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WET-SUITED SCUBA DIVER PERFORMANCE IN 5°-25°C WATER

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As an assessment of adequacy of current Navy diving guidelines for thermal protection, the performance and physiology of three wet-suited SCUBA divers were measured over a series of 36 dives in water temperatures ranging from 5°C to 25°C. The divers performed cognitive and motor tasks during dives lasting up to 50 min at a depth of 3.35 m; heart rate, respiration rate, and skin temperatures were recorded at 5-min intervals. Results indicated that despite substantial decreases in skin temperatures, diver performance on

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cognitive tasks was not significantly affected; motor performance was impaired only when water temperature reached 5°C. These results indicate that the standard neoprene wet suit provides adequate protection during dives in shallow water at temperatures as low as 10°C and for exposure times as long as 50 min.

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During the past two decades there has been a dramatic increase in manned undersea activity. With the introduction of improved equipment and techniques, divers are no longer limited to warm water environments. Many U.S. Navy diving operations are now conducted in water temperatures between 5 and 25°C, with the majority of these operations employing self-contained underwater breathing apparatus (SCUBA) at depths shallower than 30 m of sea water (Berghage, Rohrbaugh, Bachrach, and Armstrong, 1975). This rise in diving activity in other than warm (>25°C) water is accompanied by an increased risk of diver hypothermia.

The U.S. Navy Diving Manual contains guidelines for thermal protection at various water temperatures. A wet suit is required in Navy diving operations at temperatures below 21°C, and is deemed adequate for short duration dives in less than 60 ft of water down to temperatures of 7°C (p. 4-10, U.S. Navy Diving Manual). Previous research conducted in relatively warm (~25°C) water and in cold (~5°C) water has documented significant performance differences (e.g., Bowen, 1968; Baddeley, Cuccaro, Egstrom, Weltman, and Willis, 1975; Biersner, 1976); however, little systematic research has been directed at examining the possible effects of intermediate water temperatures on diver performance. One previous attempt was conducted by Stang and Wiener (1970) who exposed wet-suited SCUBA divers once to each of three water temperatures: 50°, 60°, 70°F. During each dive the subjects performed a variety of underwater tasks. Analysis of the results indicated a large decrement in diver performance at 50°F as reflected by task completion times. In addition, this study was noteworthy for controlling water temperatures and using a subjects-by-treatments design. Studies of diver performance as a function of water temperature have traditionally been hampered by one or more of the following: lack of control over water temperature, absence of repeated performance and physiological measures during a dive, failure to provide repeated exposures to each water temperature, limited range of water temperatures studied, limited physiological monitoring, and variability in diver experience.

The purpose of this study was to examine systematically the effects of a range of water temperatures (5-25°C) on the cognitive, psychomotor, and physiological performance of wet-suited SCUBA divers, and to assess the adequacy of current Navy thermal protection guidelines. We sought to accomplish this goal by extending the range of water temperatures studied, by monitoring additional physiological functions at repeated intervals during the dive, and by exposing each experienced diver twice to each water temperature.

METHOD

Subjects

Three male U.S. Navy divers stationed at the Naval Medical Research Institute served as subjects. All volunteer subjects were in excellent health with extensive experience using SCUBA. Table 1 presents relevant diver characteristics.

Table 1

Characteristics of Subjects

Subjects	Ht (cm)	Wt (kg)	Age	Diving Designator	Previous Cold Water Experience
1	175.3	70.2	32	Diving Officer	No
2	182.9	70.7	32	Saturation Diver	Yes
3	185.4	89.7	28	Saturation Diver	Yes

Apparatus

Dive equipment. A modified U.S. Divers Aquamaster two-hose regulator was used. Twin-steel tanks carried on the diver's back provided an air supply of approximately 2500 litres (L). All divers wore full wet suits of 0.64-cm thick neoprene, including booties. At 10°C each diver donned a 0.64-cm thick neoprene hood and 0.64-cm thick neoprene 5-finger gloves. Each diver carried sufficient hip weights (10-20 lb) to maintain negative bouyance on the bottom. A 0.95-cm nylon line secured the diver to the surface tender. Standard face masks were used.

Testing tank. All dives were conducted in a 27,000-L open tank located inside Bldg. 119 at the Naval Medical Research Institute. The tank measured 3.05 m in diameter, and divers worked in 3.35 m of fresh water. Divers were observed from the surface, and through one 0.61- × 0.91-m window and three 25-cm diameter viewports located at 90° angles around the tank periphery. Heating and cooling of tank water were via an in-line steam and freon refrigerant system. Water temperature was maintained at ±0.6°C of the desired setting by this system, and was measured using a YSI series 400 thermistor located 1.2 m above the center bottom of the tank. A YSI telethermometer (Model 43TA) provided a continuous readout of water temperature.

Test equipment. Two subtasks, top hatch and tooker patch, of a work battery composed of four standardized tasks, SP^2, (Brady, 1979), were used to assess diver manual dexterity. Figure 1 shows the SP^2 work battery. A 1.3-cm reversible drive ratchet, 1.9-cm socket, and 1.9-cm open-end wrench were used on the top hatch task. A uniquely designed underwater torque wrench was used to measure the diver's ability to judge different torque values. The wrench was connected via a 15.2-m cable to a locally constructed surface console which measured the torque in foot pounds.

