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Mental Abilities During a Simulated Dive to 427 Meters Underwater

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An experiment was conducted with six divers at a simulated depth of 427 m to investigate the possibility that the underwater environment affects mental abilities. The effects of depth, immersion, their interaction, and repeated testing were assessed with a battery of 10 tests representing seven cognitive abilities. Results show impairment of Perceptual Speed and Number Facility and improvement of Associative Memory at 427 m, compared with abilities at sea level. Hidden Patterns and Division test scores improved with repeated testing. Possible causes of the results, and implications for design of divers' tasks, are discussed.

The psychological effects of the diver's underwater environment range from airy "rapture" to somnolent nausea. "Rapture of the deep," which is due to nitrogen in the pressurized air that divers breathe, has been likened to the effect of imbibing one dry martini for each 10 m of depth beyond 30 m; a more precise and scholarly description is given by Bennett (1975b). Because the nitrogen in high-pressure air has intoxicating effects, an alternative respirable mixture of helium and oxygen was developed by the U.S. Navy during the 1930s. This artificial atmosphere has enabled men to dive as deep as 1,148 ft (350 m) in the ocean and 610 m in dive simulation facilities, which use compressed helium to duplicate underwater pressure. However, despite the use of helium, divers have been adversely affected by high-pressure exposure beyond about 150 m. For example, the high pressure nervous syndrome (Bennett, 1975a; Fructus, Agarate, Naquet, & Rostain, 1976) includes trembling, nausea, and sleepiness, which are more severe as the degree or rapidity of pressurization increases.

Furthermore, some simulated dives in a helium-oxygen atmosphere have resulted in poorer mental performance at maximum depth than at sea level. Biersner and Cameron (1970b) found a decline of Associative Memory at a depth of 600 ft (163 m), compared with standards at sea level. (Capitalized mental ability names are defined in Table 1.) O'Reilly (1974) found impaired Associative Memory, Perceptual Speed, Flexibility of Closure, and Spatial Orientation at 152 m, compared with abilities measured at sea level. Baddeley (Note 1) detected a reduction of Perceptual Speed, serial recall of digits, visual search, Stroop test performance, and Number Facility during a dive to 1,000 ft (305 m).

In contrast to these results, other dive simulations in a helium-oxygen atmosphere have not produced impairment of divers' mental abilities. Biersner and Cameron (1970a) compared divers at a depth of 1,000 ft (305 m) with a control group at

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Table 1
Mental Ability Tests and Factors

Test	Factor	Description of factor[a]
Hidden Patterns	Flexibility of Closure	"The ability to keep one or more definite configurations in mind so as to make identification in spite of perceptual distractions" (p. 19)
Addition	Number Facility	"The ability to manipulate numbers in arithmetical operations rapidly" (p. 28)
Card Rotations	Spatial Orientation	"The ability to perceive spatial patterns or to maintain orientation with respect to objects in space" (p. 28)
Division	Number Facility	
Number Comparison	Perceptual Speed	"Speed in finding figures, making comparisons, and carrying out other very simple tasks involving visual perception" (p. 31)
Multiplication	Number Facility	
Word–Number	Associative (Rote) Memory	"The ability to remember bits of unrelated material" (p. 22)
Subtraction	Number Facility	
Choosing a Path	Spatial Scanning	"Speed in visually exploring a wide or complicated visual field" (p. 42)
Surface Development	Visualization	"The ability to manipulate or transform the image of spatial patterns into other visual arrangements" (p. 47)

[a] From French, Ekstrom, and Price (1963).

sea level and found no difference using tests of Flexibility of Closure and Associative Memory. Hamilton (1976) found no change between performance at sea level and at 1,200 ft (366 m). He tested arithmetic ability, reaction time, manual dexterity, coordination, strength, time estimation, and critical fusion frequency. Brady (Note 2) found no decline of mental abilities at 1,500 ft (456 m). He used tests of Flexibility of Closure, Spatial Orientation, Number Facility, Perceptual Speed, Associative Memory, Spatial Scanning, and Visualization.

Overall, divers' mental abilities are sometimes reduced during high-pressure exposures and are sometimes unaffected. These apparently contradictory findings suggest that pressure is not the only cause of reduced mental abilities in these situations. They also suggest that the ability factors that have been found to be affected—Associative Memory, Perceptual Speed, Number Facility, Flexibility of Closure, and Spatial Orientation—should be investigated further.

