Factors influencing manual performance in cold water diving

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Abstract

With the introduction of new communications and display technologies, the ability of divers to operate complex controls becomes an important factor in systems design. This study evaluates the effects of pressure, gloves, and cold on three components of manual performance: grip strength, tactile sensitivity and manual dexterity. Performance was evaluated at 0.4 and 40 msw: with and without gloves in 25^{o}C water, and with gloves in 4^{o}C water. Results show that narcosis did not affect manual performance at 40 msw ($p>0.05$). In 25 ^{o}C water, three fingered neoprene gloves caused a significant impairment of grip strength (23%), tactile sensitivity (35%) and manual dexterity (45%). There was an interaction effect between gloves and pressure, with the compression of neoprene providing an improvement in grip strength and manual dexterity at 40 msw. Tactile sensitivity and manual dexterity were both affected by cold at 40 msw when wearing gloves ($p < 0.05$). The combined effects of gloves, pressure and cold water resulted in a 30% decrement in grip strength and a 60% decrement in tactile sensitivity and manual dexterity. Based on these findings, ergonomic recommendations are made for design and usability testing of underwater equipment and controls.

Résumé

L’arrivée de nouvelles technologies de communication et d’affichage fait en sorte que l’aptitude des plongeurs à utiliser des systèmes de commande complexes constitue un facteur important de la conception des systèmes. La présente étude évalue les effets de la pression, des gants et du froid sur les trois composantes de la dextérité, soit : la force de préhension, la sensibilité tactile et la dextérité proprement dite. Le rendement (en anglais *performance* ou p) a été évalué à des profondeurs de 0,4 m et de 40 m : avec et sans gants dans l’eau à une température de 25 ºC et avec gants dans l’eau à une température de 4 ºC. Les résultats montrent que « l’engourdissement » n’avait pas d’incidence sur la dextérité à une profondeur de 40 m ($p > 0,05$). Dans l’eau à 25 ºC, les gants en néoprène à 3 doigts ont entraîné une diminution significative de la force de préhension (23 %), de la sensibilité tactile (35 %) et de la dextérité (45 %). On a relevé une interaction entre les gants et la pression, la compression du néoprène améliorant la force de préhension et la dextérité à une profondeur de 40 m. Chez les plongeurs portant les gants à une profondeur de 40 m, le froid a diminué la sensibilité tactile et la dextérité ($p < 0,05$). Les effets combinés des gants, de la pression et de l’eau froide ont entraîné une diminution 30 % de la force de préhension et de 60 % de la sensibilité tactile et de la dextérité. Comte tenu de ces résultats, des recommandations en matière d’ergonomie ont été faites en vue de soumettre à des essais de conception et d’utilisabilité les commandes et l’équipement de plongée.

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Executive summary

Introduction: When diving in cold water, the ability to operate equipment and controls is limited by the use of protective gloves. With the introduction of new communications and display technologies, the ability of divers to operate complex controls becomes an important factor in systems design.

Methods: This study evaluates the effects of pressure, protective gloves, and cold water immersion on three components of manual performance: grip strength, tactile sensitivity and manual dexterity. Performance was evaluated at 0.4 and 40 msw: with and without gloves in 25°C water, and with gloves in 4°C water.

Results: Narcosis did not have a significant effect on these components of manual performance ($p>0.05$). In 25°C water, three fingered neoprene gloves caused a significant impairment of grip strength (23%), tactile sensitivity (35%), and manual dexterity (45%) averaged over both pressures. There was an interaction effect between gloves and pressure with the compression of neoprene providing an improvement in grip strength and manual dexterity at 40 msw. When wearing gloves, tactile sensitivity and manual dexterity were both affected by cold ($p < 0.05$). Tactile sensitivity showed a 45% decrement due to cold when averaged over both pressures. Manual dexterity showed a 33% decrement due to cold at 40 msw, but there was no significant change at 0.4 msw. The combined effects of gloves, pressure and cold water resulted in a 30% decrement in grip strength and a 60% decrement in tactile sensitivity and manual dexterity.

Significance: Based on these findings, ergonomic design recommendations are made to accommodate the decrements in grip strength, tactile sensitivity and manual dexterity in the design of underwater equipment and controls. Due to the antagonistic effects of compression of neoprene and cold water immersion on manual performance, it is concluded that usability testing of design prototypes in cold water at surface pressure can give a good indication of the performance capabilities of divers when using these systems at pressure. Further research is required to confirm suitable key size and spacing for design of multifunction underwater keypads.

Sommaire

Introduction. Pendant la plongée en eau froide, l'utilisation de gants de protection limite l'aptitude des plongeurs à utiliser de l'équipement et des commandes. L'arrivée de nouvelles technologies de communication et d'affichage fait en sorte que l'aptitude des plongeurs à utiliser des systèmes de commande complexes constitue un facteur important de la conception des systèmes.

Méthodes. La présente étude évalue les effets de la pression, des gants de protection et du froid sur les trois composantes de la dextérité, soit : la force de préhension, la sensibilité tactile et la dextérité proprement dite. Le rendement (en anglais *performance* ou p) a été évalué à des profondeurs de 0,4 m et de 40 m, avec et sans gants dans l'eau à une température de 25 ºC et avec gants dans l'eau à une température de 4 ºC.

Résultats. « L'engourdissement » n'avait pas d'incidence significative sur ces composantes de la dextérité ($p > 0,05$). Dans l'eau à 25 ºC, les gants en néoprène à 3 doigts ont entraîné une diminution significative de la force de préhension (23 %), de la sensibilité tactile (35 %) et de la dextérité (45 %), ces valeurs étant pondérées en fonction des deux pressions. On a relevé une interaction entre les gants et la pression, la compression du néoprène améliorant la force de préhension et la dextérité à une profondeur de 40 m. Chez les plongeurs portant les gants à une profondeur de 40 m, le froid a diminué la sensibilité tactile et la dextérité ($p < 0,05$). La diminution de 45 % de la sensibilité tactile due au froid a été pondérée en fonction des valeurs aux deux pressions. Même si la dextérité due au froid a diminué de 33 % à une profondeur de 40 m, elle n'a pas diminué de façon significative à 0,4 m. Les effets combinés des gants, de la pression et de l'eau froide ont entraîné une diminution 30 % de la force de préhension et de 60 % de la sensibilité tactile et de la dextérité.

Portée. Compte tenu de ces résultats, des recommandations en matière de conception ergonomique sont faites pour tenir compte de la diminution de la force de préhension, de la sensibilité tactile et de la dextérité découlant des commandes et de l'équipement de plongée. En raison des effets contradictoires de la compression du néoprène et de l'immersion en eau froide sur la dextérité, on a conclu que des essais d'utilisabilité des prototypes d'équipement en eau froide et à des pressions de surface pourraient fournir un bon indice de l'aptitude de rendement des plongeurs utilisant ces dispositifs à des pressions données. D'autres études sont nécessaires afin de confirmer l'espacement et la taille des touches en vue de la conception de claviers multifonctions destinés à des activités sous-marines.

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Overview

Manual performance is an important issue when diving because of high manipulative requirements, the sensitivity of the hands to cold water and the need for protective gloves. Divers may be required to identify and operate equipment and controls by touch when visibility is limited or when equipment and controls are located outside the visual field. Canadian divers routinely operate in temperatures below 10^{o}C and temperatures may reach as low as -2^{o}C. Cold water and the use neoprene gloves are both associated with decreased manual performance.

To optimize the design of equipment and controls, it is important to understand how each component of manual performance is affected by individual stressors, and how these stressors interact to cause performance impairment. Components of manual performance that are important to divers include grip strength, tactile sensitivity and manual dexterity. Factors associated with diving that affect manual performance include cold, pressure, immersion in water (Heus *et al.,* 1995; Morton and Provins, 1960; Provins and Morton, 1960; Mackworth, 1953; Bowen, 1968), equipment burden (Morrison *et al.*, 1998) and anxiety (Bowen, 1968; Enander, 1984).

Bradley (1969) investigated a number of different glove designs to determine what factors were associated with degraded manual performance. Bradley (1969) determined that there are four glove characteristics that influence manual performance: tenacity, snugness, suppleness, and protectiveness. Tenacity refers to the coefficient of friction between the glove and the object being handled. Snugness refers to the fit of the glove at the joint between the finger and the palm. Suppleness is a function of the pliability of the material and the stiffness and location of the seams. It refers to the ability of the glove to conform to the position of the fingers within. Protectiveness refers to the ability of the glove to protect from the environmental conditions. Snugness and tenacity were positively correlated with performance, while suppleness correlated positively with performance, and negatively with protection (Bradley, 1969).

Parsons and Egerton (1985) investigated the effects of cold, both with and without gloves, on manual dexterity. They investigated different glove designs beyond the traditional five-fingered glove to three-fingered gloves and full mittens. Their conclusion that gloves offering more protection were associated with larger manual performance decrements supported Bradley (1969). The work of Parsons and Egerton did not include diving gloves.

Although there is considerable data on the effects of gloves on manual performance, few studies have focused on diving or the use of neoprene gloves. Bellinger and Slocum (1993) investigated the effects of neoprene gloves on the ability to perform basic movements of the hand and fingers in air. Wrist flexion/ extension was not affected, but both supination/ pronation and abduction/ adduction were degraded. No specific information was provided in terms of manual performance decrements. Banks and Goehring (1979) showed that three fingered neoprene gloves significantly decreased tactile sensitivity.