Learning and memory were assessed by a hand-held underwater repeated-acquisition console. The console, shown in Fig. 2, was constructed of

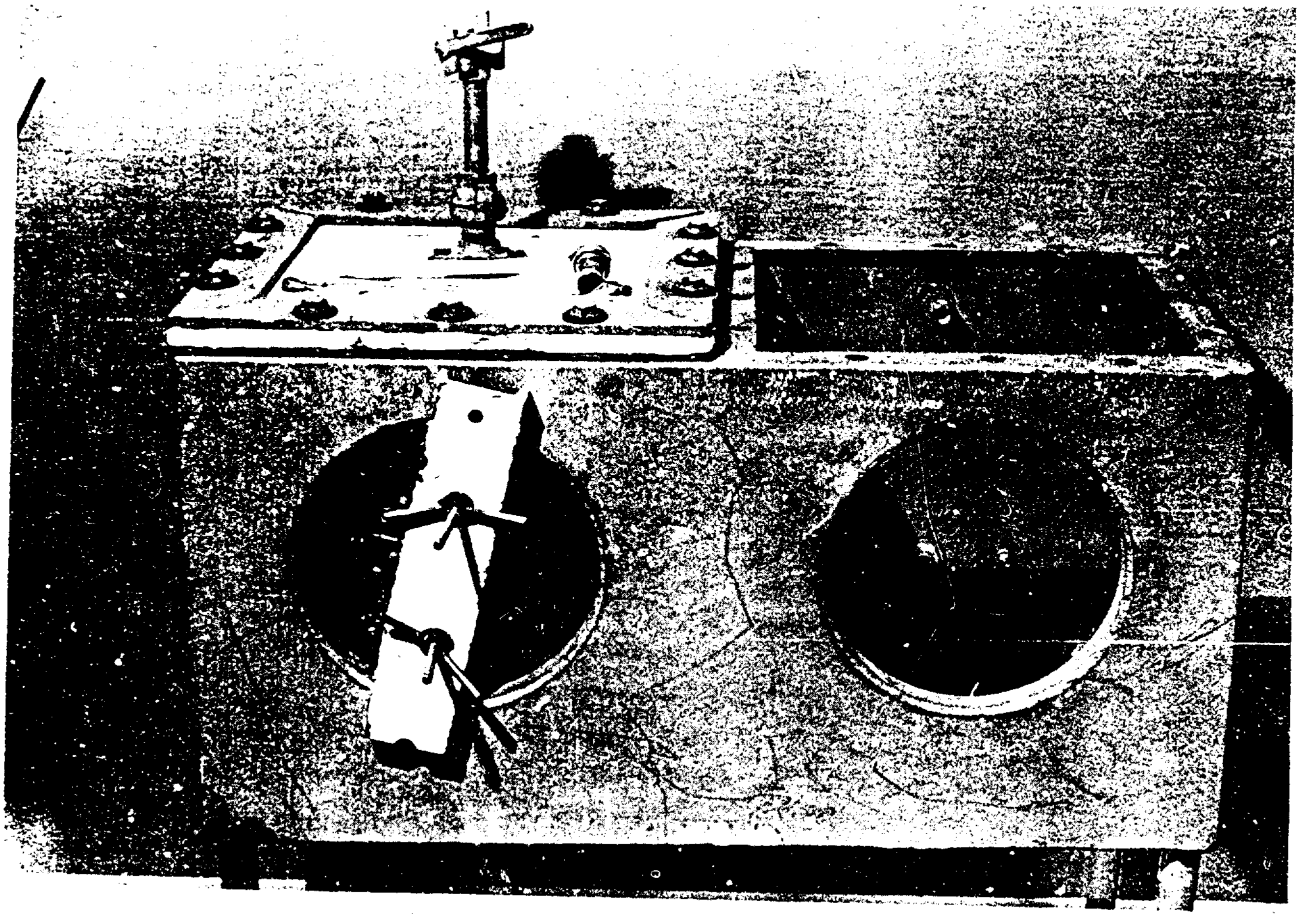

Fig. 1. Underwater work battery, SP^2.

