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Diver performance: the effect of cold

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Davis, F. M., A. D. Baddeley, and T. R. Hancock. 1975. Diver performance: the effect of cold. Undersea Biomed. Res. 2(3):195-213.– Fifteen divers performed five tasks in water of temperatures 20°C and 5°C, using standard scuba equipment. A significant deterioration of performance occurred under the colder condition in: simple arithmetic 13%; logical reasoning 17%; word recall 37%; word recognition 11%; and manual dexterity 17%. Throughout each dive, rectal and five skin temperatures were monitored. Average fall in rectal temperature was 0.5°C during 20°C dives and 1.1°C during 5°C dives. Average body surface temperature fell by 5°C and 12.5°C respectively. Average heat losses calculated from the data were 95 $kcal \cdot m^{-2} \cdot hr^{-1}$ (20°C dives) and 245 $kcal \cdot m^{-2} \cdot hr^{-1}$ (5°C dives). The impairment in word recognition was significantly correlated with the fall in rectal temperature for the 5°C dives. For other tests, the deterioration did not appear to be correlated with body-temperature changes, but rather, occurred rapidly upon cold water immersion. The significance of these findings is discussed in relation to current understanding of the mechanisms by which cold is thought to influence performance underwater.

air diving	monitoring equipment
cold	diver performance
body temperature	wet suits

It is well recognized that many factors influence diver performance and, as field studies on divers accumulate, the wide disparity between these and pressure chamber experiments has become obvious (Baddeley 1966a; Baddeley, de Figueredo, Hawkswell-Curtis, and Williams 1967; MacInnis 1971). Field studies present major problems for the experimenter and require robust experimental designs. Experimental variables can seldom be strictly controlled and one can only hope to minimize the influence of the many in order to study the effect of any one factor.

To date, performance testing of divers underwater has taken two approaches: either the use of a battery of performance tests (Bowen 1968; Davis, Osborne, Baddeley, and Graham 1972; Egstrom, Weltman, Baddeley, Cuccaro, and Willis 1972) or the analysis of a single, more complex task (MacInnis 1971; Egstrom et al. 1972). Both approaches have value. Whereas it has been argued that complex tasks have greater immediate relevance to operational diving, their analysis may be difficult and is often hard to interpret in theoretical terms. For this reason we have chosen the test-battery approach for both this and previous studies (Davis, Charlier, Saumarez, and Muller 1972).

Much commercial and scientific diving is performed in temperate or polar waters and, while large commercial enterprises may have extensive back-up and heating systems for deep diving in these waters, most operators still rely on simple scuba equipment using wet suits or similar insulation for most of their work. It is therefore essential to have basic data on cold water performance for planning realistic underwater work programs and assessing the operational costs of suit heating systems in terms of improved diver efficiency.

There are few studies on cold water performance available in the literature. Bowen (1968) used a large battery of tests to show an impairment of manual tasks in the cold, which was progressive with a reduction in water temperature from 72°F (25°C) to 44°F (7.5°C). He distinguishes two influences: one that he calls a "water" effect–due simply to immersion in water–and the other, a "cold" effect when water temperature is lowered. Stang and Weiner (1970) carried out a laboratory experiment at water temperatures between 50°F and 70°F in which they showed that manual performance decrement in experienced divers was progressive with length of exposure to cold water. In neither of these experiments was body temperature fully monitored. Baddeley, Cuccaro, Egstrom, Weltman, and Willis (*in press*) have shown an impairment of memory in 5°C water using a verbal-recall test, but no impairment of vigilance, reaction time, or reasoning. They concluded that there was no unequivocal evidence of anything other than a peripheral distraction effect of cold on human performance.

It is clear from this that further work on the effects of cold, particularly on intellectual skills, is essential and that adequate body temperature monitoring should be a necessary part of such studies. The present study was carried out in water temperatures of 5°C and 18-21°C in sheltered inland water, using a *test battery* of cognitive and manual tasks, and monitoring peripheral and central body temperature.

DIVING PROTOCOL

The subjects were 16 experienced divers from the United London Hospitals Diving Group (Table 1). The experiment was conducted in a flat-bottomed, fresh water quarry about 30 ft deep. A floating laboratory was moored in the middle of the quarry and contained all necessary back-up facilities, including AC and DC power supplies, hoists, dry changing facilities, etc. The dives were conducted from this laboratory. Water temperature is 4-5°C during winter; in summer, a marked thermocline develops and, while the bottom water remains at about 5°C (range: 4.5°C to 5.5°C during the experiment), the upper layer warms to a mean of about 20°C (range: 18°C to 21°C during the experiment).

TABLE 1

Subject data, showing means and ranges for 16 divers

	Mean	Range
Age (years)	25.5	22–31
Number of dives	125	20–500
Height (cm)	180	167–193
Weight (kg)	76	61–96
Body surface area	1.92	1.75–2.16

Diving was carried out on weekends over 2 years. During the first year the divers familiarized themselves with the diving site and the equipment to be used. Also various pieces of apparatus were made and tested. Two test benches were set up underwater, adjacent to the floating laboratory: one in cold water with the subject at a depth of approximately 9 m and one in warm water with the subject at a depth of 2 m. Each bench was constructed of two large aluminum A-frames joined between the cross-arms by a large

(1 m by 1 m) table top at which the diver sat. Artificial lighting was provided to ensure sufficient light despite minor variations in natural light intensity in the quarry water.

The subjects carried out a 5°C *(cold)* dive on one day and a 20°C *(warm)* dive on the other day, each at the same time of day. Half the divers began with the cold condition and half with the warm. Temperature probes were positioned under each diver's foam, 3/16th-inch neoprene wet suit. Breathing apparatus consisted of a single 60 ft^3 aqualung fitted with a Royal Mistral demand valve. A mouth-mask sealing over the mouth and chin replaced the standard mouthpiece, allowing the diver to talk intelligibly. A bone-conducting transducer was fitted behind one ear over the mastoid process, for two-way communication with the surface by means of a MacMurdo Instruments DUCSET.