Pressure affects manual performance through a number of pathways. Exposure to increased air pressure causes narcosis, which has been shown to affect both cognitive and manual performance (Keisling and Maag 1962; Fowler *et al,* 1985). Increased pressure will alter the properties of neoprene gloves as the air spaces within the material compress. As the gloves become thinner and less snug, range of motion, flexibility, and tactile sensitivity will change. The insulative properties of the neoprene will also change, leaving the diver more susceptible to local cooling.

As most research on gloves and manual performance has been conducted in an air environment, it is not directly applicable to diving. While it seems obvious that the use of neoprene gloves in diving will degrade manual performance, many questions remain unanswered. There are little quantitative data on performance impairment caused by neoprene gloves, or the effects of cold water and narcosis on manual performance while wearing neoprene gloves.

Manual performance may also be affected by the level of arousal of the diver. Whereas moderate levels of arousal can improve manual performance, higher levels of arousal associated with anxiety are likely to cause impairment of manual performance. A slightly cool environment can increase arousal, which may correlate with an increase in task performance for simple, highly rehearsed tasks (Parsons, 2003) In contrast, a cold environment can increase arousal to a level associated with a decrease in performance (Parsons, 2003), particularly for complex or novel tasks.

In addition to cold, factors such as narcosis, the equipment burden, operating in a low light level, and operating in an unfamiliar underwater environment have been associated with increase arousal and anxiety in divers. Researchers have noted that performance decrements in open water diving are significantly higher than those in a hyperbaric chamber (Baddeley *et al*., 1975; Ellis, 1982; Stang & Wiener, 1970 and Bowen, 1968). Although it is difficult to isolate the effect of anxiety from the effects of narcosis, light level, or immersion, research suggests that apart from immersion and narcosis, anxiety is higher in deeper dives, and night dives, and that these dives are associated with lower manual dexterity scores (Baddeley and Fleming 1967; Mears and Cleary, 1980).

Although there have been several studies showing a decrement on manual performance underwater, there is little information on how the individual components of grip strength, tactile sensitivity and manual dexterity are affected. There is also very little information on the importance of contributing factors, such as narcosis, gloves and cold.

It is hypothesized that the combined effect of exposure to increased pressure (40 msw) and cold (4°C) while wearing neoprene gloves will degrade the three components of manual performance. The individual factors contributing to performance impairment will include narcosis, neoprene gloves, and exposure to cold, while compression of neoprene will enhance performance when wearing gloves. It is hypothesized that narcosis, gloves, compression, and cold will have a different effect on the components of manual performance (grip strength, tactile sensitivity and manual dexterity).

Experimental Design

The purpose of this study is to quantify the effects of gloves, pressure, and cold water immersion on manual performance in divers. This information is important in determining parameters for the design of diving equipment and controls. The components of manual performance identified as important to the operation of underwater controls are grip strength, tactile sensitivity, and manual dexterity (Morrison *et al.,* 1998). The study was designed to test these components in progressively more stressful environmental conditions; to quantify the effect of each stressor, and to measure how they interact and combine to impair the manual performance of divers. The experimental design was approved by the Simon Fraser University Ethics Review Board.

Ten male divers between the ages of 20 to 40 years participated in the experiment. Each diver completed a diving medical examination and an informed consent form prior to participation. Divers were asked not to ingest alcohol, caffeine (coffee, tea, chocolate) or energy drinks, or to smoke cigarettes on the days of the experiments. Divers were asked not to exercise in the four hours before the experiment, and for twelve hours after diving. Divers were acclimatized to approximately 22°C in an air environment for 30 minutes prior to dressing and entering the water.

Performance Measures

The performance measures used in this study were grip strength (motor function), tactile sensitivity (sensory function) and manual dexterity (fine motor control). These measures were selected based on feedback from Canadian Forces mine countermeasures (MCM) divers and previous literature on the components of manual performance (Morrison *et al.*, 1998).

Grip Strength was measured using a manual hand grip dynamometer. Divers gripped the dynamometer in their dominant hand. Three measures of grip strength were obtained and the maximum value recorded.

Tactile Sensitivity was measured using an adapted Braille test. Each diver was provided with a board with four rows of embossed characters (consisting of a combination of embossed tabs) of the form shown in Figure 1. Each row of characters was progressively smaller in size. Character sizes and the dimensions of embossed tabs (dots) are provided in Table 1. The board measured approximately 90 cm wide by 40 cm high. The board was placed below a screen to prevent the diver from seeing the characters. Characters were identified by touch and by comparison of each pattern with a set of eight Braille characters displayed to the diver (Figure 1). The diver verbally reported each character to the tester. Performance was measured by the number of characters in each row that could be identified correctly in one minute, and by accuracy (measured by the number of correct responses divided by total responses). A tactile sensitivity score was calculated as the total number of Braille letters correctly identified in four minutes.

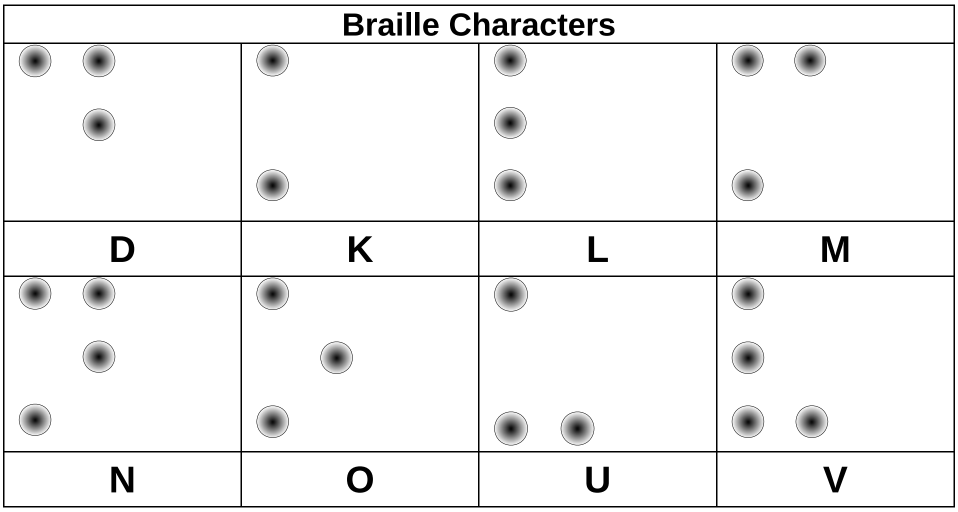
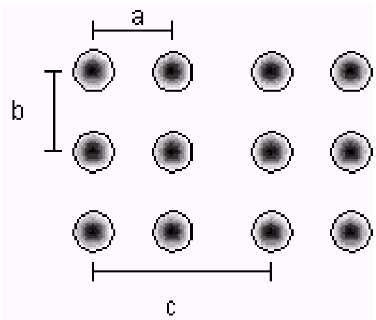


Figure 1: Description of Braille Characters Used in Tactile Sensitivity Test

Table 1: Size and Spacing of Braille Characters

Diagram of characters	Tab Size and Spacing				
	**Dimension**	**Row 1 (mm)**	**Row 2 (mm)**	**Row 3 (mm)**	**Row 4 (mm)**
	Tab Base	11	6.5	5.0	3.5
	Tab Height	5.0	3.5	3.0	2.5
	A	28	16	12.5	7.5
	B	28	16	12.5	7.5
	C	70	42	31	18

Manual Dexterity was measured using a nut-bolt test. The test was designed to simulate task elements that are commonly performed in diving operations. The diver was provided with a board mounted with three bowls. One bowl was filled with bolts, and one with nuts. The diver was asked to retrieve a nut and a bolt, screw the nut onto the bolt and place the assembly into the third bowl. The diver was given two minutes to complete as many nut-bolt combinations as possible. The number of combinations correctly completed in the two-minute time limit measured performance. Only nut-bolt combinations that were assembled properly and deposited in the third bowl were counted. The number of dropped nuts and bolts was also recorded. A nut and bolt size of 7/16 was chosen based on pilot studies of divers capabilities to manipulate nuts and bolts while wearing gloves.

The three manual performance tests required approximately seven minutes to complete.

Experimental Conditions

The study consisted of two sets of experimental conditions, completed consecutively. The first set comprised four conditions at a water temperature of 25°C. The second set comprised two conditions at a water temperature of 4°C. Divers completed the three manual performance tests (grip strength, tactile sensitivity, and manual dexterity) in each condition.

In the two cold conditions, measures were made during 18 to 27 minutes of elapsed bottom time to allow the effect of cold on manual performance to stabilize. The experimental conditions are summarized in Table 2.

Table 2: Summary of Experimental Conditions in Which Divers Completed Manual Performance Tests.

Condition Set	Experimental Condition	Water Temperature	Pressure	Gloves
1	1	25°C	0.4 msw	No
1	2	25°C	0.4msw	Yes
1	3	25°C	40 msw	No
1	4	25°C	40 msw	Yes
2	5	4°C	0.4 msw	Yes
2	6	4°C	40 msw	Yes

All six conditions were completed in the wet section of a hyperbaric chamber. The divers wore a full dry suit and weight belt, and were immersed to the neck for the duration of each experiment. Three-fingered Rubatex neoprene gloves were worn where required by the experimental condition (Table 2).