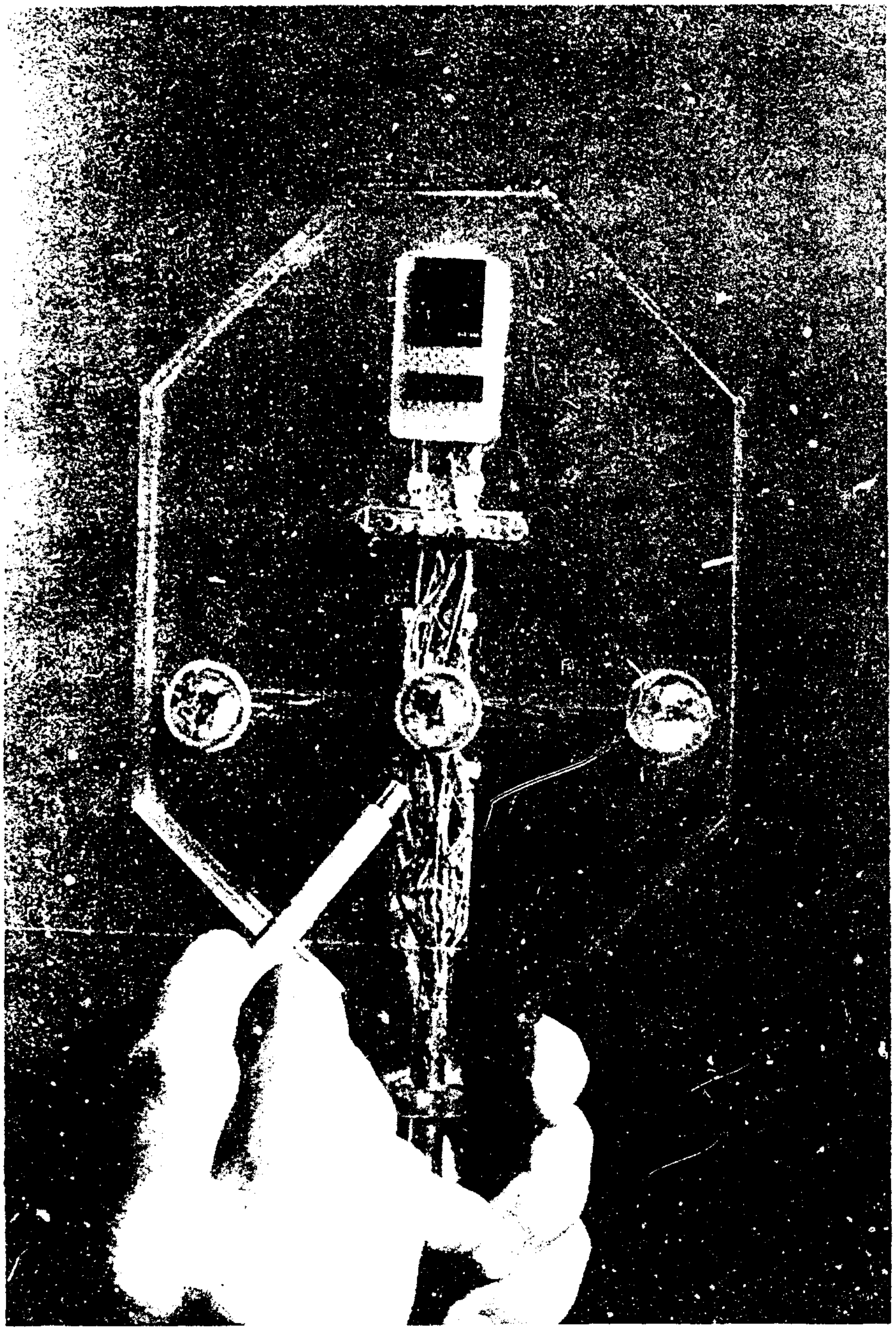

Fig. 2. Underwater repeated acquisition console.

Plexiglas and measured approximately 15 × 20 × 3 cm with a 10-cm handle. Located on the face of the console were a lighted digital display, three colored light-emitting diodes, and three magnetized transistor response chips. A response was made by touching a 11-cm pencil magnet to a response chip. Programming of the console was done by BRS/LVE solid-state digital logic packages. Data were recorded on BRS decimal counters and Gerbrands cumulative recorders. Flash cards measuring 20 × 31 cm were printed with the time and torque estimation standards for view by the diver through the observation window. A Chronus model 3-5 digital electronic stopwatch was used for timing purposes.

Physiological recording. Skin temperature was recorded by a YSI thermistor #409 located on the right medial thigh, a location thought to provide the best single estimate of mean skin temperature (Teichner, 1958). A YSI scanning telethermometer model 47 provided temperature readout. Electrocardiogram was recorded via NDM silver/silver chloride stress-test electrodes and snap leads. Electrodes were secured in place with Blenderm surgical tape, tincture of benzoin, and moleskin. Respiration rate was assessed by a heat thermistor obtained from Technology Versatronic, Inc., Yellow Springs, Ohio. The thermistor was located in the inhalation hose and measured temperature changes on inhalation. Electrocardiogram and respiration leads entered a stainless steel monitoring canister attached to the SCUBA tanks. This canister contained a sensor amplifer, signal conditioner, and multiplexer, which sent signals through an umbilical to an in-house integrated circuit unit (Mints and Long, 1981) and a two-channel Clevite Brush Recorder Model Mark 220.

Procedure

Before commencing experimental dives subjects received between 7 and 12 dry baseline sessions on all tasks, and between 1 and 3 familiarization dives at 25°C to insure stable performance. Baselines ended when subject performance on a task ceased to improve on consecutive test sessions after a minimum of six practice sessions had been conducted. Each subject then made two dives at each of the following water temperatures: 25°, 20°, 15°, 10°, 5°, and 25°C. As the study progressed water temperatures became increasingly colder, and a minimum interdive interval of 48 h was established for each subject. During each dive the tasks were performed in this order: response acquisition (Performance), response acquisition (Learning), top hatch, tooker patch, time estimation, torque wrench, response acquisition (Performance), response acquisition (Learning). Task completion times and error rates were recorded by observers. Electrocardiogram, respiration rate, and skin temperature were monitored continuously throughout the dive, with measurements recorded every 5 min during the dive. Following dives at 15°, 10°, and 5°C, the subjects were immersed in warm water showers and closely observed for any aftereffects of cold exposure. Postdive interviews were conducted with each subject after each dive.