The subject dived slightly negatively buoyant, for comfort when sitting at the test bench. He descended accompanied by a buddy diver, who was responsible for handing him various test boards during the dive. The buddy diver was not required to remain in the cold water throughout the dive. The entire dive was managed from the surface via the DUCSET and lasted about 40 min (range: 35-50 min). Bottle air pressure was recorded immediately before and after each dive. Useful data was obtained on all but 1 of the 32 dives.

SECTION ONE: TEMPERATURE MONITORING

METHOD

BANJO-type temperature probes (YSI Thermistors Series 400B; time constant 0.6 s) were placed at five sites over the body:

1. ulnar aspect of the forearm about 5 cm proximal to the wrist (Wrist – W),
2. the lateral aspect of the upper arm (Arm – A),
3. on the back in the midline about the level of D5 (Back – B),
4. anterior abdominal wall just above and medial to the superior iliac crest (Loin – L), and
5. anterior aspect of the mid-calf on the medial border of the tibia (Calf – C).

In addition, a rectal temperature probe (YSI Probe 401; time constant 7 s) was inserted about 8 cm into the rectum.

After the probes were secured lightly in position with tape, the diver donned his suit. This helped to secure the probes in place. The six cables bound together ran from under the suit jacket to a sealed junction box at the diver's waist. From this box a single multicore cable ran with the DUCSET communication cable/life-line to the surface, where temperatures were read on a six-channel, battery-operated recorder (YSI Model 41TD Telethermometer). Accuracy of each channel was checked against a mercury-in-glass thermometer accurate to ± 0.1°C; no recalibrations were required despite the 50 ft of cable.

Temperatures were recorded during suiting and immediately before and after divers entered the water. During the dives, recordings were taken every 2 min until completion of the manual dexterity test (*see below*) and every 5 min thereafter. During the early part of a cold dive, accurate skin recordings were difficult to obtain due to the rapid changes that were occurring. Therefore readings were taken at a set time interval after switching channels and read to the nearest degree Celsius. One final set of readings was taken immediately after divers exited from the water and, thereafter, rectal temperature was measured at intervals using a clinical mercury-in-glass rectal thermometer calibrated against the rectal probe, until a *normal* rectal temperature was regained.

RESULTS

Typical temperature graphs for the dives are shown in Figs. 1-3. Average skin and average body temperatures and heat losses were calculated using the formulae devised by Burton (1935) (*see Appendix to this article*). These values were based on the difference between the immediate predive readings and the last indive readings.

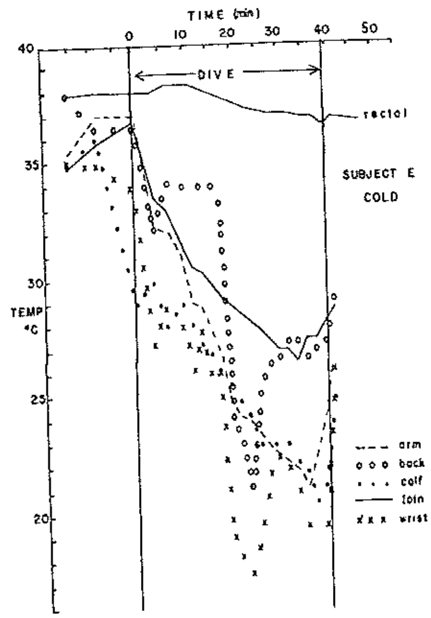

Fig. 1. Skin and rectal temperature changes (°Celcius) for Subject E in wet suit during a cold (5 °C) dive (see text for explanation).

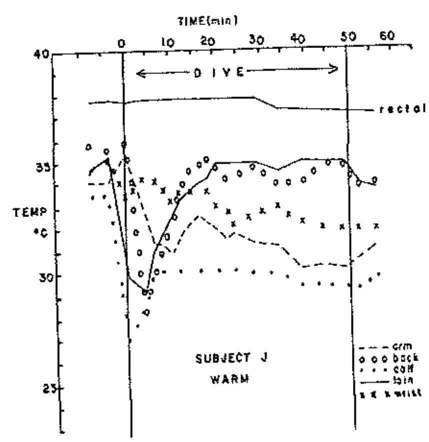

Fig. 2. Skin and rectal temperature changes (°Celcius) for Subject J in wet suit during a warm (20°C) dive (see text for explanation).

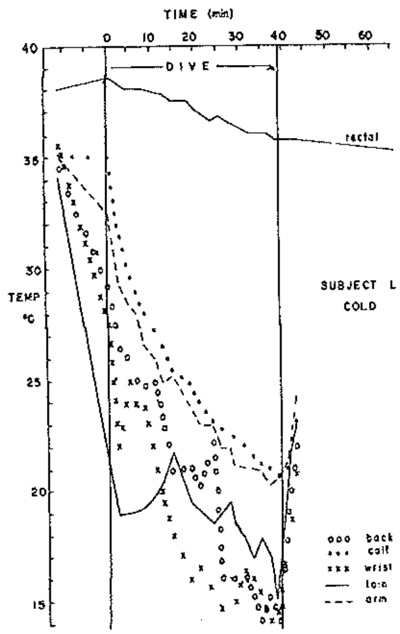

Fig. 3. Skin and rectal temperature changes (°Celcius) for Subject L in wet suit during a cold (5°C) dive (see text for explanation).

