heliox mixtures. This would make comparison to the current study at greater depth somewhat difficult.

Simulated deep dives at the F. G. Hall Laboratory for Environmental Research at Duke University have used an oxygen-helium-nitrogen breathing mixture (trimix) that provided some alleviation of both nitrogen narcosis and HPNS. Although no change in performance was reported on arithmetic tests (14) for 3 divers using trimix to 305 m it does appear that divers' cognitive performance may deteriorate during deeper dives even when the effects of nitrogen narcosis and HPNS are reduced using trimix. For example, impaired cognitive functioning on the Halstead-Reitan neuropsychological test battery was reported for 3 divers breathing trimix during a 500-m simulated dive (15).

More recently, Bennett and colleagues (16) at Duke University Medical Center simulated a world record deep dive to 686 m using a 10% nitrogen trimix breathing mixture. This paper describes the ancillary clinical assessment of depth effects on the cognitive functioning and emotional state of the 3 divers involved in the project. In evaluating the ability of divers to perform useful work with minimal risk during deep dives, this investigation particularly addresses the need for a more involved cognitive assessment at maximum depth, and thorough pre- and postdive neuropsychological investigations.

METHOD

Three volunteer, right-handed, commercial divers (ages 24, 25, and 29) were subjected simultaneously to hyperbaric conditions for 42 d in an 8 × 8-ft chamber ("Golf" chamber, Fig. 1), and were compressed to a maximum depth of 686 m (2250 ft) before

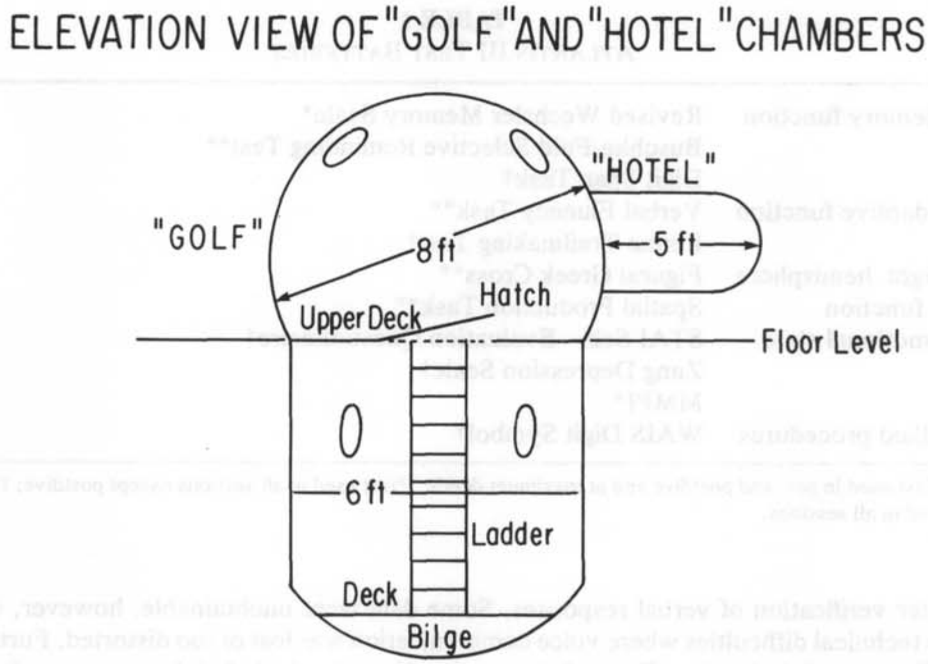

Fig. 1. Plan view of part of the F. G. Hall Laboratory chambers in which divers resided and were tested during compression to 686 m and decompression to 304 m.

decompression to surface pressures. Tests were administered to each diver 28 and 3 d before and 1 wk after the simulated dive. Testing was also accomplished at intervals during compression [Days 2 (400 m), 4 (520 m), 6 (600 m), 8 (650 m), 12 (670 m)] and once during decompression [Day 33 (295 m)]. More detailed neuropsychological evaluations were conducted both pre- and postdive, while abbreviated sets of tests were given during the compression and decompression periods. The divers had no prior exposure to the tests.

Compression to 686 m was initiated using trimix (10% nitrogen). Changes in the gas mixture and decompression rate occurred secondary to divers' reports of decompression illness symptoms. A more detailed description of the dive profile, procedures, and subjective impressions of the divers in the Atlantis dive series can be found elsewhere (6, 16). Table 1 lists the tests given during the dive. Alternate forms were chosen whenever possible for the test instruments to encompass the multiple serial nature of this investigation. Three measures of memory were used: (a) the Russell Revision of the Wechsler Memory Scale (RWMS) (17), (b) forward and backward digit spans, and (c) the Buschke Selective Reminding procedure (SRT) (18, 19). Memory storage, retention, and retrieval functions were assessed using the SRT. Tests selected required either written or brief verbal reports. This helped circumvent communication problems imposed by diver voice distortion resulting from the dive chamber's high pressure atmosphere.