Descriptions of each task in the work test battery are as follows:

Repeated acquisition: Repeated acquisition procedures have been extensively used to assess the effects of drugs, toxins, and other variables on animal and human performance (e.g., Thompson, 1973; Galloway, 1975; Thompson and Dews, 1979). This task required the subject to acquire behavioral chains and was composed of two components, each consisting of a 10-step sequence of conditional discriminations. In the Performance component the discrimination task remained the same from dive to dive and within dives, providing a measure of the subject's ability to perform a well-learned task. In the Learning component the subjects were required to learn in a trial-and-error manner new discrimination sequences each time they did the task; this provided a measure of cognitive functioning. For example, in the Learning component the subject was required to learn the sequence LCRCRLRCLR, with L(left)-C(center)-R(right) referring to positions on the response console. Each subject was required to move through this sequence ten times in order to complete the component. Sequences were generated randomly by computer, with criteria that no position would follow itself (e.g., L-L) and each position must appear at least three times in a sequence.

Time estimation. Subjects were signaled the number of seconds they were to estimate by the flash cards. The subject signaled the start and stop of a timing interval by tapping on the observation window. Presentation of times to be estimated was randomized. Raters recorded all times; inter-rater times all fell within ± 0.2 sec of each other.

Torque wrench. Each subject placed the torque wrench on a 1.9-cm bolt located on the frame of SP^2, assumed a comfortable resting position, and signaled that he was ready to begin. Before starting the test series on each dive, the subject was given one familiarization trial at each of the torque standards during which he was told when he had reached the correct torque standard. Thereafter each subject received a counterbalanced series of 10 trials at each of the four torque standards. The subject applied force until he perceived he had reached the appropriate standard; he then proceeded to hold the pressure constant for a full second before releasing the pressure and returning the wrench to the neutral resting position. Recordings of torque were made during the full second at constant pressure.

Top hatch. In this task the subject was required to disassemble, move, and reassemble the top hatch found on the SP^2. He was provided with a ratchet, socket, and open-end wrench to aid in nut and bolt removal. The subject was allowed to use any strategy he desired to accomplish the task providing the following criteria were met: the project must be assembled so that its finished form was identical to the way he found it; all nuts and bolts must be tight so as not to be movable by hand; any dropped item or deviation in correct assembly counted as an error. Subjects were instructed to use the same strategy on each dive.

Tooker patch. This task required the subject to remove and reinstall a collapsible circular wood/rubber patch from one side of the SP^2 frame to another. In order to be judged error free, the patch was to be properly seated and secured so as to prevent water leakage upon testing.

RESULTS

All results are presented in the form of group means, and are representative of individual functions except where noted in the text. A repeated measures analysis of variance was used to determine the significance of differences among means.

Physiological Measures

Skin temperature. Readings obtained from the skin thermistor showed systematic decreases in skin temperature at each water temperature level except 25°C as the dives progressed. As seen in Fig. 3, there was little overlap in the mean skin temperatures at any water temperature. As the water became colder, the subjects experienced a greater drop in skin temperature during the dive. At 5°C, mean skin temperatures decreased as much as 6°C over a period of 30 min. While not as severe, skin temperature drops of 4° and 2°C were also recorded at water temperatures of 10° and 15°C, respectively. The differences in skin temperatures at the five water temperatures were significant [F (5,10) = 14.16, p < 0.001], as were the readings taken every 5 min within the dives [F (5,10) = 18.40, p < 0.001]. Further, there was a significant interaction between water temperature and 5-min readings [F (5,10) = 4.67, p < 0.05]; the magnitude of the difference between skin temperatures at each water temperature increased as the duration of the dive increased. Shivering occurred in two of the divers towards the end of dives at 20°C, and was present intermittently at 15°, 10°, and 5° in all three divers.

Heart rate. There was no significant main effect of water temperature on heart rate across subjects; however, there were statistically significant differences in heart rate as a function of recording intervals during the dive [F (5,10) = 4.95, p < 0.05]. Mean heart rate rose substantially between the 5- and 10-min recording intervals and was lowest at the 30-min record. These results correspond well with the tasks the divers were performing when heart rate was recorded. At the 5-min record the subjects were engaged in the repeated-acquisition task 97% of the time; at 10 min they had moved on to the top hatch assembly (93%) and remained on that task at the 15-min mark into the dive (100%). Starting at the 20-min mark, however, there was wide divergence in the tasks being performed. For example, at the 30-min mark subjects were engaged in torque estimation (47%), time estimation (20%), repeated acquisition (20%), top hatch (10%) or tooker patch (3%).

Respiration rate. The number of respirations per minute by each diver was recorded at 5-min intervals during the dive. Analysis of variance for the mean respiration rate over the first 30 min of the dives revealed no significant differences as a function of water temperature or 5-min recording intervals. Considerable individual variability was present; for example, after 40 min of exposure at 5°C, respirations ranged from 10 to 26 per min.