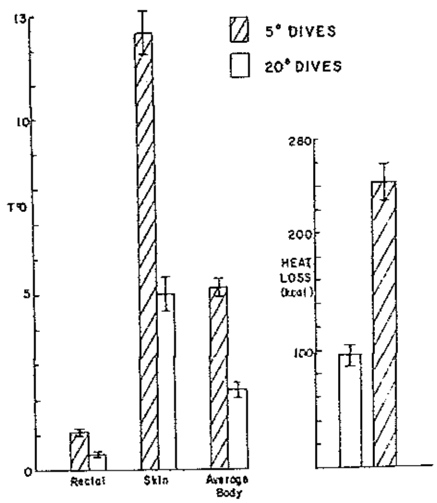

Fig. 4. (a) The mean drop (with SE) in rectal, average skin, and average body temperatures (°Celcius) in 15 wet-suited divers during cold (5°C) and warm (20°C) dives. (b) Calculated average body heat losses ($kcal \cdot m^{-2} \cdot hr^{-1}$) for the same dives (with SE).

Dives in 5°C water. Average skin temperature decreased by a mean of 12.5°C from 34°C predive to 21.5°C at the end of the dive, and rectal temperature by 1.1°C from 37.9°C predive to 36.8°C at the end. This gave a mean drop in average body temperature of 5.2°C (Fig. 4). The average indive drop in rectal temperature (1.4°C) was greater than that used for the heat-loss calculations. This was due to an initial mean rise of 0.3°C in rectal temperature upon immersion in cold water (see Fig. 1). An indive drop in rectal temperature of greater than 2°C occurred in two divers: Subject L, 2.8°C (Fig. 3) and Subject S, 2.2°C. Both *subjects were unable to complete the full sequence of performance tests in cold water.* Average heat loss during the cold dives was 245 $kcal \cdot m^{-2} \cdot hr^{-1}$ (Fig. 4; *see* Table 2 for individual values).

Dives in 20° C water. Average skin temperature decreased by a mean of 5°C from 34°C predive to 29°C at the end of the dive, and rectal temperature by 0.5°C from 37.9°C predive to 37.4°C at the end. This gave a mean drop in average body temperature of 2.3°C (Fig. 4). There was only a minimal initial rise in rectal temperature upon immersion at the start of the warm dives (*see* Fig. 2). Average heat loss during the warm dives was 95 $kcal \cdot m^{-2} \cdot hr^{-1}$ (Fig. 4; *see* Table 2 for individual values).

Divers commenced both dives with normal or slightly raised average body temperatures (for example, Fig. 3), presumably due to the exertion of suiting in warm surroundings out of the wind. An "after-drop" in rectal temperature (Keatinge 1969) did not occur following the warm dives (for example, Fig. 2) and was only slight (mean, 0.25°C) following the cold dives, reflecting the sheltered surface facilities (e.g. Figs. 1 and 3). As a result, the recovery phase was not examined in detail. The memory-recall and recognition tests (*see below*) were given soon after each dive at a stage when body temperatures were still close to those at the end of the dive.

Peripheral temperatures showed some interesting patterns. Marked drops in back and loin temperatures, in some divers upon immersion, even in warm water, suggest leaks or areas of poor fit of the wet suit jacket (Fig. 2). The warm dives in general were unremarkable except that skin temperatures tended to drop rapidly initially and then to remain relatively constant (Fig. 2). In some there was a definite rewarming phase following this initial drop as the water getting into the suit was warmed by the body (Fig. 2).

During the cold dives sharp discontinuities in the wrist and arm temperature curves were occasionally seen (Fig. 1). These occurred during the manual dexterity test (*see below*), presumably due to the resultant increased activity of the diver during this test. Typically a fall in wrist temperature, sometimes accompanied by a similar drop in arm or back temperature, occurred, followed by a rise of a few degrees on completing the task (Fig. 1).

Rectal temperature was maintained for a period of about 5 to 20 min during the cold dives and then dropped steadily. During the warm dives rectal temperature was maintained for at least 30 min in all but two subjects.

Air consumption. Air consumption for each dive was calculated from the bottle pressures recorded immediately before and after the dive and corrected to 1 ATA. These values together with calculated heat losses are shown in Table 2. Air consumption and calculated heat loss show a significant linear correlation ($r = 0.74; P < .001$; Fig. 5). The relationship is described by the following equation:

$$\text{air consumption} = 4.2 + 0.7 \text{ heat loss } (l \cdot m^{-2} \cdot min^{-1}) \tag{1}$$

TABLE 2

Air consumption ($L \cdot m^{-2} \cdot min^{-1}$, corrected to 1 ATA) and heat loss ($kcal \cdot m^{-2} \cdot min^{-1}$) for 15 divers at two different water temperatures

	20°C Dives		5°C Dives	
Subject	*Air consumption*	*Heat loss*	*Air consumption*	*Heat loss*
A	3.7	0.33	7.4	3.33
B	4.0	1.66	6.5	3.9
C	4.5	1.8	7.4	5.25
D	–	–	8.5	4.67
E	4.25	0.8	6.0	4.2
F	4.8	2.5	5.4	4.1
G	5.4	0.9	6.5	3.33
H	6.8	1.25	6.8	2.67
J	4.5	0.8	6.5	3.33
K	5.1	0.8	8.0	3.2
L	6.0	2.75	8.0	6.2
N	6.8	2.8	9.1	3.8
P	4.8	1.33	–	–
R	5.4	2.2	6.8	5.25
S	5.4	2.2	8.8	4.4

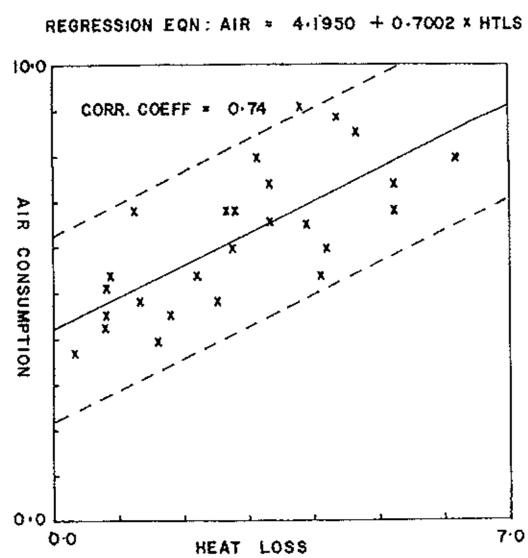

Fig. 5. The relationship between calculated heat loss ($kcal \cdot m^{-2} \cdot min^{-1}$) and air consumption ($L \cdot m^{-2} \cdot min^{-1}$) during 26 wet-suited dives in cold (5°C) and warm (20°C) water (regression line with 95% confidence limits shown).