To avoid learning effects, divers were provided with training time in an air environment at 25°C. Once tests results reached a plateau, indicating an end to the learning curve, the diver progressed through the test conditions. A plateau was defined as the point where divers receive three consecutive scores that are not significantly different. Because the tests were quite simple, the learning curve was short, and most divers were trained in less than 30 minutes.

Condition Set 1: water temperature 25°C.

Condition 1 was designed to provide baseline data on manual performance when immersed at a neutral water temperature without gloves.

Condition 2 was designed to identify the separate effect of wearing 3-fingered neoprene gloves when immersed at a neutral temperature.

Condition 3 was designed to identify the effect of narcosis on manual performance. The diver was immersed and pressurized to 40 msw with no gloves.

Condition 4 was designed to identify the combined effects of pressure (narcosis and the compression of neoprene) on manual performance when wearing neoprene gloves.

Condition Set 2: water temperature 4°C.

Condition 5 was designed to identify the combined effect of cold (4°C water) and 3-fingered neoprene gloves on manual performance. The diver was immersed at surface pressure for approximately 25 minutes while wearing gloves.

Condition 6 was designed to identify the combined effect of cold (4°C water), gloves, and pressure (narcosis and the compression of neoprene). The diver was immersed and pressurized to 40 msw for approximately 25 minutes while wearing gloves.

In order to minimize the number of dives required by each diver, conditions 3 and 4 were completed during a single dive to 40 msw. Conditions 1 and 2 were also collected during a single immersion. Divers completed both sets of conditions, except for one diver that dropped out of the second set due to an unrelated hand injury. Condition set # 2 followed the same protocol as set # 1, except manual performance data was collected between 18 to 27 minutes of exposure to cold water.

To avoid order effects (practice and fatigue) a counterbalanced design was used. A Latin Square design was modified to allow conditions 3 and 4 to be completed during a single compression, while controlling for order effects across conditions. Because the three tests were simple and divers reached a learning plateau quickly, it is unlikely that learning or fatigue had a significant effect on the data. However, to control for a possible order effect due to test sequence, the tests were completed in the same order by each diver, and in each condition. Grip strength was measured first, followed by tactile sensitivity, then manual dexterity.

A number of factors were considered in designing the experiments. The effect of neoprene compression is not separated from the narcotic effect. The exposure to increased air required to achieve neoprene compression also causes narcosis. Thus, the two effects normally occur together. The separate effect of narcosis is assessed in condition 3. The effect(s) of exposure to cold and pressure without gloves are not included in the experimental design. Initial pilot studies indicated that the divers tolerance of prolonged exposure to 4°C water without gloves was low, and therefore these conditions were eliminated from the final design. In addition, these conditions (4°C, no gloves) are not realistic scenarios when diving in cold water or for developing design criteria for divers' equipment.

In the two conditions that include exposure to cold, manual performance is expected to be time dependent due to progressive cooling of the hand and fingers, while in the other four conditions (at 25°C), time is not likely to be a factor. In condition 2, data were collected during 18 to 27 minutes of bottom time as this was considered to be representative of maximum bottom times in cold water MCM diving operations. The time dependent effects of cold on hand skin temperature and the progressive effects of hand cooling on the manual performance of divers wearing neoprene gloves at depth is reported in a separate study (Morrison and Zander, 2004).

In all experimental conditions the diver was accompanied in the wet chamber by a tender who was also dressed in a dry suit with weight belt. In conditions 2, 4 and 6, following completion of data collection, the diver and tender left the water and transferred to the dry section of the hyperbaric chamber. Divers were decompressed using the appropriate decompression profile (Canadian Forces Air Diving Table 2: in-water oxygen decompression tables).

Analysis

The experiment was designed so that a subset of results from the first set of conditions could be compared to the results of the second set of conditions. The data collected in condition set #1 was first analyzed independently, then components from the two sets were compared to answer specific research questions.

The Effects of Pressure and Gloves on Manual Performance: Condition Set 1

The effects of three-fingered neoprene gloves and pressure on manual performance were analyzed using a 2 (pressure condition) x 2 (glove condition) factorial design with repeated measures on both factors. Figure 2 shows a diagram of the experimental design. Each component of manual performance (grip strength, tactile sensitivity, manual dexterity) was analyzed independently. Hypotheses were tested for significant differences at $p<0.05$. Results were examined for main effects of pressure and gloves, and interaction effect between the two variables. In this design, the main effect of pressure included the separate effects of narcosis and compression of neoprene. Therefore, the separate effect of narcosis was identified by comparing conditions 1 and 3 (no gloves). The separate effect of compression of neoprene will be manifest as an interaction effect.

	No Gloves	Gloves
O.4 msw	Condition 1	Condition 2
40 msw	Condition 3	Condition 4

Figure 2: Analysis of the effects of Pressure and Gloves on the Components of Manual Performance

The Effects of Temperature and Pressure on Manual Performance: Combination of Condition Set 1 and 2

In order to examine the effects of water temperature and pressure on manual performance when wearing gloves, a 2 (temperature condition) x 2 (pressure condition) factorial design with repeated measures on both factors was used. The data for conditions 2 and 4 (25°C water with gloves) were compared with the data from conditions 5 and 6 (4°C water with gloves). Figure 3 shows a diagram of the experimental design. Hypotheses were tested for significant differences at $p < 0.05$. Results were examined for main effects of temperature and pressure, and interaction effect between the two variables. As with condition set 1, each component of manual performance was analyzed independently.

The effects of cold when wearing gloves, and the combined effects of cold and pressure were identified by comparing the results of conditions 2 and 4 with conditions 5 and 6. The effect of narcosis alone is not included in this analysis as it was considered in condition set 1 (conditions 1 and 3), and cannot be isolated from the effects of compression of neoprene in this design.

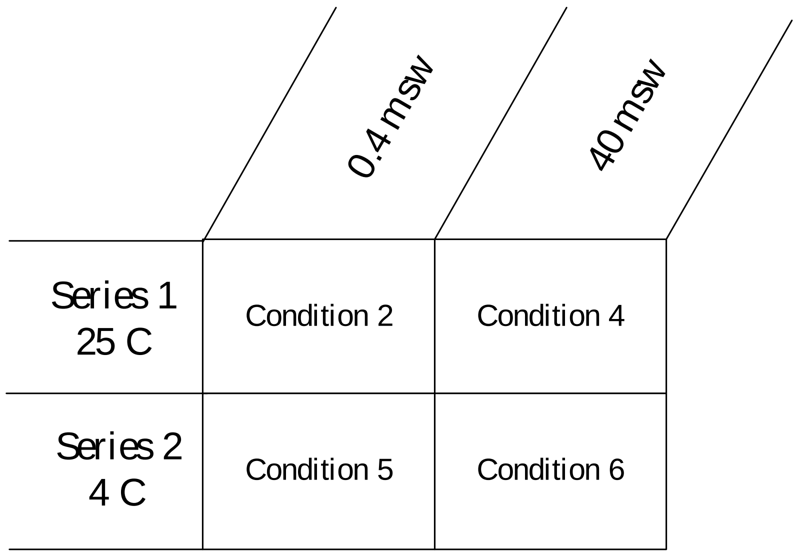


Figure 3: Analysis of the effects of Temperature and Pressure on the Components of Manual Performance

Additional analysis was completed on the tactile sensitivity data of condition set 2. The four rows of the tactile sensitivity test were analyzed separately in conditions 5 and 6. The purpose was to determine the optimal size and spacing configuration for controls or equipment to be used by divers in cold water. The tactile sensitivity score and accuracy for each of the four rows were analyzed in each condition using a 1 (pressure) x 4 (character size) factorial design with repeated measures. Hypotheses were tested for significant differences at $p < 0.05$. Results were examined for main effects of character size.

Results

The effects of pressure and gloves on manual performance

Effects of pressure and gloves on grip strength, tactile sensitivity and manual dexterity are shown in Tables 3, 4 and 5.

Table 3: Effects of Pressure and Gloves on Grip Strength (Newtons)

	Grip Strength (n=10)			
	No gloves		3-fingered gloves	
0.4 msw	465.0±95.2		340.4±78.5	
40 msw	461.1 ±91.2		375.7±76.5	
Statistics				
	F	Sig.	η^2	Power
Main Effect Pressure	2.7	0.13	0.23	0.33
Main Effect Gloves	129.4	0.00	0.94	1.00
Interaction Pressure x Gloves	12.5	0.006	0.58	0.88

Table 4: Effects of Pressure and Gloves on Tactile Sensitivity

	Tactile Sensitivity (n=10)							
	Score (letters correct)				Accuracy (% correct)			
	No gloves		3-fingered gloves		No gloves		3-fingered gloves	
0.4 msw	36.5 ±14.1		22.0 ±11.3		0.86 ±.012		0.78 ±0.14	
40 msw	36.0±11.7		25.4 ±10.5		0.87 ±0.01		0.83 ±0.13	
Statistics								
	F	Sig.	η^2	Power	F	Sig.	η^2	Power
Main Effect Pressure	0.5	0.48	0.06	0.10	1.3	0.29	0.12	0.17
Main Effect Gloves	60.0	0.00	0.87	1.00	8.6	0.02	0.49	0.74
Interaction Pressure x Gloves	2.0	0.19	0.18	0.24	0.3	0.63	0.27	0.07

Table 5: Effects of Pressure and Gloves on Manual Dexterity

	Manual Dexterity (n=10)							
	Score (number of nut-bolt combinations competed)				**Drops (number of nuts or bolts dropped)**			
	No gloves		3-fingered gloves		No gloves		3-fingered gloves	
0.4 msw	13.3 ±1.9		5.5 ±1.5		0.4 ±0.5		2.8 ±2.3	
40 msw	12.5 ±2.5		8.6 ±3.3		1.3 ±1.2		2.0 ±1.2	
Statistics								
	F	Sig.	η^2	Power	F	Sig.	η^2	Power
Main Effect Pressure	5.8	0.04	0.39	0.58	0.01	0.92	0.001	0.05
Main Effect Gloves	40.3	0.00	0.82	1.00	12.6	0.006	0.58	0.88
Interaction Pressure x Gloves	9.6	0.01	0.52	0.79	4.3	0.07	0.33	0.46

Grip Strength

The means and standard deviations of grip strength are provided in Table 3 and shown in Figure 4. There was no main effect of pressure on grip strength, but grip strength was significantly lower when wearing gloves (F=129, p<0.001). Analysis indicates that 94% of the variability in the grip strength between the two glove conditions can be accounted for by the use of 3-fingered neoprene gloves (Eta-squared (η^2)=0.94). There was a significant interaction between the effects of pressure and gloves (F=12.5, p=0.006). The decrement in grip strength associated with wearing gloves in warm water was 27% at 0.4 msw, but only 19% at 40 msw.