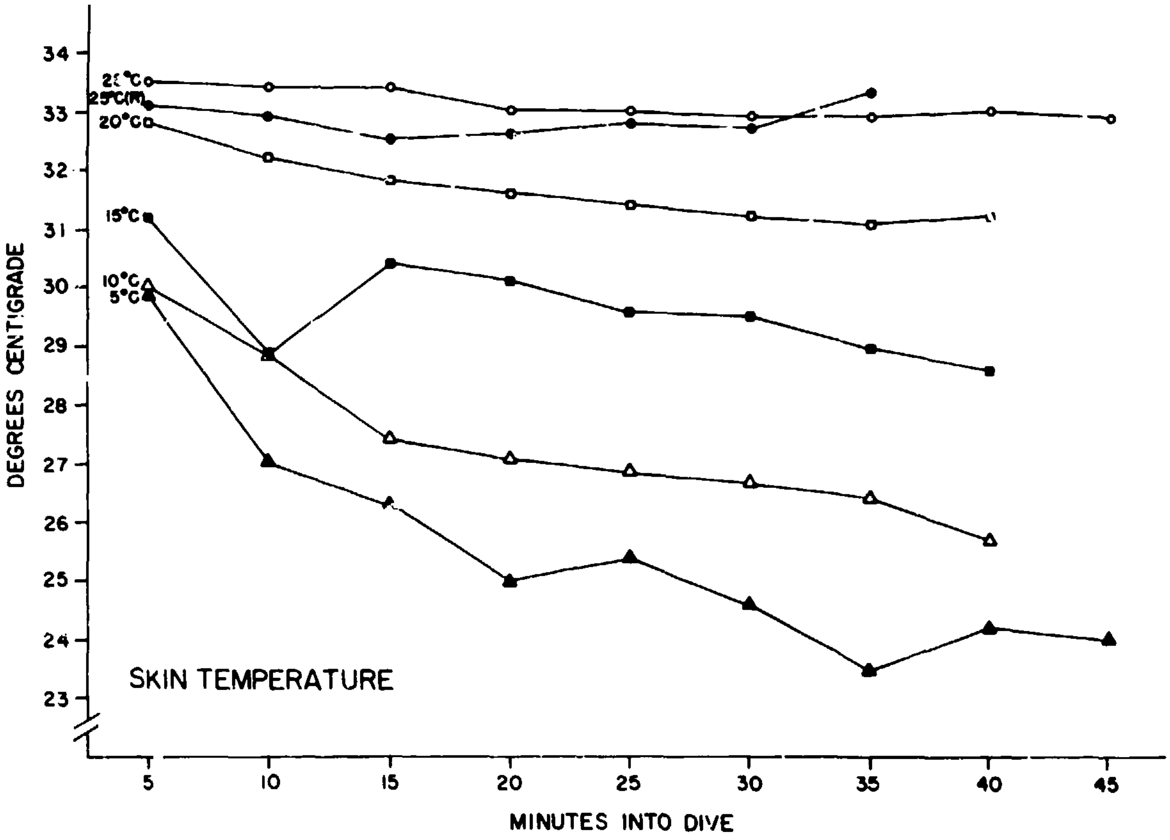

Fig. 3. Mean skin temperatures at each water temperature by 5-min blocks.

Performance Measures

Repeated acquisition (Learning component). As shown in the upper portion of Fig. 4, the quickest times for completing this task occurred at the repeat 25°C exposure; however, there were no significant differences in completion time or task errors as a function of water temperature.

Repeated acquisition (Performance component). During the first exposures at 25°C, performance times increased substantially over surface baseline times as shown in Fig. 4; this was followed by a stabilization from 20° to 5°, and a return to surface baseline levels at the repeat 25°C exposure. Water temperature did have a significant effect on the time to complete this component [F (5,10) = 3.98, $p < 0.05$], reflecting the difference between the initial 25°C dives and all other exposures. The mean number of errors on the performance component was greatest during the initial 25°C exposure, and near baseline levels at all other temperatures.

Top hatch. Times to complete the top hatch removal and transfer underwater were consistently longer than when performed on the surface, although mean times at 20°C and repeat 25°C nearly equalled surface baseline levels. The main effect of water temperature was significant [F (5,10) = 11.34, $p < 0.001$]. At 5°C the time to complete this task almost doubled above the mean completion time at 10°C, going from approximately 15 to 29 min. This is shown in Fig. 5. With the repeat exposure at 25°C, completion times returned to surface baseline levels.

The number of errors made while performing this task was significantly affected by water temperature [F (5,10) = 6.86, $p < 0.01$]; however, only at 5°C ($\bar{x}$ = 1.67) did the mean number of errors exceed 0.33.

Tooker patch. Upon initial exposures to 25°C, the divers' completion times increased substantially over surface baseline levels as shown in Fig. 6. As the study progressed, however, times dropped to near baseline levels except at 5°C, where it took the divers an average of 30 sec longer to finish this task when compared to surface performance. Water temperature did not significantly affect performance on this task.

Torque estimation. The mean torque estimates of the subjects on the surface and at the five water temperatures were consistently higher than the four torque standards, with this overestimation most pronounced at the 20 ft lb standard. However, temperature effects only approached statistical significance ($p < 0.10$).