During the dive, each diver was tested separately through single channel audio communication lines with visual contact available through ports and television monitors. The upper sphere of the chamber test sessions were recorded on audiotape for

TABLE 1
ATLANTIS III TEST BATTERIES

Memory function	Revised Wechsler Memory Scale*
	Buschke-Fuld Selective Reminding Test**
	Digit Span Task†
Adaptive function	Verbal Fluency Task**
	Reitan Trailmaking Test†
Right hemisphere function	Figural Greek Cross**
	Spatial Production Task**
Emotional state	STAI Self—Evaluation Questionnaire†
	Zung Depression Scale†
	MMPI*
Allied procedures	WAIS Digit Symbol†

*Test used in pre- and postdive and at maximum depth; **test used in all sessions except postdive; † test used in all sessions.

later verification of verbal responses. Some data were unobtainable, however, due to technical difficulties where voice communication was lost or too distorted. Further efforts to minimize the effects of diver voice distortion included the presence of two experimenters during tasks requiring verbal report. Each experimenter independently scored the tests based on direct observations, and confirmed these responses by later referring to the audiotapes. Final scores reflected consensus scoring between both experimenters. Given that each test session yielded only three data points for each measure, statistical tests of significance were not conducted. Instead, the results are presented for each diver as percent of baseline scores or raw scores for the three major assessment points of the dive, i.e., predive, 670 m (maximum depth assessed), and postdive.

RESULTS

The first category of cognitive function assessed concerned the memory performance of the divers. As seen in Table 2, divers' memory performance declined at depth (670 m) in comparison to the decompression and/or surface comparisons. This pattern of change held for each of the RWMS measures as well as for digit span. Further, while the average postdive scores of figural memory exceeded both depth and predive scores, mean semantic memory scores also returned to predive levels.

For the SRT, total recall, long-term storage, and long-term retrieval measures showed declines at 670 m compared to predive scores. Recovery of function was observed for decompression. The most dramatic change, roughly 80% decline, was observed for the consistent long-term retrieval measure. As seen in Figs. 2 and 3 there appears to be considerable variation in each diver's memory performance as assessed by the SRT. Part of this variation is due to repetitions of test forms (e.g., diver CC at 650 m). However, as the critical assessments at predive, 670 m, and decompression reflect novel test forms, some decline in memory functioning can be inferred that does not appear to be the result of practice or individual effects.

TABLE 2
MEMORY SCORES FOR PRE-, 670 M, AND POSTDIVE ASSESSMENTS BY DIVER

Test	Predive			670 m			Postdive		
RWMS:	AA	BB	CC	AA	BB	CC	AA	BB	CC
Short-term semantic	21	26	28	22	19	15	27	23	22
Long-term semantic	20	20	20	22	15	09	15	25	12
Short-term figural	12	14	08	07	12	09	14	14	12
Long-term figural	12	12	08	08	12	07	14	14	12
Digit span:									
Forward	07	06	09	07	06	06	09	05	06
Backward	06	04	06	06	06	05	07	06	05

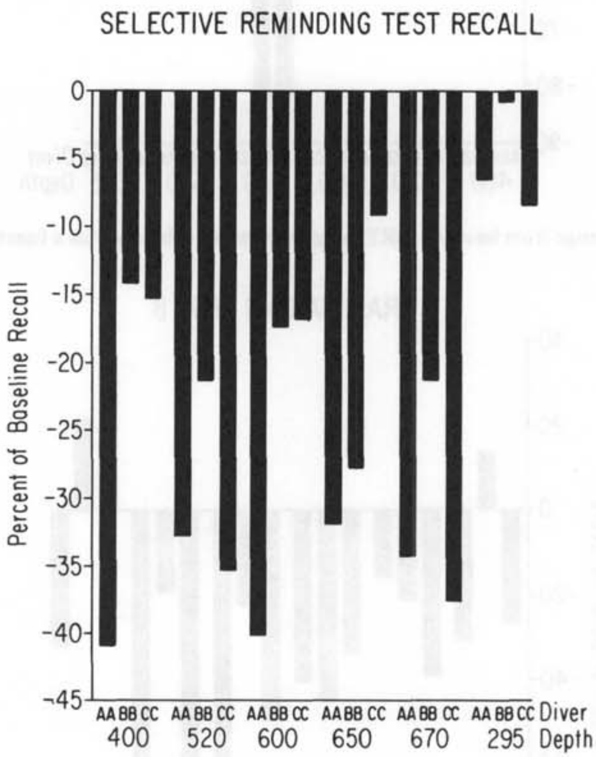

Fig. 2. Percent change from baseline (SRT) recall by diver as a function of depth.