Such an investigation was conducted as part of a study of the interaction of diving technology with human physical and mental capabilities underwater. Mental abilities were examined in the context of state-of-the-art diving equipment at a simulated depth of 427 m. The depth of the simulation was chosen to be at the frontier of ocean diving.

Method

Subjects

The subjects were six male U.S. Navy divers; five had extensive experience with dives of this type and one was a veteran of shallower dives. They were highly motivated volunteers in excellent physical condition. The divers were given detailed orientation to the tests before testing began.

Psychological Tests

The tests chosen for this investigation were adapted from French, Ekstrom, and Price (1963). They were Hidden Patterns, Word–Number, Addition, Division, Subtraction, Multiplication, Number Comparison, Card Rotations, Choosing a Path, and Surface Development. The mental ability factors measured by these tests are listed and defined in Table 1.

Test items were stored on photographic slides. Each slide contained 5–10 items, except slides for the Choosing a Path test, each of which had a single complex item. Six forms of the 10-test battery were made by assigning the slides to six slide trays, each tray having sections for all tests. The tests were always administered in the order shown in Table 1.

Divers were examined individually during test sessions, which lasted about 45 min per diver. Test slides were projected through a porthole in the dive simulation facility onto a rear-projection screen. A diver, sitting about 1 m from the screen, responded to the test items via an intercom. The experimenter recorded the diver's responses, timed the tests, advanced the projector, and reminded the diver of procedures before each test was begun.

Test Context and Dive Profile

The dive simulation facility consists of six interconnected pressure vessels. One of these, which was filled with about 100 m^3 of 5°C clear fresh water, was the site of immersed testing. During immersion the divers wore water-heated suits and KMB-10 bandmasks (Schmitt, 1977) with breathing gas heaters. Dry testing was conducted in one of the remaining five chambers of the facility, each of which has a volume of about 16 m^3 and was filled with a helium-oxygen atmosphere. (The partial pressure of oxygen was 304 mm of mercury.) The divers remained in these chambers throughout the 29-day dive simulation.

Several days prior to the experimental dive, the test battery was administered to the divers in both dry and immersed environments at sea level pressure. On the first day of the dive the facility was pressurized to 368 m (depth in sea water). Medical investigations were conducted between 368 m and 305 m on Days 2 and 3, and on the afternoon of Day 4 the facility was pressurized from 305 m to 427 m at 1 ft (.3 m) per minute. Psychological testing at 427 m began on the next morning and continued for 8 days in both dry and immersed environments. At the end of the dive, on Days 27, 28, and 29, the test battery was again administered to each diver in dry and immersed conditions. This final testing was conducted during the shallowest phase of decompression, from 50 m to the surface.

Experimental Design

The design of the experiment was a Latin square with six divers, six test forms, and six treatment conditions. Hence, each diver was tested once in each treatment condition and saw each test form once during the experiment. The treatment conditions were (a) dry at sea level before the dive, (b) immersed at sea level before the dive, (c) dry at 427 m, (d) immersed at 427 m, (e) dry near sea level during decompression, and (f) immersed near sea level during decompression. The scores obtained at or near sea level were used as standards with which to compare scores obtained at 427 m. The treatments were in the same order for all subjects because they all had the same dive profile, and the subjects were tested in random order at each treatment condition. The order in which each subject saw the six test forms was randomized in the body of the Latin square.

Data Analysis

Four orthogonal analysis of variance contrasts between the treatment conditions were planned. In one contrast, the pre- and postdive standards are compared with scores obtained at 427 m. Two other contrasts compare sea level standards with each other and performances under immersed versus dry conditions. The fourth contrast represents interaction of immersion with depth change.