DISCUSSION

Beckman, Reeves, and Goldman (1965) showed that even a 1-inch thick foam neoprene diving suit provided inadequate thermal protection in 4°C water. Craig and Dvorak *(in press)* pointed out, however, that the marked initial heat loss seen in a naked swimmer is considerably reduced by a wet suit and that the protective value is accounted for more by the jacket than the trousers. The latter is to be expected if the formulae derived by Burton (1935) are valid for water immersion as well as in a gaseous environment. (Webb [1973] questioned the validity of these formulae for cold water immersion but, for the present, they provide the only convenient way of assessing heat balance in an operational as opposed to a laboratory setting.)

In many instances divers in wet suits did not attain thermal equilibrium even during the warm dives, although the resulting cold stress was small in comparison with the cold dives. During the 5°C dives severe cold stress stimulated a vigorous metabolic response, whereas in the 20°C dives heat loss in some cases was probably insufficient to increase metabolism at all. Shivering commenced after about 10 to 15 min in all subjects during the cold dive and, in a few, became severe towards the end. Only one subject was noted to be shivering on his warm dive.

In their cold water studies Stang and Weiner (1970) confirmed the close relationship between oxygen uptake and air consumption measured from bottle pressures. Since oxygen uptake increases with an increase in cold-induced metabolism, it is not surprising that we found a correlation between air consumption and calculated heat loss. Calculated with the regression equation derived from our data, oxygen consumption ranged from 1.7 liters·min^{-1} (Subject A, warm dive) to 3.4 liters·min^{-1} (Subject L, cold dive).

The physical distress of cold peripheries and shivering is most likely to make a diver curtail his dive. However, it is not until core temperature has dropped significantly that a dangerous situation will arise. Two subjects had to be brought up from their cold dives before completing all the tests. In each case rectal temperature had fallen by over 2°C (the only subjects in whom this occurred [e.g. Fig. 3]). Surprisingly, one of these divers had a rectal temperature of 36.8°C, within normally acceptable limits, at the end of his dive, since he had commenced the dive in an overheated state from kitting-up. Several subjects had lower end-dive rectal temperatures with far less subjective evidence of distress.

Earlier studies (Davis, Charlier et al. 1972) suggest that divers tolerate a drop in rectal temperature of up to 1.5°C but beyond this become increasingly distressed and disabled by cold. Within certain limits (that is, above 35°C) the absolute temperature seems to be less important than rate of fall in temperature. One may conclude that the rate of heat loss and resultant physiological response are the key factors. A drop in core temperature, measured rectally, of 2°C or more or to below 36°C will place a diver's safety in jeopardy. A good case can be made for the use of routine body-temperature monitoring during cold water diving operations, whether or not a suit heating system is employed, since cold stress probably constitutes the major risk factor in these conditions (Rawlins 1972). The Canadian Navy has recently adopted just such an approach using temperature-sensitive radio pills.

The increase in core temperature on immersion is more pronounced in colder water and is presumably due to a more vigorous peripheral vascular shut-down with pooling of warm blood centrally. This phenomenon is well recognized (Skreslet and Aareflord 1968; Davis, Charlier et al. 1972). Another well-recognized aspect of cold water immersion is the after-drop (Keatinge 1969). In our series of dives this was slight and even the coldest subjects had rewarmed within 1 hour of the dive. This again reflects the importance of warm, dry facilities for any cold water diving program.

The relationship between these results and diver performance are considered in the next section.

SECTION TWO: PERFORMANCE TESTING

PERFORMANCE TESTS

Five performance tests were used: arithmetic, logical reasoning, digit span, memory, and manual dexterity. On each dive eight tests were presented; the memory and manual-dexterity tests were sandwiched in the middle of the dive between two series of arithmetic, logical-reasoning, and digit-span tests. The second series was presented in the reverse order to the first; in addition, the order of the three tests was randomized from subject to subject. An example of a full test sequence might be:

digits/	arithmetic/	logic/	dexterity/	memory/	logic/	arithmetic/	digits
1	2	3	4	5	6	7	8

Subjects were given a full explanation of and practice at this test procedure 1 or 2 days before the dives. Also they practiced the manual dexterity task and the digit-span test on the morning of their first dive. Thus all tests except the memory test were practiced more than once.

Tests were presented underwater on Formica® boards covered with an adhesive clear-plastic covering. Divers wrote on strips of matte white PVC tape with a soft lead pencil; these strips were removed easily immediately following the dive and stuck into the subjects' records. Good two-way communication between the diver and surface was an essential part of the experimental design since tests were run entirely from the surface.

Arithmetic test. A series of 50 five-digit additions were presented. In order to minimize the amount of writing involved, each problem was followed by an answer that was either correct or differed from the correct answer by one. Subjects responded by ticking or crossing each answer and attempted as many sums as possible in a 3-min period. The number of sums completed and the number of errors were recorded for each series. By simplifying the writing involved in this test it was hoped to avoid the problem encountered by Bowen (1968) who was unable to distinguish between a manual dexterity influence on such a test and a real effect on arithmetic ability. As a further safeguard, an attempt was made to measure any changes in performance of the simplified manual process by the use of a writing-time test, which was performed after the second series for each dive. In this test the subject wrote over all his ticks and crosses again as fast as possible and the time taken was recorded. This allowed an assessment of any writing speed changes in the two conditions.