Adaptive functions were assessed by the verbal fluency (20) and trailmaking (21) tasks. As seen in Fig. 4, adaptive function varied by depth and diver. Clear declines were observed on the trailmaking test. On the other hand, the verbal fluency measure did not on the average indicate a decline. One subject, however, did show a decrement in adaptive function as assessed by the verbal fluency task during compression, but

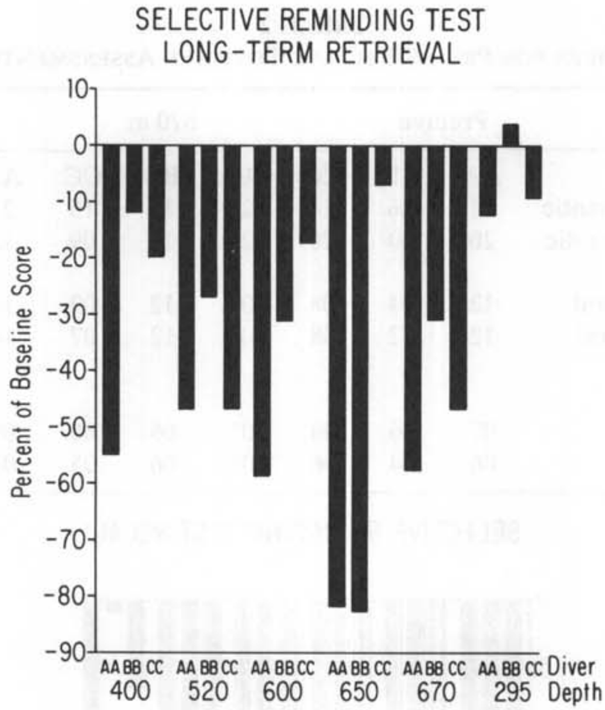

Fig. 3. Percent change from baseline (SRT) long-term retrieval by diver as a function of depth.

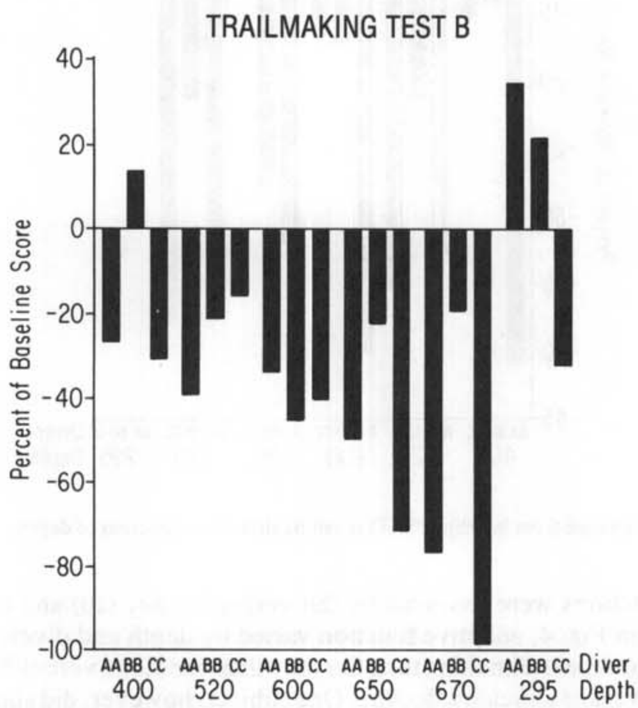

Fig. 4. Percent change from baseline trailmaking test performance by diver as a function of depth.

recovered to predive levels at depth and decompression assessments. Again, all divers showed normal levels of performance during a complete postdive evaluation.

Right hemisphere function as reflected in spatial production (22) and figural Greek cross (23) was also relatively unaffected by increasing depth, except for minor signs of tremor. The Wechsler Adult Intelligence Scale (WAIS) digit symbol task, however, showed a marked reduction in the number of digit-symbol pairs completed by the divers at depth vs. either of the surface measurements. Further, digit symbol and trailmaking test performance appeared to show a more consistent decline with increasing depth for 2 of the 3 divers (Figs. 4 and 5).