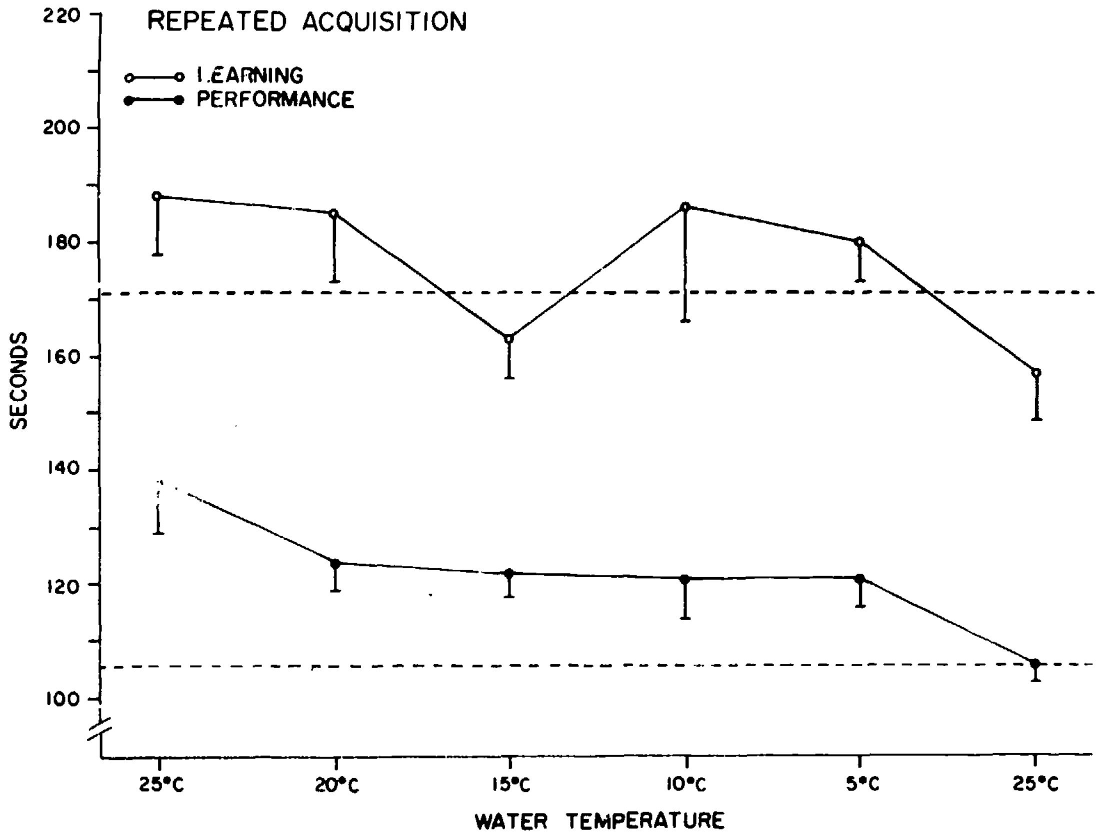

Fig. 4. Mean completion times on learning and performance repeated acquisition tasks as a function of water temperature. Brackets indicate one standard deviation. Dashed lines indicate mean surface baseline completion times.

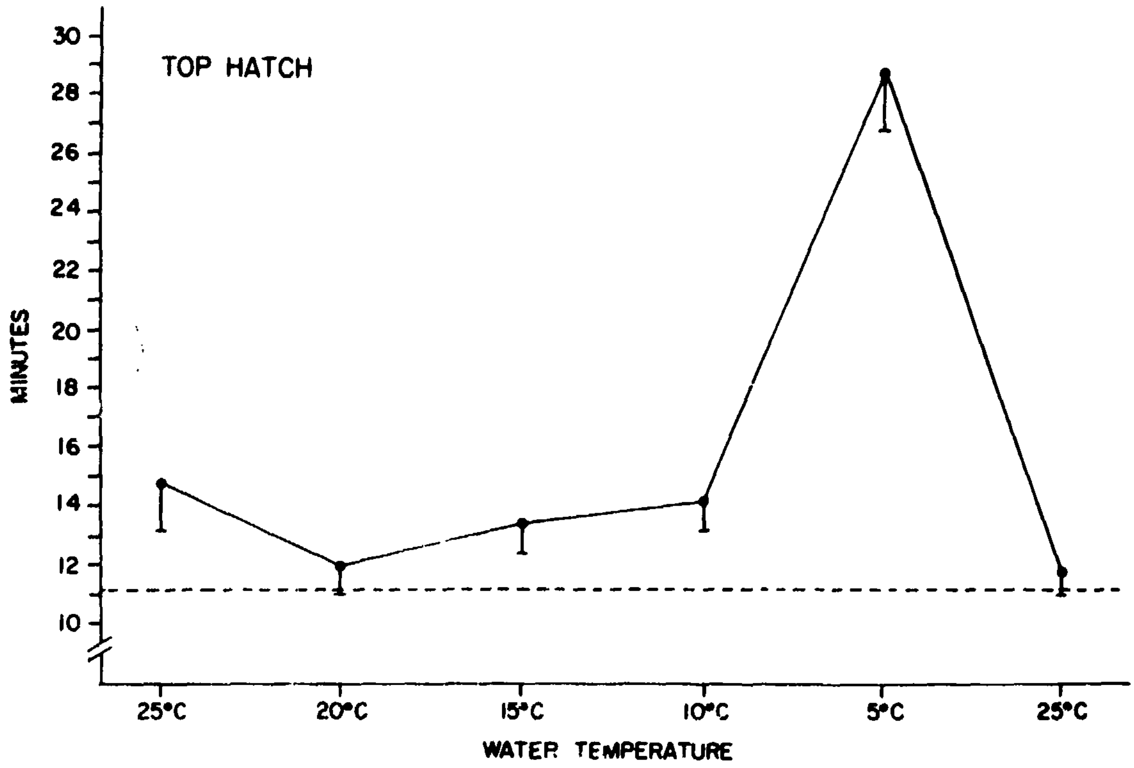

Fig. 5. Mean completion times for the top hatch task as a function of water temperature. Brackets indicate one standard deviation. Dashed line indicates mean surface baseline performance.