A different series of sums was presented on each occasion. Thus series A and B were used for practice, C and D for the first dive, and E and F for the second dive, irrespective of whether the dive order was warm/cold or cold/warm.

Logical-reasoning test. Ten items were presented. Each item consisted of two statements followed by four conclusions. The subject examined each pair of statements and decided which of the four given conclusions was the correct one; a correct solution was derived from both statements and from those statements alone.

e.g. All divers are swimmers
Some divers are sailors
therefore:
A. Some sailors are swimmers.
B. Some swimmers are not divers.
C. All sailors are swimmers.
D. Some divers are not sailors.

As many items as possible were attempted in 3 min, a different series being presented on each occasion. Thus, as with the arithmetic test, series A and B were used for practice, C and D for the first dive, and E and F for the second dive. The number done and the number of errors were recorded for each series (based on Fort and Mills 1972).

Digit-span test. The experimenter called out a series of random digits evenly spaced at 1-sec intervals. At the end of each sequence the subject tried to repeat it in the correct order at his own speed. Sixteen sequences of numbers were given at each testing, a different set being used on each occasion.

Each subject's digit span was determined during practice and he was tested at that length throughout the dives. A few subjects were tested at two sequence lengths when only eight sequences of each length were presented. Each sequence was scored simply as correctly or incorrectly repeated.

Memory test. The subject was required to memorize underwater a list of 30 nouns printed on a board. Each word was viewed in turn by the subject when the numbers (1 to 30) alongside them were called out by the surface operator at 5-sec intervals. During each interval the subject called back to the experimenter an adjective he associated with that noun (e.g. if the noun was "tiger," the subject might respond "striped"). This use of semantic processing holds the subject's attention on each word and helps to standardize the memorization process (Hyde and Jenkins 1969).

Thirty minutes later, back in the laboratory, the subject was allowed 4 min to write down as many words from the list as he could remember. Immediately afterwards, he was presented with a longer list (60 words) containing the words from the original (e.g. steeple) and others similar in meaning (e.g. spire), sound (e.g. stable), or associatively related (e.g. church), and was asked to tick any words that he recognized from the original list. Three lists were used: List A for practice, List B for the first dive, and List C for the second dive. The number of words recalled, errors of recall, the number of words recognized, and the false-positives in recognition were recorded.

Manual-dexterity test. A modification of the Bennett Hand Tool Dexterity Test (Bennett 1965) was used. This consisted of two vertical brass plates, each with 12 bolt holes, mounted at either end of a brass base-plate. Nuts, bolts, and washers were transferred from one vertical plate to the other in a set manner using three spanners. Modification—omitting the middle row of nuts and bolts from the test—was necessary so that the task could be completed within the bounds of the dive time. Hexagonal nuts and bolts of head diameters 14 mm and 8 mm were used.

The task was performed wearing 3-mm thick neoprene diving gloves on every occasion including practice, but a facemask was not worn for the dry-land condition. Time taken to complete the task was recorded. This test has been used in a number of previous studies (Davis, Osborne et al. 1972; Hamilton *in press*).

Statistical analysis. Actual scores for each individual were used for analysis. A Student paired t test was used to compare performance of each task in the two conditions. For the logical-reasoning,. digit-span, and arithmetic tests, the first warm dive test (W_1) was compared with the first cold dive test (C_1); the second warm (W_2) with the second cold (C_2); the first (W_1) and second (W_2) warm tests with each other, and the first (C_1) and the second (C_2) cold tests with each other, for each subject. For the manual-dexterity and memory tests, cold performance (C) was compared with warm performance (W). In addition all five tasks in warm water were compared with dry-land performance.

Mean differences in performance for each test are expressed as percentages in the text for convenience only. Percentage changes rather than actual scores were used only for statistical analysis of: *a.* percentage errors in logical reasoning; *b.* percentage false positives in word recall and recognition, and *c.* percentage arithmetic errors.

A least-squares regression analysis to determine the correlation coefficient r was employed to study the relationship between performance and body-temperature changes, and additional nonparametric tests were employed to examine indive changes.

RESULTS

Arithmetic test. Scores for the arithmetic test are shown in Table 3. There was a 13% decrease in the number of sums attempted between the second practice and warm-water immersion ($P < .005$). Speed of performance in the cold was markedly reduced compared with warm water—by 9% for C_1 ($P < .025$), and by 15% for C_2 ($P < .02$). There was no significant change between C_1 and C_2 ($P < .3$). The mean percentage of errors varied between 3% and 6%, but these differences were not significant.

Writing times are also shown in Table 3. There was a mean difference in writing time of 0.1 sec per sum between the warm and cold dives. This was not significant ($P < .3$). The mean time taken to perform each sum was 6.0 sec in the warm and 7.2 sec in the cold, a difference of 1.2 sec. Thus the simplified response procedure was successful in reducing the effect of impaired writing skill to a level that contributed a negligible amount to the overall performance decrement.

TABLE 3

Mean numbers of sums attempted (with SD), mean number of errors, and mean writing time per sum (with SD) for the arithmetic test

	Dry land practice	20°C Dive	5°C Dive
Sums attempted	33.5 ± 8.4	29.25 ± 9.4 (W_1) 29.6 ± 7.7 (W_2)	26.7 ± 9.3 (C_1) 25.1 ± 9.3 (C_2)
Errors	1.6	1.3 (W_1) 1.0 (W_2)	1.6 (C_1) 0.7 (C_2)
Writing time (s)	–	0.8 ± 0.07	0.9 ± 0.07

Logical reasoning. Scores for the logical-reasoning test are shown in Table 4. No change in performance occurred upon immersion and the change seen during the warm dives was not significant (5% increase; $.1 > P > .05$). The number of problems attempted was less during the cold dives–13% for C_1 ($.1 > P > .05$) and 19% for C_2 ($P < .02$)–than in the warm dives. Percentage of errors showed considerable variability, with a mean increase during the cold dives (27% and 32% for C_1 and C_2 respectively compared with 20% and 21% for W_1 and W_2 respectively), though this is not statistically significant (on a Wilcoxon test, $n = 14$; $T = 37$; $P > .05$).