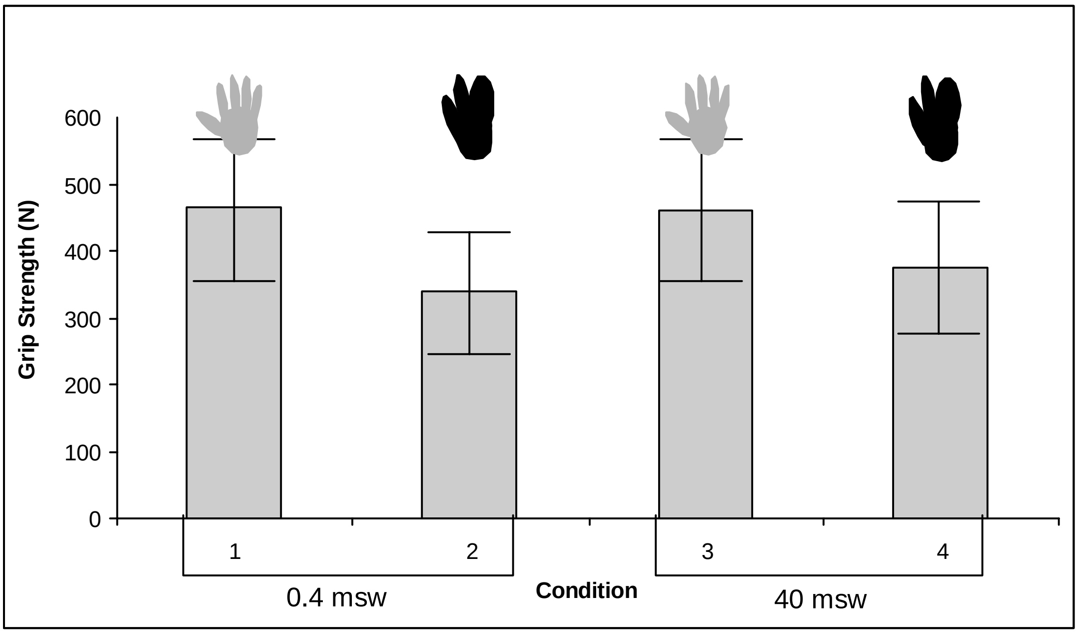


Figure 4: Effects of Pressure and Gloves on Grip Strength

Hence, data were analyzed for simple effects to identify contrasts between conditions 1 and 3 and between 2 and 4. Without gloves (conditions 1 and 3), there was no significant difference in grip strength due to pressure. This result indicates that there is no significant narcosis effect on grip strength. When wearing gloves, grip strength was 11% higher at 40 msw than at 0.4 msw (F=10.4, p<0.05). As there is no significant effect of narcosis on grip strength, the interaction effect between gloves and pressure is most likely due to compression of neoprene (condition 2 vs. condition 4). The divers reported that it was easier to grip the dynamometer at 40 msw with the thinner, compressed neoprene gloves, and that the compressed gloves offered less resistance than the gloves at the surface.

Tactile Sensitivity

Mean tactile sensitivity scores are provided in Table 4, and shown in Figure 5. Results are reported as a single score representing the total number of Braille letters correctly identified in four minutes.

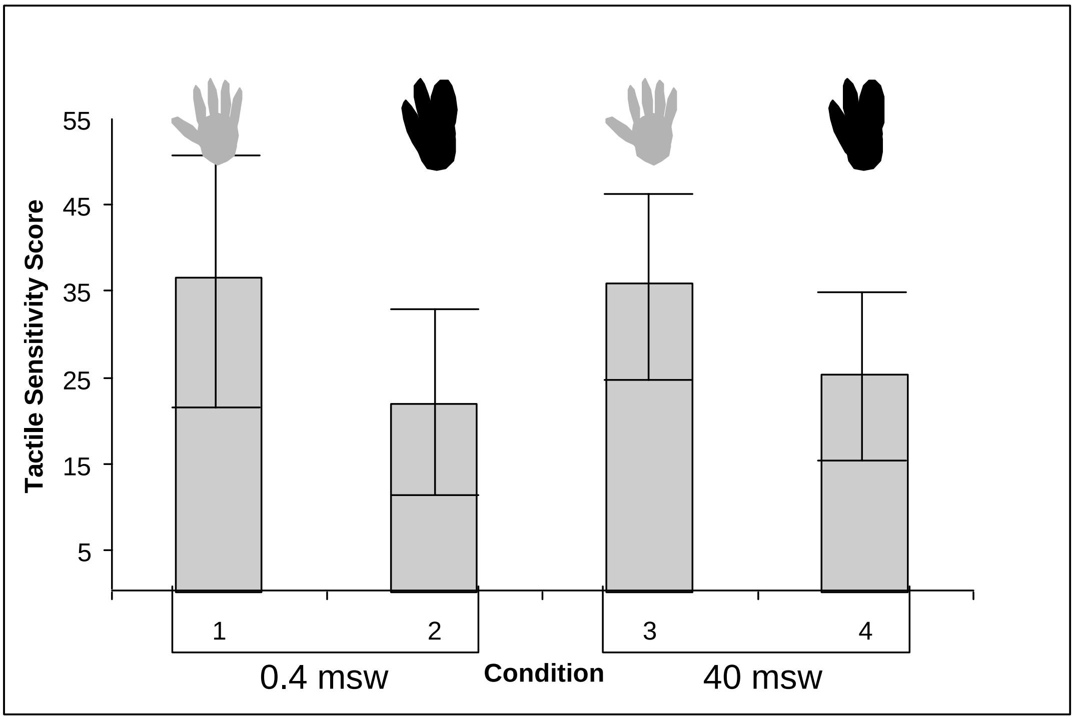


Figure 5: Effects of Pressure and Gloves on Tactile Sensitivity Score

There was no main effect of pressure on tactile sensitivity score ($p>0.05$). The mean tactile sensitivity scores were significantly lower when wearing gloves ($F=60.0$, $p<0.001$). The marginal means for each glove condition (36.3 without gloves and 23.7 with gloves) indicate that wearing 3-fingered neoprene gloves is associated with a 35% decrease in tactile sensitivity averaged over the four sizes of Braille characters. Analysis indicates that 87% ($\eta^2=0.87$) of the variability between the two glove conditions can be attributed to the 3-fingered neoprene gloves.

There was no significant interaction effect between pressure and gloves. This result indicates that there is no significant narcosis effect on tactile sensitivity, and that the effect of wearing three- fingered neoprene gloves is not significantly different at the surface than when at depth.

The tactile sensitivity data were also analyzed for accuracy. Results are provided in Table 4, and shown in Figure 6. There was no main effect of pressure on accuracy, but accuracy was 6.9% lower when wearing gloves ($F=8.6$, $p=0.02$). There was no interaction between the effect of pressure and gloves. Results indicate that there is no significant effect of narcosis or compression of neoprene on the accuracy of tactile sensitivity.