Emotional state measures were less dramatically affected by increasing atmospheric pressure than were the cognitive tasks. Situational anxiety (24) showed little change across conditions. A similar pattern was observed for the Zung Self-rating Depression Scale (SDS) measure of depression (25). While the average SDS score remained fairly constant and below 50 (the lower cutoff for mild depression), one diver showed signs of a mild depressive affect near maximum depth.

Minnesota Multiphasic Personality Inventory (MMPI) scores remained essentially within normal limits throughout the dive with the exception of one diver's scores. In this case, scale 9 was elevated predive, declined at depth, and once again increased postdive. These changes most likely reflected his anticipation of the record dive, given his role as lead diver, and then the emotional energies upon exit from the cramped living quarters of the diving chamber. Further, postdive testing was within normal limits and revealed no apparent ill effects of the diving experience (Table 3).

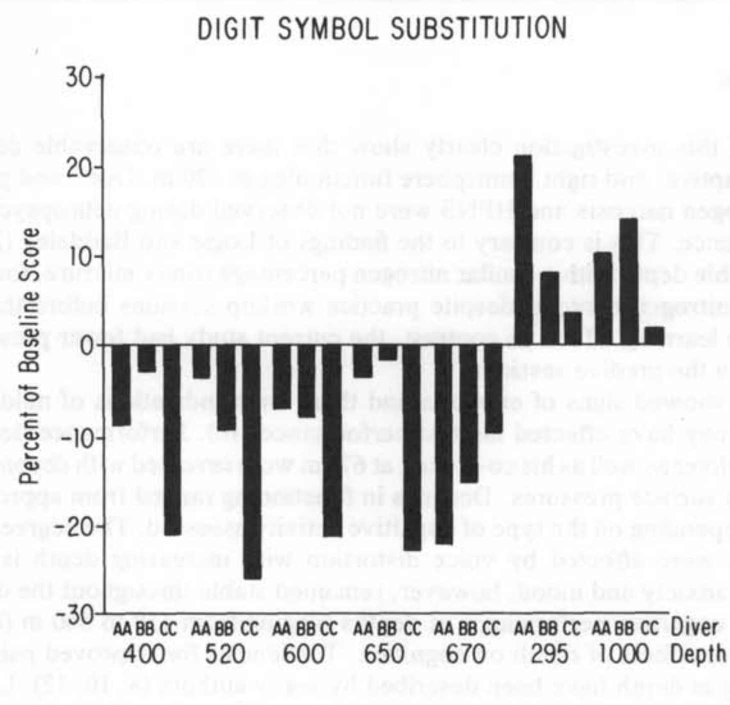

Fig. 5. Percent change from baseline digit symbol substitution scores by diver as a function of depth.

TABLE 3
POSTDIVE ALLIED TEST SCORES BY DIVER

	Raw Scores			Scaled Scores		
Test Diver:	AA	BB	CC	AA	BB	CC
WAIS						
Information	23	21	20	14	13	12
Comprehension	25	25	22	17	17	14
Arithmetic	17	11	12	16	10	11
Similarities	20	22	18	13	15	12
Digit span	16	11	11	16	10	10
Vocabulary	67	64	58	15	14	12
Digit symbol	62	73	64	12	15	12
Picture completion	16	18	18	11	13	13
Block design	44	48	40	14	17	12
Picture arrangement	31	32	24	13	14	10
Object assembly	43	43	44	17	17	18
Verbal:	91	79	71	131	118	111
Performance:	67	76	65	121	135	119
Full scale:	158	155	136	129	127	115

DISCUSSION

Results of this investigation clearly show that there are observable declines in memory, adaptive, and right hemisphere functioning at 670 m. Overt and prolonged signs of nitrogen narcosis and HPNS were not observed during neuropsychological test performance. This is contrary to the findings of Logie and Baddeley (26), who, at a comparable depth with a similar nitrogen percentage trimix mixture, found some evidence of nitrogen narcosis despite practice workup sessions before the dive to minimize the learning effect. In contrast, the current study had fewer presentations of each test in the predive sessions.

One diver showed signs of euphoria and there were indications of mild narcosis that clearly may have effected his test performance (16). Performance decrements seen for this diver as well as his co-divers, at 670 m were reversed with decompression and return to surface pressures. Declines in functioning ranged from approximately 15 to 80%, depending on the type of cognitive activity assessed. The degree to which these results were affected by voice distortion with increasing depth is unclear. Measures of anxiety and mood, however, remained stable throughout the dive.