TABLE 4

Mean number of problems attempted (with SD) and mean number of errors for the logical reasoning test

	Dry land practice	20°C Dive	5°C Dive
Problems attempted	7.8 ± 2.0	7.9 ± 2.0 (W_1) 8.3 ± 1.6 (W_2)	6.9 ± 1.6 (C_1) 6.7 ± 2.2 (C_2)
Errors	1.3	1.3 (W_1) 1.5 (W_2)	1.8 (C_1) 1.9 (C_2)

Digit span. Scores for the digit-span test are shown in Table 5. The decrease in performance in the cold compared with the warm was not statistically significant ($W_1 - C_2$, 4% decrease; $P > .1$) and ($W_2 - C_2$, 14% decrease; $P > .1$).

TABLE 5

Mean scores (with SD) for the digit-span test

Dry land practice	20°C Dive	5°C Dive
10.5 ± 2.6	9.6 ± 3.7 (W_1) 10.7 ± 3.4 (W_2)	8.9 ± 4.3 (C_1) 9.2 ± 4.3 (C_2)

Memory test. Scores for the memory test are shown in Table 6. Immersion in warm water resulted in a sharp drop in word recall (48%; $P < .001$) but no significant change in word recognition (5% decrease; $P < .2$). There was a further marked impairment of word recall following the cold dives compared with the warm dives (37% decrease; $P < .05$). In addition, there was a significant decrease in word recognition (11% decrease, $P < .05$) for the cold dives compared with warm dives. As a result the overall deterioration in word recall from dry land to cold water was over 70%.

The number of false positives in word recall remained remarkably constant on dry land and for the dives. This does imply, however, that the percentage of erroneously recalled words to correctly recalled words rises from about 10% on dry land to 20% following warm

TABLE 6

Mean scores (with SD) for word recall and recognition, and false positives in the memory test

	Dry land practice	20°C Dive	5°C Dive
Word recall	9.3 ± 3.8	4.8 ± 2.9	3.0 ± 1.9
False positives in word recall	0.9	0.8	0.8
Word recognition	23.8 ± 3.2	22.7 ± 3.6	20.2 ± 4.6
False positives in word recognition	1.7	2.5	1.8

dives and to 30% after the cold dives. False positives in word recognition increased significantly from 7% on dry land to 11% for the warm dives ($P < .05$). There was no significant difference between the warm and cold dives ($P > .1$).

Manual Dexterity. The mean times taken to complete the manual-dexterity test are shown in Table 7. There was a marked drop in manual performance upon immersion in warm water ($P < .001$), such that divers were 31% slower than on dry land wearing gloves but without facemasks. In addition, there was a further marked reduction in performance of 17% in cold water ($P < .05$), as well as an increase in the variability of performance.

TABLE 7

Mean performance times in seconds (with SD) for the manual dexterity test (Bennett Hand Tool Dexterity Test)

Dry land practice 1	Dry land practice 2	20°C Dive	5°C Dive
323 ± 50	318 ± 54	418 ± 72	490 ± 137

Of the 16 subjects, 4 were not considered in the analysis of this test: 2 because of doubts over the adequacy of lighting (one warm and one cold dive); 1 because of a severe hand deformity which might have led to a marked learning effect; and 1 who did not perform the task in the cold. Surprisingly, there was no difference between the two dry-land practice runs as one would anticipate from learning effects. This probably reflects the previous familiarity with the test of 9 of the 12 subjects used.

Indive performance changes for arithmetic, logical-reasoning and digit-span tests

Three tests were presented twice on each dive. The order of their presentation on the first occasion was randomized and this order was reversed on the second occasion. It was then possible to divide the subjects into three subgroups, depending on the three possible positions in each dive when a particular test might be given:

Group 1: Test done at start and finish of the test sequences (longest intertest interval).

Arithmetic (1) - 2 - 3 - 4 - 5 - 6 - 7 - (8) Arithmetic

Group 2: Test done in middle of test sequence (medium intertest interval).

1 - Arithmetic (2) - 3 - 4 - 5 - 6 - (7) Arithmetic - 8

Group 3: Test done at finish and start of test sequences (shortest intertest interval).

1 - 2 - Arithmetic (3) - 4 - 5 - (6) Arithmetic - 7 - 8

Differences between these groups in the change of performance during a dive ($W_1 - W_2$; $C_1 - C_2$) were compared for each task using a Kruskal-Wallis test (Siegel 1951). This was used to assess whether a longer interest interval, associated with a greater difference in deep body temperature, might result in a more pronounced performance decrement.

There were no significant differences between the groups for any of the three tests during the warm dives. In addition, there were no significant differences for the logical-reasoning and digit-span tests during the cold dives. For the arithmetic test, however, there appears to be a significant difference in the change in performance of the three groups (Kruskal-Wallis $H = 6.13$; $P < .05$). There is an indive improvement in performance shown by Group 1 (longest intertest interval) which was significantly different from either Group 2 (medium intertest interval; Mann Whitney Test, $U = 2$; $n_1 = 4$; $n_2 = 5$; $P < .032$) or Group 3 (shortest intertest interval; Mann Whitney Test, $U = 1$; $n_1 = 4$; $n_2 = 5$; $P < .02$), in both of which there was a slight indive deterioration. Such a result is, of course, the reverse of that predicted on the basis of drop in body temperature. There was no significant difference between Groups 2 and 3 (Mann Whitney Test, $U = 10$; n_1 and $n_2 = 5$; $P > .3$).

Performance and body temperature

Performance and various aspects of body temperature changes during the dives were compared for each subject using the least-squares regression method and the determination of the correlation coefficient r.