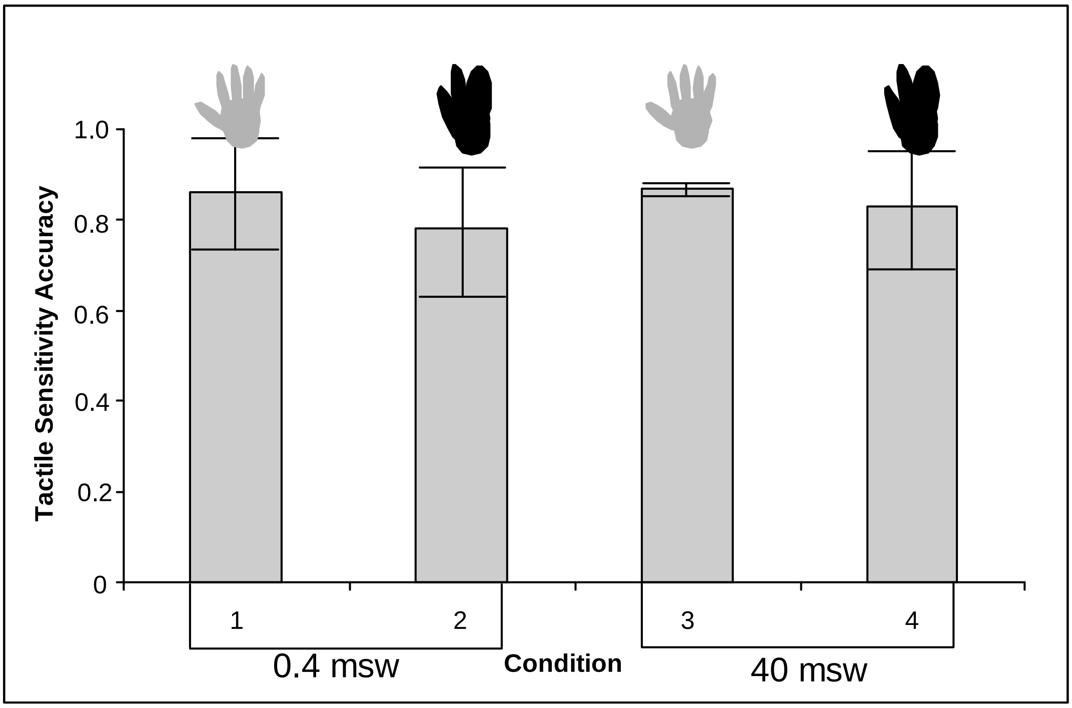


Figure 6: Effects of Pressure and Gloves on Tactile Sensitivity Accuracy

Manual Dexterity

Mean manual dexterity scores are provided in Table 5 and shown in Figure 7.

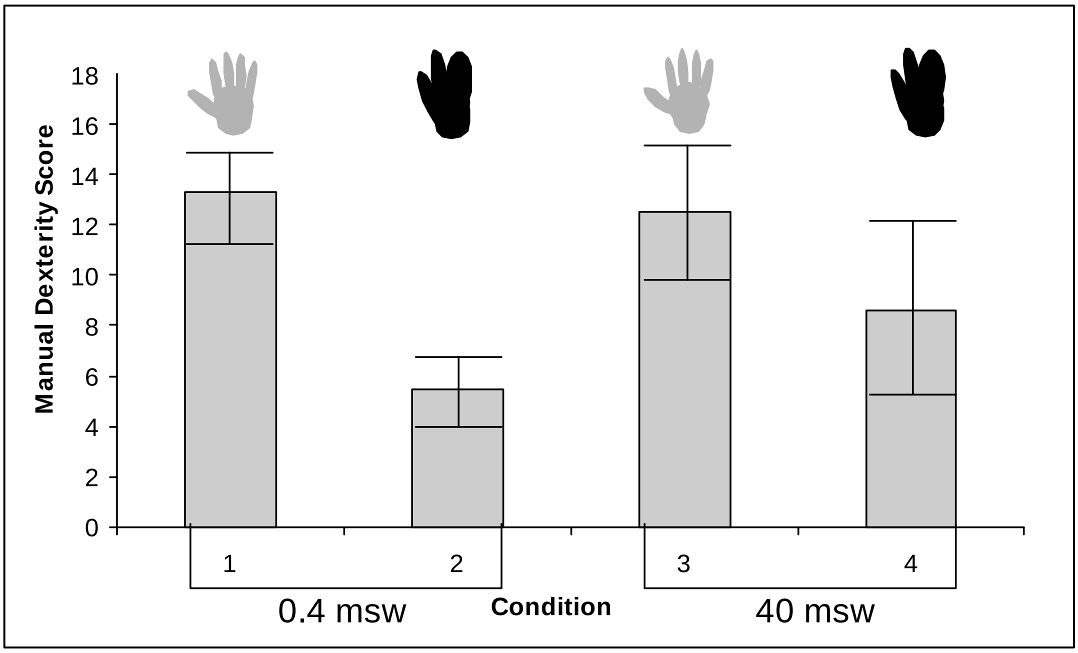


Figure 7: Effects of Pressure and Gloves on Manual Dexterity Score

There was a main effect of pressure (F=5.8, p=0.04) and a main effect of gloves (F=40.3, p=0.00) on manual dexterity score. Scores were approximately 45% lower when wearing gloves. There was also a significant interaction between the effects of pressure and gloves. Hence, data were analyzed for simple effects to identify contrasts between conditions 1 and 3; 2 and 4; and 3 and 4. When divers were not wearing gloves (conditions 1 and 3), there was no significant difference in score due to pressure, indicating that there was no effect of narcosis on manual dexterity score. When wearing gloves (conditions 2 and 4), score increased 56% from 5.5 at 0.4 msw to 8.6 at 40 msw (F=12.1, p<0.05). This improvement suggests that the interaction effect between pressure and gloves is due to compression of neoprene. Manual dexterity scores were significantly lower in condition 4 than in condition 3 (F=5.6, p<0.05), confirming that the decrement associated with wearing gloves remains significant at pressure, despite the improvement due to compression of neoprene.

The number of nuts and bolts dropped by each diver (drops) was also analyzed. Mean data are provided in Table 5 and shown in Figure 8.

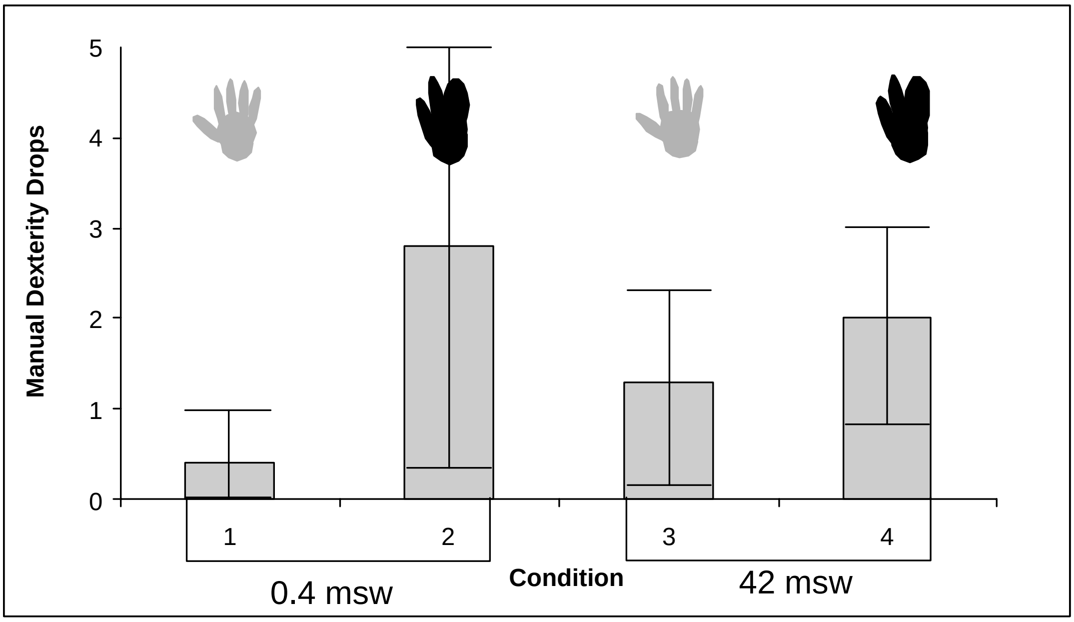


Figure 8: Effects of Pressure and Gloves on Manual Dexterity Drops

There was no significant difference in the number of nuts and bolts dropped reduces due to the effect of pressure. However, marginal means for each glove condition indicated that the number of nuts and bolts dropped was 280 % greater when wearing 3-fingered neoprene gloves (F=12.6, p=0.006). Although there was a trend towards an interaction between pressure and gloves, the effect was not significant (p = 0.07).

The effects of temperature and pressure on manual performance

Conditions 2 and 4 were compared with conditions 5 and 6 to identify the effects of cold when wearing gloves, and the combined effects of cold and compression. The effects of temperature and pressure on grip strength, tactile sensitivity and manual performance are provided in Tables 6, 7 and 8.

Table 6: Effects of Temperature and Pressure on Grip Strength (Newtons)

	Grip Strength (n=9)			
	25°C		4°C	
0.4 msw	320.8 ±52.9		324.7 ±187.4	
40 msw	359.0 ±57.9		310.0 ±124.6	
Statistics				
	F	Sig.	η^2	Power
Main Effect Cold	0.2	0.64	0.03	0.07
Main Effect Pressure	0.3	0.62	0.03	0.07
Interaction Cold x Pressure	1.8	0.216	0.19	0.23

Table 7: Effects of Temperature and Pressure on Tactile Sensitivity

	Tactile Sensitivity (n=9)							
	Score (letters correct)				**Accuracy**			
	25°C		4°C		25°C		4°C	
0.4 msw	21.6 ±11.9		12.0 ±8.2		0.78 ±0.1		0.82 ±0.3	
40 msw	24.0 ±10.1		13.0 ±11.1		0.82 ±0.1		0.69 ±0.4	
Statistics								
	F	Sig.	η^2	Power	F	Sig.	η^2	Power
Main Effect Cold	23.2	0.001	.074	0.99	0.2	0.70	0.02	0.06
Main Effect Pressure	1.2	0.31	0.13	0.16	2.3	0.16	0.23	0.27
Interaction Cold x Pressure	0.1	0.72	0.02	0.06	1.4	0.27	0.15	0.18