The multivariate data analysis strategy advocated by Hummel and Sligo (1971) was adopted: If the multivariate effects of the treatments were statistically significant, then univariate analyses would be conducted on each of the 10 tests' scores. The univariate analyses, consisting of the four planned contrasts, would show which abilities were affected by which treatments. Effects of test forms

Table 2
Means for Each Treatment and Test

	Sea level (before dive)		426.7 m		Near sea level (after dive)	
Test	Dry	Immersed	Dry	Immersed	Dry	Immersed
Hidden Patterns	66.5 (11.9)	65.8 (17.4)	74.2 (11.5)	62.8 (17.8)	86.8 (14.4)	83.2 (18.0)
Addition	6.8 (6.5)	9.2 (5.6)	4.3 (6.1)	3.7 (2.3)	10.0 (4.0)	7.8 (4.0)
Card Rotations	34.0 (16.3)	34.7 (8.8)	31.2 (11.6)	29.2 (12.2)	36.5 (8.1)	41.3 (23.6)
Division	9.0 (6.8)	8.3 (7.2)	8.2 (7.1)	7.8 (5.7)	14.0 (8.2)	12.2 (8.3)
Number Comparison	16.5 (2.4)	19.5 (3.3)	12.2 (5.3)	9.2 (6.7)	19.0 (6.5)	17.5 (5.8)
Multiplication	11.8 (4.1)	11.3 (7.8)	9.7 (2.7)	5.5 (3.3)	12.8 (4.1)	12.8 (5.5)
Word–Number	1.2 (11.2)	−4.0 (7.2)	3.0 (9.0)	3.3 (11.1)	.7 (11.4)	−4.0 (6.9)
Subtraction	19.7 (5.4)	21.3 (8.4)	21.0 (9.3)	16.3 (7.4)	20.8 (3.9)	20.7 (6.8)
Choosing a Path	2.2 (2.6)	.3 (7.0)	4.3 (3.3)	.5 (5.7)	3.3 (6.2)	1.3 (3.3)
Surface Development	12.1 (6.7)	4.5 (8.5)	9.2 (5.3)	4.3 (7.1)	16.8 (11.2)	7.2 (5.0)

Note. Standard deviations appear in parentheses.

Table 3
Statistical Analyses of Contrasts for Each Mental Ability Test

Test	Standards vs. 427 m $F(1, 20)$	Standards before vs. after dive $F(1, 20)$	Immersed vs. dry $F(1, 20)$	Immersion × Depth $F(2, 20)$	MS_e
Hidden Patterns	2.47	13.09**	1.61	.56	162.63
Addition	16.55**	.52	.03	1.64	9.61
Card Rotations	2.46	.93	.09	.26	135.81
Division	6.46*	11.44**	.78	.18	10.23
Number Comparison	52.29**	.04	.26	3.44	8.31
Multiplication	16.50**	.90	2.10	1.50	10.37
Word–Number	4.77*	.01	2.43	.75	37.16
Subtraction	1.37	.42	.45	1.42	22.39
Choosing a Path	.23	.51	4.23	.27	13.88
Surface Development	2.21	1.91	11.65**	.42	42.18

* $p < .05$.
** $p < .01$.

and divers would be isolated to reduce the experimental error of the analyses.

Results

Means and standard deviations of scores for all tests under all treatment conditions are shown in Table 2. Scores are the number of items correctly solved within time limits minus the number of incorrect answers.

The multivariate Wilks's criterion indicated that test scores were affected by the treatment conditions, $F(50, 53) = 1.80$, $p < .05$. This multivariate finding was followed by univariate analyses, presented in Table 3, of planned contrasts for each mental ability test.

Column 2 of Table 3 consists of F ratios for contrasts that compare performance at 427 m with performance in the standard (sea level) conditions. Four mental ability tests—Addition, Division, Number Comparison, and Multiplication—elicited poorer performance at 427 m; the direction of the effect is shown in Table 2. Conversely, Word–Number scores improved significantly at 427 m. Column 3 of Table 3 has F ratios for contrasts between standard performance before and after the dive. Hidden Patterns and Division scores changed significantly, and Table 2 shows that the change was an improvement from the earlier standard to the later. Column 4 of Table 3 presents F ratios comparing dry with immersed performance. Only the Surface Development test was significantly affected; an adverse effect of immersion is indicated by Table 2. Finally, the absence of any significant Depth × Immersion interaction in Column 5 of Table 3 indicates that performance was equally altered by depth change in an immersed or dry environment.