Memory test. On the word-recognition test the difference in performance between the warm and cold dives (11%, *see above*) showed a significant correlation with the difference in drop in rectal temperature in each subject for the two conditions ($r = 0.69$; $P < .01$). Performance impairment in the cold dives also was significantly correlated to the actual drop in rectal temperature during the cold dives as measured from the time at which the test was presented underwater until the time the recognition test was done postdive ($r = 0.82$; $P < .001$). These results indicate a significant relationship between word-recognition impairment and the fall in rectal temperature during the cold dives.

For the word-recall test there were no significant associations between performance and body temperature.

Logic test. A correlation between the $W_2 - C_2$ performance difference and the difference in enddive rectal temperature was noted ($r = 0.79$; $P < .001$), suggesting that impairment of performance of this test in cold water is related to the fall in central body temperature. However, it must be noted that this is an isolated finding amongst several possible relationships calculated for this test, which were not significantly correlated.

Arithmetic, digit-span, and manual-dexterity tests. Analysis of tests revealed no significant relationships between changes in body temperatures and performance on arithmetic, digit span, and manual dexterity. In particular, no relationship was seen between the deterioration in manual-dexterity and wrist-temperature changes.

DISCUSSION

Cold water exposure may influence performance in three ways. First, there is a peripheral effect on the extremities impairing tactile sensitivity and weakening muscle power (Bowen 1968; Clark 1961). Second, there is a central effect on the brain as central body temperature drops, slowing metabolism. Third, there is what has been called a "distraction" effect (Teichner 1958); that is, the perceived threat of cold exposure may distract attention and interfere with the continuity of performance.

The way in which performance may be altered should be different for each of these mechanisms. Peripheral effects on manual performance are dependent on the ambient temperature (Stang and Weiner 1970) and show progressive impairment with length of exposure as skin temperature drops. Clark (1961) concluded that on dry land a hand-skin temperature of about 15°C is the minimum for unaffected manual performance. Stang and Weiner (1970) showed a marked decrease in manual performance in their coldest condition (10°C) but little at either 15°C or 21°C. This would seem to indicate similar critical temperatures for immersed and dry-land subjects.

Central effects would only show themselves after a variable latent period, since physiological responses to cold stress tend to prevent central body temperature from falling right from the start of exposure. There is little evidence at present to show the stage at which such effects would become apparent. A severe drop in body temperature causes progressive impairment of consciousness with semicoma ensuing at about 33°C (Golden 1972). Baddeley (1966b) showed an impairment in time judgment following dives in 5°C water but he measured only oral temperature which, in cold conditions, does not reflect changes in core temperature but, rather, behaves as part of the periphery. Subjective evidence from various sources seems to suggest that, if central body temperature falls to 35°C or below, confusion, increased difficulties in concentration, and physical distress ensue. It is not yet clear what happens to performance with less pronounced falls in central body temperature.

The distraction effect, on the other hand, should make itself apparent from the start of cold water exposure, impairing performance at a stage when body temperatures have not yet dropped to any extent. Bowen (1968), for instance, could find no difference between the effects of long and short exposures to cold water on the performance of various cognitive tasks. However, most of his tests involved a considerable manual element in their execution and any deterioration in performance could be attributed to peripheral effects. It is difficult, in that case, to explain why the progressive effect due to peripheral cooling clearly demonstrated by Stang and Weiner (1970) in a more tightly controlled experiment was not apparent. These discrepancies mean that any interpretation of Bowen's results must remain cautious. On dry land, learning a task under cold conditions appears to help overcome the detrimental effects of cold exposure (Clark and Jones 1962) and this may be due to minimizing the distraction effect of cold.

In the open-sea environment, where all three factors would have influence, the overall picture would be one of an immediate impairment of performance due to distraction, followed by a progressive deterioration in manual skills and later by further deterioration in cognitive skills. In the present study a significant deterioration in performance occurred early in a cold immersion, demonstrating the importance of the distraction effect of cold on cognitive tasks. Since these tests were designed to minimize or exclude any manual influence on their execution, this change is not due to a peripheral (manual) effect of cold.

Depth and performance. Nitrogen narcosis effects are not generally detectable in depths of less than 30 m and would certainly not be expected in the present instance with a maximum depth of 9 m (Bennett, Poulton, Carpenter, and Catton 1967).

Logical-reasoning, digit-span, and arithmetic. To distinguish between distraction and central effects the results of the arithmetic test are of particular interest. Subjects in Group 1 (longest intertest interval) showed an indive improvement in performance significantly different from those subjects who did the two sets of tests closer together, when, in fact, a slight but nonsignificant indive deterioration in performance was noted. This suggests that performance of this test was at its worst at the very start of cold water exposure. However, in none of these three tasks is the $W_1 - C_1$ difference statistically dependent on the order in which the three tests were presented.

Teichner (1958), using a reaction-time test on dry land, was unable to show any correlation between body temperature and performance and it was on this finding that he based the distraction hypothesis. An extensive analysis of our data has revealed little or no relationship between performance of these three tests and body temperature. The correlation between the logic test and rectal temperature is an isolated finding that should be viewed cautiously until confirmed by further testing. Thus there is little to support the hypothesis that the performance decrement in these three tests is due to a central effect of cold, whereas there is evidence to support the distraction hypothesis.

Memory test. Using a prose-passage memory task, Baddeley, Cuccaro, Egstrom, Weltman, and Willis (*in press*) showed a marked deterioration in recall of the relevant items together with a nonsignificant tendency to impairment of word recognition. We have shown a significant impairment of both word recall and word recognition using a different test.

The very marked immersion effect seen in word recall is probably due to a state-dependent effect on memory; recall is optimal when it occurs in the same environment as the original learning process (Greenspoon and Ranyard 1957). Godden and Baddeley (*in press*) have demonstrated a substantial context-dependent memory effect in divers. Such an effect is likely to be more marked if the environmental stress is greater, i.e. cold water, and may alone account for the deterioration in recall after cold dives. However, it is difficult to account for the significant relationships between the impairment of word recognition and central body temperature on this basis. Our results suggest that word recognition is indeed influenced by changes in central body temperature.