Table 8: Effects of Temperature and Pressure on Manual Dexterity

	Manual Dexterity (n=9)							
	Score (number of not-bolt combinations completed)				Drops (number of nuts or bolts dropped)			
	25°C		4°C		25°C		4°C	
0.4 msw	5.2 ±1.3		5.3 ±2.5		3.0 ±2.4		2.7 ±1.8	
40 msw	7.8 ±2.1		5.2 ±1.9		1.9 +1.2		3.2 ±2.0	
Statistics								
	F	Sig.	η^2	Power	F	Sig.	η^2	Power
Main Effect Cold	7.7	0.02	0.49	0.68	0.6	0.48	0.07	0.10
Main Effect Pressure	15.2	0.005	0.66	0.93	0.6	0.48	0.07	0.10
Interaction Cold x Pressure	17.1	0.003	0.68	0.95	1.1	0.32	0.12	0.16

Grip Strength

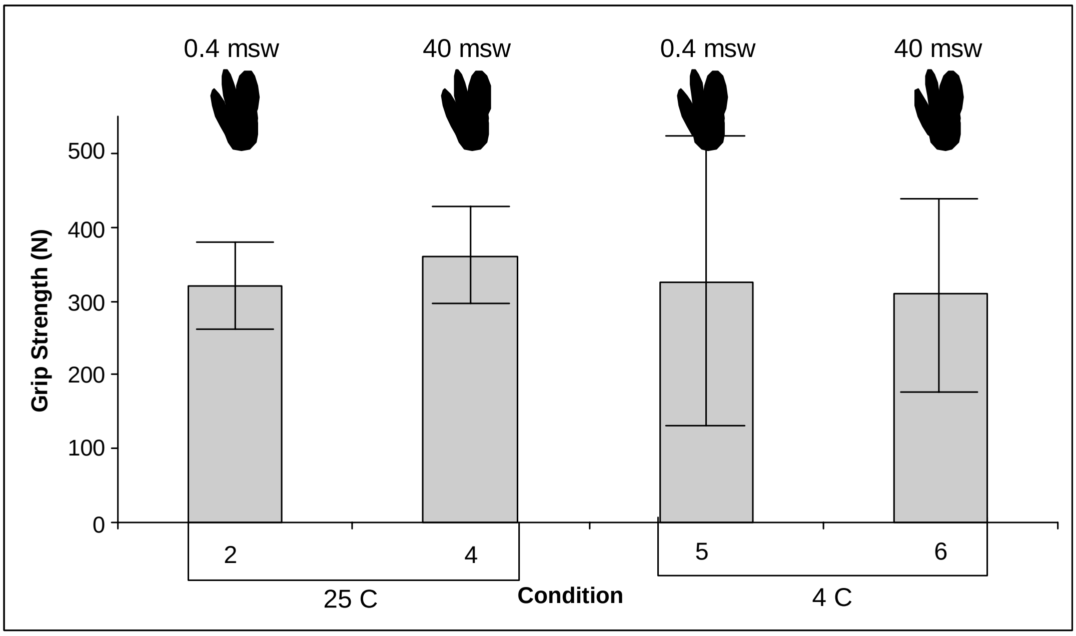


Figure 9: Effects of Temperature and Pressure on Grip Strength

The means and standard deviations of grip strength are provided in Table 6, and shown in Figure 9. Results indicate that there were no main effects and no interaction effect of temperature and pressure on grip strength when wearing gloves.

Tactile Sensitivity

Mean tactile sensitivity scores are provided in Table 7, and shown in Figure 10.

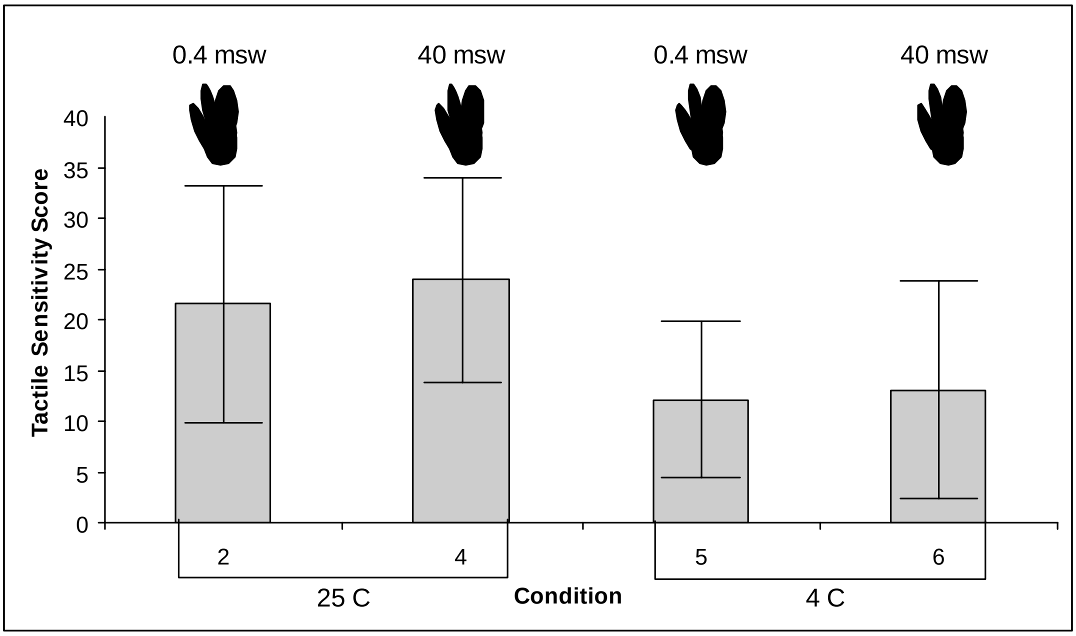


Figure 10: Effects of Temperature and Pressure on Tactile Sensitivity Score

Results show that there was a main effect of temperature on tactile sensitivity score. The marginal mean score (averaged over both pressures) was reduced from 22.8 in 25°C water to 12.5 after approximately 20 minutes of immersion in 4°C water (F=23.2, p=0.001). Analysis indicates that 74% of the variance in tactile sensitivity score is explained by the effect of temperature (η^2=0.74). There was no main effect of pressure and no interaction effect between temperature and pressure.

The accuracy of tactile sensitivity responses are presented in Table 7 and shown in Figure 11. There were no significant differences in accuracy of tactile sensitivity responses due to the effects of temperature or pressure. This result indicates that the decrease in tactile sensitivity score in 0.4°C water is due to a slowing of performance.

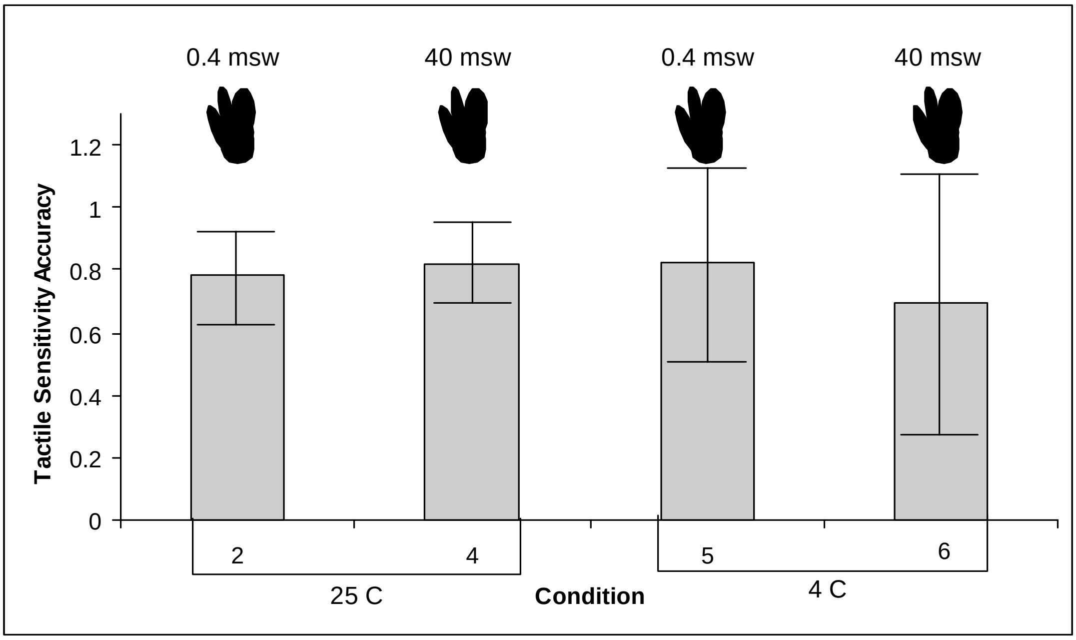


Figure 11: Effects of Temperature and Pressure on Tactile Sensitivity Accuracy

Manual Dexterity

The mean manual dexterity scores are provided in Table 8 and shown in Figure 12.

There was a main effect of temperature on manual dexterity score (F=7.7, p=0.02). There was also a main effect of pressure (F=15.2, p=0.005), and an interaction between the effects of temperature and pressure (F=17.1, p=0.003). Data were analyzed for simple effects. There was an increase in manual dexterity score in condition 4 vs. 2 (F=12.1, p<0.05) indicating an effect of pressure in 25°C water, but no significant difference between manual dexterity scores in conditions 5 and 6 (F=12.0, p<0.05). Manual dexterity scores were significantly lower in condition 6 than in condition 4 (F12.0, p<0.05) indicating an effect of cold at 40 msw. In contrast, there was no significant effect of cold on manual dexterity at 0.4 msw.