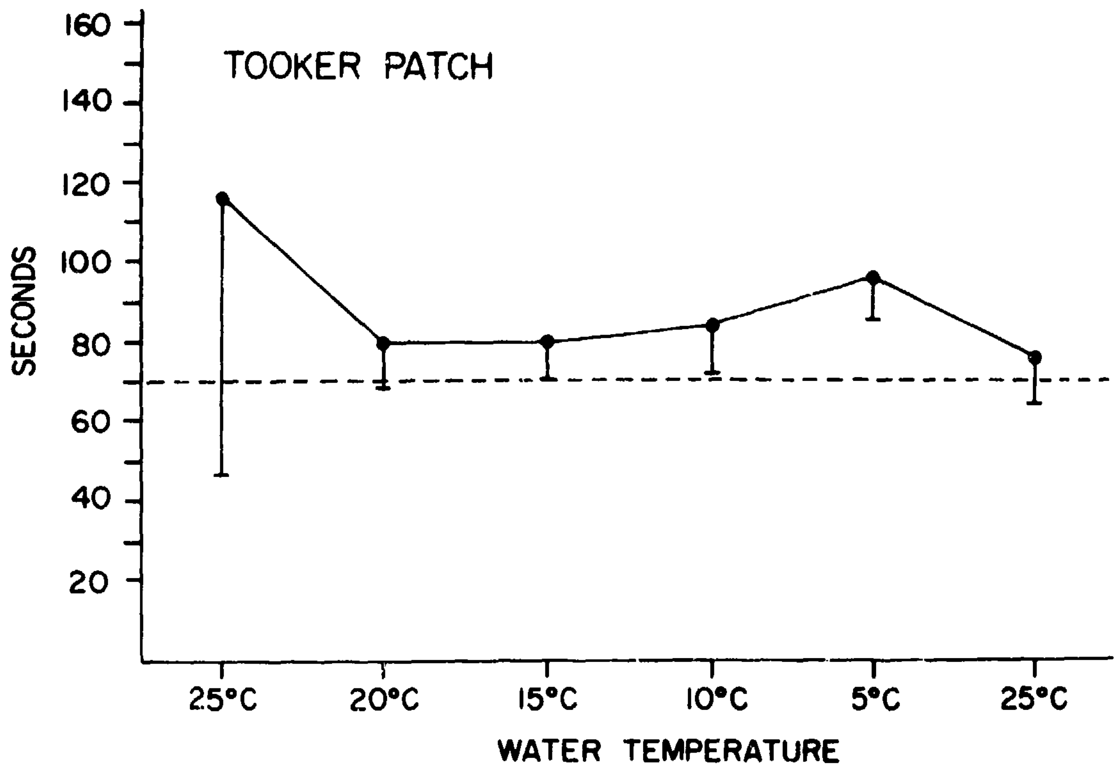

Fig. 6. Mean completion times for the tooker patch task as a function of water temperature. Brackets indicate one standard deviation.

Time estimation. The ability of the subjects to estimate time correctly was, overall, not significantly affected by changes in water temperature. However, as can be seen from the data shown in Fig. 7, systematic trends in time estimation performance were present. Mean time estimates on the surface were quite accurate as shown by the dashed lines in Fig. 7. Initial estimates conducted in the water at 25°C were followed by a decline in estimated time for 6 of the 8 standards as the water temperature dropped from 25°C to 20°C. Subsequently, this decline was then followed by a systematic increase in the mean time estimates at 6 of the 8 standards as water temperatures fell from 20° to 5°C. This effect was most pronounced at the higher time standards of 12, 16, 18, 22, and 24 sec. Estimates for the 4- and 6- sec standards remained relatively stable throughout the study.

Total dive time. From an initial dive time of 51½ min at 25°C, total dive times dropped to around 40 min at 20°C and remained there until the 5°C water temperatures were experienced. At that point total dive times again increased to around 51 min, and thereafter decreased to 35-36 min at the repeat 25°C exposure. The effect of water temperature on total dive time was significant [$F(5,10) = 4.70$, $p < 0.05$].

DISCUSSION

Despite substantial decreases in the skin temperatures of the subjects within dives and across water temperatures, performance on the tasks was not significantly impaired by cold until the water temperatures reached 5°C. The top hatch and tooker patch tasks required fine motor coordination involving the hands and fingers. The top hatch involved the blind placement and tightening of nuts, washers, and bolts through the top of the hatch and metal framing underneath; observation of the subjects working in 5°C water and postdive interviews revealed that they were experiencing difficulty in receiving adequate sensory information from their fingers, information needed for the correct placement of washers and nuts on the bolts. Stable performance at 10°C with gloves indicates that the loss of feedback was due to the cold and not to encumbrance associated with the wearing of gloves. A similar situation existed with the tooker patch, where loss of peripheral finger sensation hampered the spinning of a wing nut and an accurate check for a good seal of the rubber patch against the metal framing.

Cognitive functioning as inferred from the subjects' behavior on the repeated acquisition tasks was not significantly affected by the cold water conditions present in the study. A trend towards overestimating the passage of time was seen at the coldest water temperature (5°C), when the mean time estimates were consistently longer than the time standards and surface baseline estimates. This trend appears to support and extend the findings of Baddeley (1966), who found that a reduction in diver oral temperature taken postdive was associated with longer time estimates of a 60-sec standard. Excluding the results of the 4- and 6-sec standards, our findings taken when the divers were submerged and physiologically monitored suggest that at even longer time intervals the discrepancy between time standards and estimates would be magnified in cold water.