Whether the effect on recall is a state-dependent effect or not, in practice divers often have to commit to memory indive information which is then processed at a dive debriefing. The resulting loss of data is considerable. Hemmings (1972) found it essential to adopt a diver-to-surface radio communication system with tapes of indive verbal reports during studies on fish behavior in the North Sea. He compared tape transcripts with debriefing reports and found the latter grossly deficient and inaccurate.

Manual dexterity. The effect of cold water immersion on manual skills has been extensively studied by several workers (Bowen 1968; Egstrom et al. 1972; Stang and Weiner 1970) and it was not our intention to look in detail at this aspect of performance. The deterioration observed is in keeping with these studies, including an increased variability of performance in the cold as first reported by Dusek (1957) for dry-land experiments. No correlation between performance decrement and forearm temperature was observed and it was not possible to measure finger temperature. A slowing of 30% from dry-land performance to warm water immersion occurred. Previous studies with the Bennett Hand Tool Dexterity test showed an immersion effect of about 20% in shallow water (Davis, Osborne et al. 1972), but in these experiments subjects practiced the task once underwater, unlike the present study where this was not practicable.

Finally it must be remembered that in this experiment the diving situation was specially chosen to limit the influence of factors other than cold on performance. It can be anticipated that in operational conditions these changes will be compounded by many factors, notably by anxiety and fatigue.

CONCLUSIONS

A significant impairment of performance of four tasks – arithmetic, logical reasoning, word recall and recognition, and manual dexterity – was observed in a group of 15 experienced amateur divers in 5°C water when compared with performance at 20°C. Memory, in particular, was grossly impaired by over 70% of the performance on dry land. A fifth test, of digit span, did not show a significant deterioration.

The impairment in cognitive performance appeared from the onset of cold water immersion and can be attributed to a distraction effect of cold.

There was evidence of an association between central body temperature and impairment of word recognition, but little or no evidence of any association between body temperature and performance of the other tests.

The impairment in memory will seriously limit the value of observation and inspection work underwater in cold conditions unless indive records are made. The concomitant impairment in manual skills make writing difficult and therefore the only effective methods available would be via diver-to-surface communications or backpack recorder.

Wet suits of 3/16th-inch foam neoprene provide inadequate thermal protection in 20°C or 5°C water, and in the latter condition the diver experiences severe cold stress. Subjects tolerated this unless rectal temperature dropped by more than 2°C, when their safety and ability underwater became seriously in question.

Air consumption obtained from pre- and postdive aqualung pressure-gauge readings has been shown to be significantly correlated with calculated heat loss of divers obtained from indive body-temperature monitoring.

Central body-temperature monitoring should be routine for extensive cold water operations in the interests of diving safety.

APPENDIX

HEAT LOSS CALCULATIONS

Using whole-body calorimetry, Burton (1935) has shown that in a situation where evaporation from the skin is not occurring it is possible to calculate average skin and body temperature and heat content using relatively simple formulae.

Average change in skin temperature can be expressed as:

$$\Delta T_{skin} = 0.50\Delta T_a + 0.36\Delta T_b + 0.14\Delta T_c \qquad (2)$$

where T_a equals average trunk surface temperature,

T_b equals average temperature on the lower limb, and

T_c equals average temperature on the lower arm.

Using the data from Table 2 of Burton (1935) this formula can be modified to employ all five skin temperatures used in the present study. Thus average change in skin temperature is calculated from:

$$\Delta T_{skin} = \frac{0.48(\Delta T_{back} + \Delta T_{loin})}{2} + 0.36\Delta T_{calf} + 0.08\Delta T_{arm} + 0.08\Delta T_{wrist} \quad (3)$$

The temperature differences used for the calculations were those between the immediately predive value and the last indive value. Average change in body temperature was then derived from:

$$\Delta T_{average} = 0.64\Delta T_{rectal} + 0.36\Delta T_{skin} \quad (4)$$

Change in body heat content during each dive is then calculated from:

$$\text{Change in heat content (heat loss)} = \frac{\Delta T_{average} \times \text{body weight(kg)} \times 0.83}{\text{body surface area } (m^2)} \cdot \text{kcal}\cdot\text{m}^{-2} \quad (5)$$

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Davis, F.M., A.D. Baddeley, and T.R. Hancock. 1975. L'accomplissement des plongeurs: L'effet du froid. Undersea Biomed. Res. 2(3):195-213.—Quinze plongeurs ont accompli cinq tâches chacun dans de l'eau à des températures de 5°C et 20°C, avec un equipement standard de plongeur autonome. Une baisse significative du niveau de l'accomplissement a été constatée dans les conditions de froid en ce qui concerne: le calcul simple, 13%; la logique, 17%; le rappel des mots, 37%; la reconnaissance des mots, 11%; et la dextérité, 17%. La température rectale et 5 températures cutanées ont été controlées au cours de chaque plongée. La diminution moyenne de la température rectale était de 0,5°C pendant les plongées à 20°C, et de 1,1°C pendant les plongées à 5°C. La température cutanée moyenne est tombée de 5°C et de 12,5°C, respectivement. Les pertes moyennes de chaleur, calculées des données, étaient de 95 kcal·m^{-2}·h^{-1} (plongées à 20°C) et de 245 kcal·m^{-2}·h^{-1} (plongées à 5°C). Un rapport significatif a été trouvé entre le test de connaissance des mots et la chute de la température rectale au cours des plongées à 5°C. Pour les autres tests, la corrélation a été constatée entre les altérations et l'immersion dans l'eau froide, et non pas avec les variations de la température corporelle. L'importance de ces resultats est rapportée aux connaissances actuelles des méchanismes par lesquels le froid influe sur l'accomplissement de tâches au cours de la plongée.

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