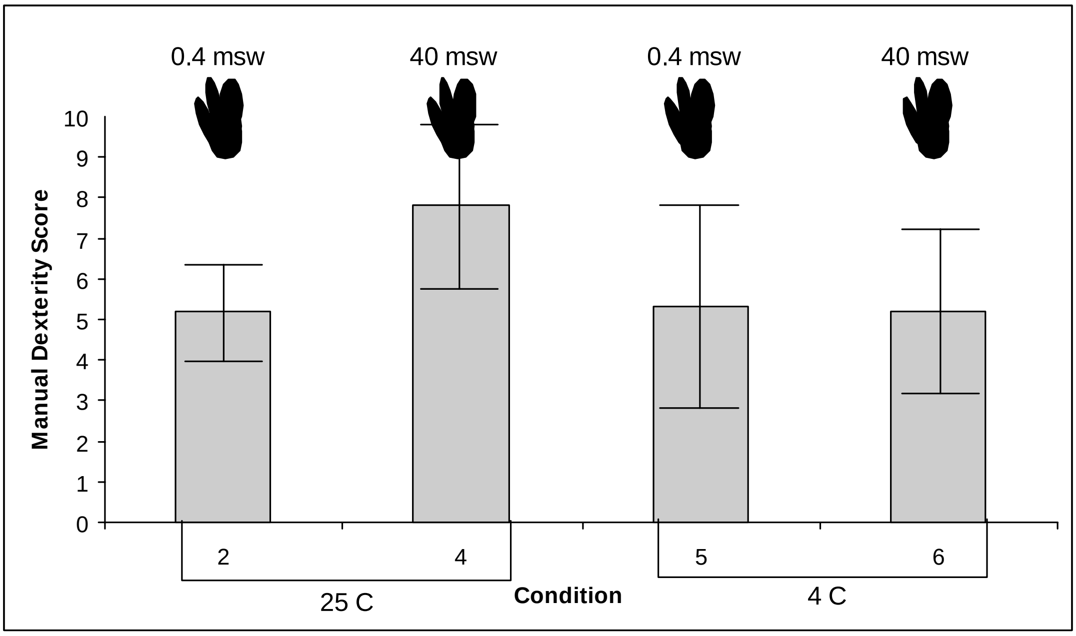


Figure 12: Effects of Temperature and Pressure on Manual Dexterity Score

The number of nuts and bolts dropped by each diver was also analyzed. Results are shown in Table 8 and Figure 13. There were no significant differences in the number of drops due to the effects of temperature or pressure. Lack of significant findings are likely due to the low number of drops and a high variability in the data.

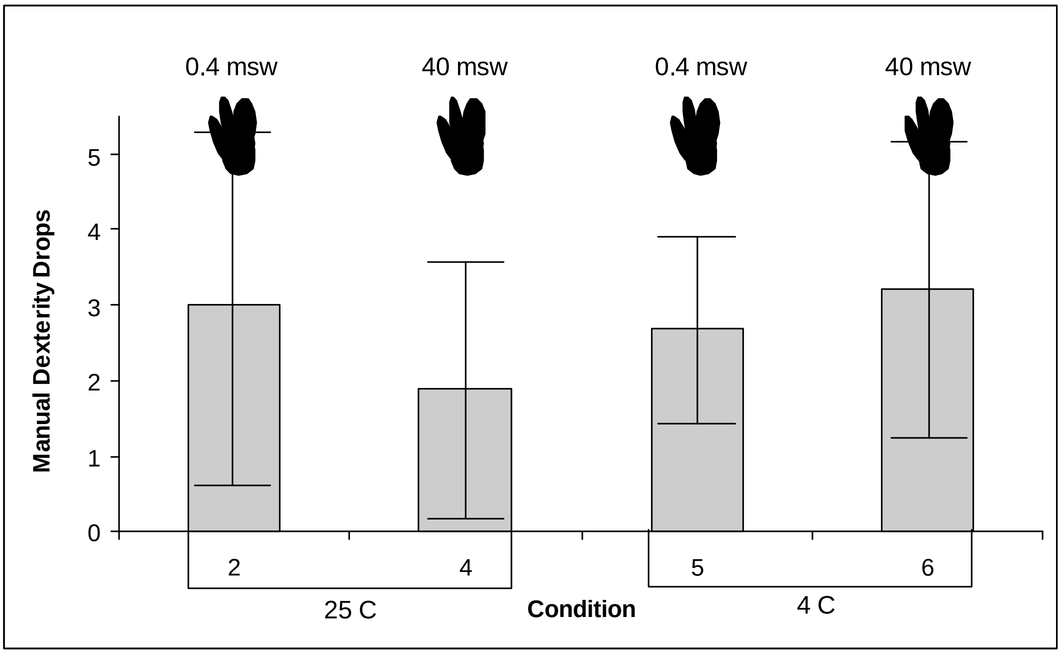


Figure 13: Effects of Temperature and Pressure on Nut or Bolt Drops

The Effects of Character Size on Tactile Sensitivity Scores

Tactile sensitivity data were further analyzed to determine the effect of character size (tab size or spacing) on tactile sensitivity when wearing gloves in cold water. The tactile sensitivity score and accuracy for each row were analyzed for conditions 5 and 6. Results are presented in Tables 9 and 10 and shown in Figures 14 and 15.

Table 9: Effect of Row (Braille tab size and spacing) on Tactile Sensitivity Score when wearing Neoprene Gloves in Cold Water

Tactile Sensitivity Score (4 °C water)									
Tab Size (mm)	Spacing (mm)	0.4 msw				40 msw			
11	28.0	3.9±2.1				4.0±2.4			
6.5	16.0	4.6±3.6				4.6±3.8			
5	12.5	2.7±2.6				3.3±4.0			
3.0	7.5	0.33±0.5				1.4±2.2			
		0.4 msw				**40 msw**			
Statistics		F	Sig.	η^2	Power	F	Sig.	η^2	Power
main effect		11.0	0.00	0.6	1.0	4.6	0.00	0.4	0.8
Regression		$y = -0.2x^2 + 2.7x - 6.4$				$y = -0.1x^2 + 2.1x - 3.7$			
		$R^2 = 0.98$				$R^2 = 0.99$			

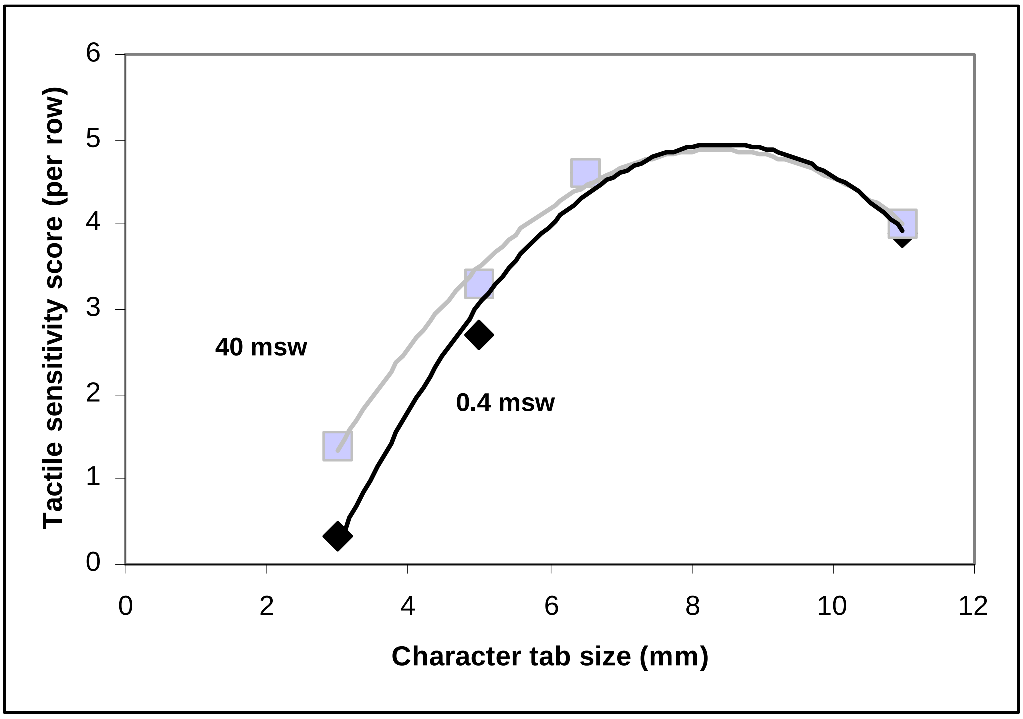


Figure 14: Effect of Tab Size on Tactile Sensitivity Score when wearing Neoprene Gloves in Cold Water

There was a main effect of character size (tab size and spacing) on tactile sensitivity score at both 0.4 and 40 msw (F=11.03, p=0.00; F=4.6, p=0.00). The highest score for both conditions was for the second largest character size (6.5 mm tabs). Post hoc analyses showed that scores for 6.5 mm tabs were significantly higher than for 5.0 mm tabs (p=0.03), but were not significantly different from the largest, 11.0 mm tabs.