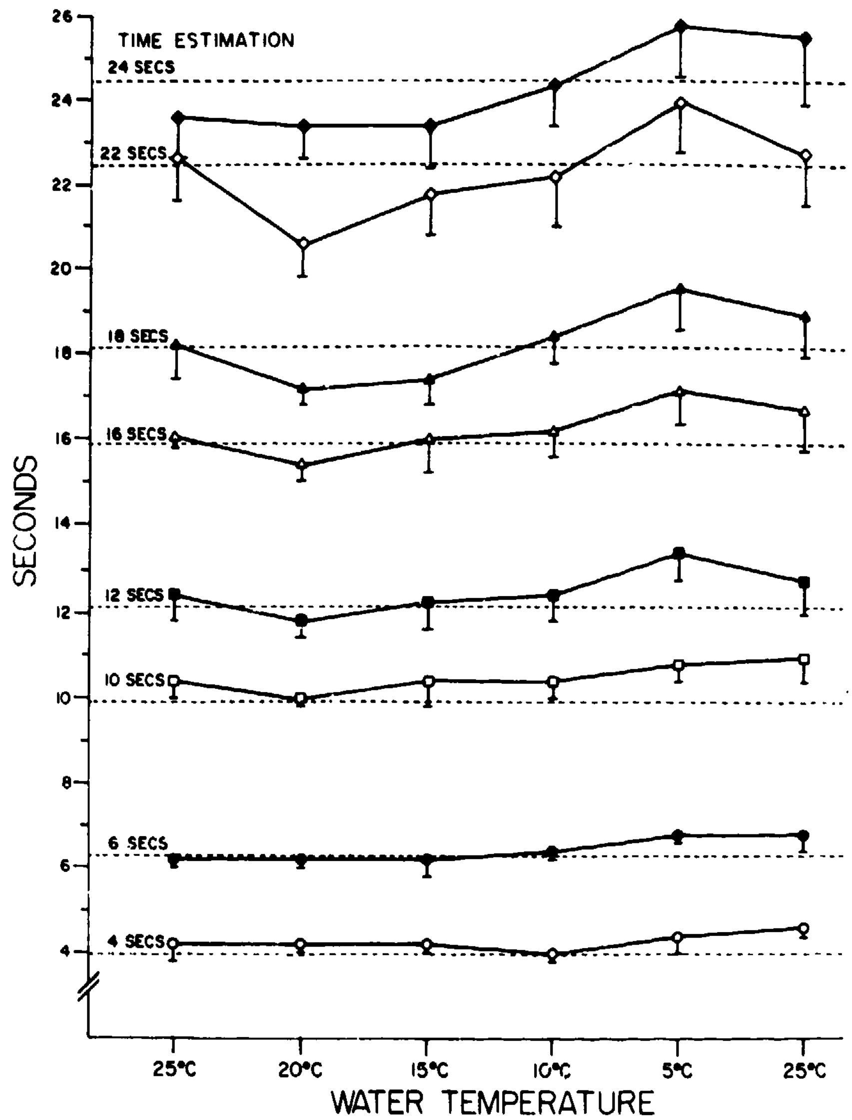

Fig. 7. Mean time estimations as a function of time standard and water temperature. Brackets indicate one standard deviation. Dashed lines indicate mean surface baseline performance.

Bowen (1968) used the phrase "water effect" to describe the impairment of performance that a diver displays when moving from a dry environment to a wet one, separate from any effects owing to cold. Factors such as bouyancy, wearing of diving gear, water viscosity, and altered perceptions and sensations contribute to this effect. The water effect was seen in three performance tasks during the initial exposures at 25°C: top hatch, tooker patch, and repeated acquisition (performance). The effects of the aqueous environment were subsequently compensated for by the divers as demonstrated by improved performance on these tasks at the 20°C water temperature; indeed, both top hatch and tooker patch performance approached surface baseline levels. Thus even with highly experienced, trained divers working in mild water temperatures, performance was initially impaired when the task requirements were moved from a dry to a wet environment. This finding supports the results of a study comparing the effects of high and low levels of surface practice on the subsequent performance of the SP^2 task underwater (Brady, 1979). When high levels of surface practice resulted in faster SP^2 task completion times underwater than low practice levels, one-trial underwater performance was greatly diminished from surface performance regardless of amount of practice.

Our findings indicate that gross heart rate and respiration rate measurements are insensitive to substantial changes in water temperature when these measures are monitored from active, working divers. At first glance these findings do not agree with the results reported by Dunford and Hayward (1981), who found significant differences in heart rate as a function of cold versus warm dives. Closer examination, however, reveals that their conclusion was based upon one recording halfway through their dives. In addition, their subjects performed steady state work on an ergometer, compared to our divers who performed a variety of tasks requiring varying energy expenditure. The systematic decreases in skin temperatures recorded over water temperatures and dive durations are in agreement with previously reported findings (e.g., Vaughn and Mavor, 1972; Stang and Weiner, 1972).

Our results are based upon a very small sample of experienced U.S. Navy divers. These men were in excellent physical condition and were accustomed to performing work underwater. The applicability of these findings to other diving populations (e.g., sport, scientific) remains to be clarified. In summary, we conclude that stable baseline performance on land may not immediately translate into similiar performance underwater, even with experienced divers in warm water. Further, from a performance perspective, the 1/4-inch-thick neoprene wet suit with hood and booties provides adequate protection during dives in shallow water with temperatures as low as 10°C (50°F) and exposure times as long as 50 min.

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