The assumptions on which these analyses are based were verified by plotting standardized residuals on normal probability coordinates and by conducting the Tukey test for nonadditivity (Kirk, 1968). The graphs and the Tukey test indicated that there were no violations of the assumptions (i.e., normally distributed error and absence of interacting effects of subjects, test forms, and treatments).

Discussion

The simulated dive to 427 m underwater produced changes in the divers' mental abilities. Impairment of Number Facility is indicated by Addition, Multiplication, and Division tests. Reduced Perceptual Speed at 427 m is evidenced by lower scores on the Number Comparison test. Scores on the Hidden Patterns and Division tests improved from the beginning of the experiment to the end of the dive. Apparently the divers were acquiring skill at division and recognition of hidden patterns because of exposure to the tests. Although this effect of repeated testing complicates interpretation of Division scores (representing Number Facility), Addition and Multiplication test results uphold the inference of reduced Number Facility at 427 m.

Another result of this experiment is that scores on the Surface Development test were lower during immersion than in a dry environment. This is probably an artifact of impeded vision. Partial fogging of a diver's faceplate is common underwater, and the divers reported that fogging interfered with perception of the detailed drawings of the Surface Development test. Hence there probably was no effect of immersion per se on mental abilities. Absence of an interaction of immersion and depth complements the finding of no effect of immersion; immersion had an equally negligible effect at 427 m and near sea level before and after the dive.

Improved Associative Memory at 427 m is reminiscent of the Fowler and Ackles (1975) hypothesis that divers' anxiety and high-pressure air have mutually canceling adverse effects on memory. Although Fowler and Ackles proposed the hypothesis to explain effects obtained in air, the principle may be relevant to results observed in a high-pressure helium-oxygen atmosphere as well. Application to the present finding would require that Associative Memory be weakened by anxiety throughout the dive, including during predive and postdive standard testing. The unknown stressor that impaired Number Facility and Perceptual Speed at 427 m may have canceled the simultaneous effect of anxiety on Associative Memory. This would have resulted in improvement of Associative Memory at 427 m compared with the sea level standards, as was observed.

Although the agent that caused the changes at 427 m cannot be identified, several possibilities were considered. It seems unlikely that the present findings represent merely an erroneous statistical inference, because similar results have been obtained by other investigators (Biersner & Cameron, 1970b; O'Reilly, 1974; Baddeley, Note 1). The possibility that the mental ability changes were caused by pressure alone is similarly reduced by the negative findings of other experimenters at similar pressure (Biersner & Cameron, 1970a; Hamilton, 1976; Brady, Note 2). Atmospheric contaminants have been ruled out by chemical tests. An attractive hypothesis is that the divers were responding to the demand characteristics of the experiment. However, the factorial specificity of the findings and the improvement of memory would not have been expected if the divers were responding to a perceived cue for reduced ability at 427 m. Finally, the 122-m compression preceding testing at 427 m was unusually rapid (.3 m/min). Rapid compression and high pressure have been known to interact to produce the high pressure nervous syndrome. They may have instead produced the subtler signs of reduced mental ability observed at 427 m during this simulated dive.

Whatever was the cause of reduced Number Facility and Perceptual Speed, both of these abilities are important to divers. Their safety depends on use of these abilities for correct performance of tasks like reading watches and gauges, making simple calculations, and comparing instrument readings with numbers on checkoff lists. To mitigate the reduction of Number Facility and Perceptual Speed during dives like this one, divers' tasks should be designed to avoid or simplify numerical operations and visual comparisons. The tasks should emphasize the relatively unaffected spatial abilities (i.e., Spatial Orientation, Spatial Scanning, Flexibility of Closure, and Visualization), which are described by French et al. (1963) as identifying, orienting to, transforming, and visually exploring spatial configurations.

The changes of human abilities noted during dives in a helium-oxygen atmosphere should be of continuing research interest because of their practical implications and the elusiveness of their causes. Further research should include tests of Number Facility, Perceptual Speed, and Associative Memory. These abilities have been found repeatedly to be affected by high-pressure exposures. However, high pressure cannot be the only reason for altered mental abilities, because they are not changed by all high-pressure exposures. Two other causes have been suggested: situational anxiety may interact with other stressors to affect memory, and a rapid rate of compression may be associated with reduced mental abilities. These and other possibilities remain to be explored by workers in this unusual area of applied psychology.

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