Studies of cognitive performance at depths ranging from 150 to 540 m (8, 10, 12) show selective effects of depth on cognition. Tendencies for improved paired-associate learning at depth have been described by many authors (8, 10, 12). Lewis and Baddeley (13) have suggested that learning abilities might not be affected by increased pressure. However, the present results for long-term storage on the SRT showed a marked (approximately 30%) decline, implicating impaired learning at 670 m. Further, this study supports Fowler and Ackles' (27) hypothesis of a retrieval failure as a result of increased pressure. On the SRT, long-term retrieval declined (approximately 50%) at depth. An even larger decline in consistent long-term retrieval also implicates disrupted retrieval from memory.

Although spatial memory declined at depth, general spatial abilities were relatively unaffected. Speed of processing declined as indexed by performance on the digit symbol and trailmaking tasks. These results resemble the reductions in perceptual speed studied by Carter (10) and visual search reported by Lewis and Baddeley (13).

Many researchers in hyperbaric pressure have hypothesized that anxiety may interact with other dive stressors to reduce mental abilities (10). Measures of situational anxiety [State Trait Anxiety Inventory (STAI)] and mood (SDS) obtained during this dive do not support this hypothesis. These data support the conclusions of Lewis and Baddeley (13) that declines in cognitive performance are unlikely to be associated with anxiety or lowered alertness at depth.

Data from this study suggest that healthy, bright, motivated, and well-trained divers can continue to function at extreme depths. However, even in the absence of HPNS, changes become apparent on tasks requiring fluid, rapid problem-solving abilities or extended long-term memory performance. Clearly, unusual or emergency situations would require skills and abilities that might have been significantly attenuated by depth. Over-practiced procedures might provide a solution to the cognitive changes associated with increasing depth.

As Logie and Baddeley have suggested, open sea performance may show a substantially greater impairment than hyperbaric chamber studies. These divers were able to maintain functioning under optimum conditions; that is, motivated, well-trained divers under laboratory rather than field conditions. It seems reasonable to assume, given earlier research, that less optimum conditions might produce a more significant drop in performance (28). The verbal communication problem was serious in that it undoubtedly increased the variance in test scores. Although the current study used what were then state-of-the-art computer translators, hardware improvement should be a major focus for future research. For example, the verbal fluency exam was probably invalidated by the distortion of the communication device.

Finally, at this time it is impossible to determine what might be the accumulated effects of multiple and successive deep dives (*note:* one diver had participated in Atlantis II). Data show that divers who have experienced near-miss diving accidents (29) or decompression illness (30) show neurologic and neuropsychologic signs of diffuse and multiple CNS lesions. Whether the neuropsychological changes seen in this dive are similar to those reported for diving accidents or decompression illness is unknown at this point. If commercial divers approached these extreme depths successively and under less ideal conditions (where a medical support team is not immediately present) the subtle blunting of memory, adaptive functioning, and spatial skills might not be apparent until it reached irreversible levels.

Beyond the obvious effects of depth, the psychological stress involved in having 3 healthy males in very confined living conditions for more than a month cannot be overemphasized. Future studies might well focus on the isolation and contingency effects in the absence of atmospheric hyperbaric conditions as well as potential relaxation techniques to reduce situational stresses. The pattern of cognitive decline was distinctly different between the 3 divers. These results may reflect individual differences in adaptation to the stresses of a deep dive. Future evaluations similar to those reported by Rostain and colleagues (7) might use predive data to predict interdiver differences and also predict those divers who are least vulnerable to the deleterious effects of high atmospheric pressure.

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Logue PE, Schmitt FA, Rogers HE, Strong GB. Changements cognitifs et émotionels durant une plongée simulée à une profondeur de 686 m. Undersea Biomed Res 1986; 13(2):225–235.—Trois plongeurs expérimentés furent soumis simultanément à des pressions hyperbares de record mondial avec un mélange respiratoire d'oxygen-hélium-10% azote. Ces plongeurs atteignirent la profondeur simulée de 686 m (2250 p). Les états cognitif et émotionel furent obtenus avant la plongée, ainsi que durant la compression, décompression et après la plongée. Quoique les plongeurs ne montrèrent aucun signe manifeste de la narcose à l'azote ou du SNPH, des régressions dans les fonctions de mémoire, d'adaptation et spatiales, furent observées à 670 m. Ces carences dans la performance, furent renversées lorsque les plongeurs retournèrent aux pressions de surface. Les diminutions observées dans la performance sont discutées en rapport avec leurs implications pour des plongées futures.

fonction d'adaptation
émotion
compression
état émotionel
SNPH
mémoire
neuropsychologie
performance
pression
trimix

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