Regression analysis of tactile sensitivity score (y) as a function of tab size (x) showed that the relationship to tab size is nonlinear, with a second order polynomial providing a good fit to the tactile sensitivity score data at both pressures (R^2=0.98 and R^2=0.99). This analysis is limited because only four tab sizes were tested. However, Figure 14 suggests an optimal tab size of approximately 8.0 mm at both pressures

Table 10: Effect of Row (Braille tab size and spacing) on Accuracy of Tactile Sensitivity when wearing Neoprene Gloves in Cold Water

Tactile Sensitivity Accuracy (4°C water)									
Tab Size (mm)	Spacing (mm)	0.4 msw				40 msw			
11	28.0	0.75±0.3				0.63±0.4			
6.5	16.0	0.55±0.3				0.63±0.4			
5	12.5	0.46±0.4				0.41+0.4			
3.0	7.5	0.07±0.1				0.14±0.2			
		Condition 5				**Condition 6**			
Statistics		F	Sig.	η^2	Power	F	Sig.	η^2	Power
main effect		13.7	0.00	0.63	1.00	8.6	0.00	0.52	0.98
Regression		$y = -0.02x^2 + 0.3x - 0.9$				$y = -0.02x^2 + 0.4x - 0.9$			
		$R^2 = 0.97$				$R^2 = 0.99$			

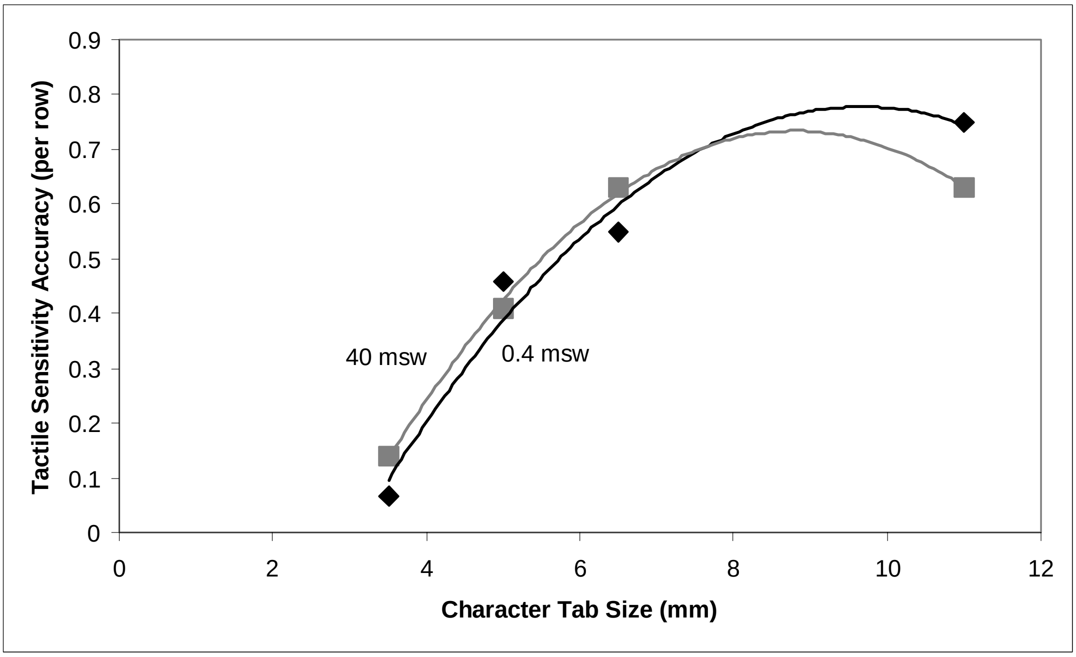


Figure 15: Effect of Tab Size on Accuracy of Tactile Sensitivity when wearing Neoprene Gloves in Cold Water

There was a main effect of character size (tab size and spacing) on tactile sensitivity accuracy at both pressures (F=13.7, p<0.01; F=8.6, p<0.01). The largest tab size (11 mm) had significantly higher accuracy (p=0.02) than the second largest (6.5mm) at 0.4 msw, but there was no significant difference between the 11mm and 6.5 mm tabs at 40 msw. There was no significant difference in accuracy between the two middle character sizes (6.5 and 5.0 mm) in either pressure condition.

The regression analysis of tactile sensitivity accuracy (y) as a function of tab size (x) showed that the relationship to tab size is nonlinear, with a second order polynomial providing a good fit to the tactile sensitivity accuracy data at both pressures (R^2=0.97 and R^2=0.99). As shown in Figure 15, the regression analysis predicts an optimal tab size of approximately 9.0 mm and 10 mm at 0.4 and 40 msw respectively.

Divers were asked to rate their preference of the different character sizes. Overall, divers preferred the second largest character size (6.5 mm tabs), followed closely by the second smallest character size (5mm tabs). The least preferred size was the smallest character size (3.5 mm tabs).

Discussion

Results indicate that grip strength, tactile sensitivity and manual dexterity are not affected by narcosis at 40 msw. This conclusion is based on the results of conditions 1 and 3, when divers were not wearing gloves. This finding is supported by Fowler *et al*.(1985) who suggest that at depths of 40 msw, narcosis affects mainly cognitive tasks such as reasoning, rather than manual performance. Manual performance at 40 msw may also have been affected by the level of arousal. The divers who participated in this experiment did not have previous experience with diving in a hyperbaric chamber. It is likely that their level of arousal was increased at 40 msw and this probably affected their performance. Although arousal can reach a level where performance is impaired, the results of conditions 1 and 3 do not support this. It is likely that the increase in arousal helped to mitigate some of the negative performance affects of narcosis.

Wearing 3-fingered neoprene gloves in warm water is associated with decrements in all three components of manual performance. Manual dexterity and tactile sensitivity are most affected by wearing gloves (45% and 35% decrements respectively) followed by grip strength (23% decrement). The fact that the tactile sensitivity and manual dexterity tasks are more susceptible to wearing gloves was expected, since both tests required tactile feedback and fine manipulation, whereas grip strength depends mainly on forearm muscle force with relatively low need for tactile feedback or fine manipulation. When wearing gloves, the divers reported that identifying the embossed tabs required a higher finger pressure and was more fatiguing.

In warm water, the effect of pressure interacted with the effect of gloves for both grip strength and manual dexterity. Both measures showed an improvement at 40 msw when wearing gloves. The interaction effect is most likely due to the compression of the air spaces in neoprene and the resultant thinning of the neoprene (Morrison and Zander, 2005). The improvement in grip strength and manual dexterity between the surface and depth suggests that it is the bulkiness of the gloves that hinders manual performance. As the neoprene was compressed, it became thinner, and also fit more tightly onto the wearer's hand, improving the fit of the glove. Bradley (1969) suggests that manual performance when wearing gloves was affected by four factors: tenacity, snugness, suppleness and protectiveness. The improved performance at 40 msw was most likely influenced by the loss in protection combined with improved snugness (better fit). The gloves used were made from Rubatex G-231-N neoprene, which is designed to resist compression. Different neoprenes have different compression rates. Consequently, the depth effect on glove thickness will vary with differing neoprenes.

Tactile sensitivity and manual dexterity were both affected by cold when wearing gloves. There was a 45% decrease in tactile sensitivity scores in 4°C water, averaged over both pressures, suggesting that the insulation provided by neoprene gloves is insufficient to preserve hand temperature. The impairment of tactile sensitivity is most likely due to local cooling of the hand. As there was no significant effect of temperature on accuracy, impairment of tactile sensitivity was due primarily to a slowing in performance. At 40 msw there was a 33% impairment of manual dexterity due to cold, indicating that the insulation provided by the compressed neoprene gloves was inadequate. However, manual dexterity was not affected by cold at 0.4 msw, indicating that the insulation provided by the uncompressed gloves was adequate for this task.

Results show that when wearing neoprene gloves, pressure affects manual dexterity differently in the warm water than in the cold water. In 25°C water, manual dexterity scores were higher at 40 msw than at 0.4 msw, indicating an improvement in performance due to compression of neoprene. In 4°C water there was no significant difference in scores at 0.4

msw vs. 40 msw. Thus, in 4°C water, when comparing conditions 5 and 6, the expected improvement in manual dexterity due to compression of neoprene at 40 msw was negated by the antagonistic effect of cold. It is also possible that in condition 6 the combined effects of compression to 40 msw and exposure to 4°C water increased arousal to a level that contributed to performance decrement.

When viewed in conjunction, these data provide insight into the susceptibility of the different measures of manual performance (grip strength, tactile sensitivity and manual dexterity) to the independent and combined effects of the environmental stressors.

Grip strength represents a motor component of manual performance, and it is the least effected by environmental stressors. The only factors that significantly affected grip strength was the use of 3-fingered neoprene gloves and compression of neoprene in 25°C water. In 4°C water there was no improvement effect of compression of neoprene, most likely due to the antagonistic effects of cold. However, exposure to cold did not significantly affect grip strength. This suggests that for a duration up to 27 minutes, 3-fingered neoprene gloves provide sufficient insulation for divers performing basic motor tasks, such as gripping a handgrip tool.

Tactile sensitivity represents a psycho-sensory component of manual performance. The test used in this study also had a cognitive component, as the diver was required to match Braille characters sensed by touch with visual representations of the characters. Tactile sensitivity was affected by the use of gloves, the compression of neoprene, and exposure to cold but was not significantly affected by narcosis.

Manual dexterity, a psychomotor component of manual performance, was affected by all environmental stressors, except narcosis. However, unlike tactile sensitivity, the effect of cold was only apparent at 40 msw where neoprene gloves were compressed, reducing their insulative properties.

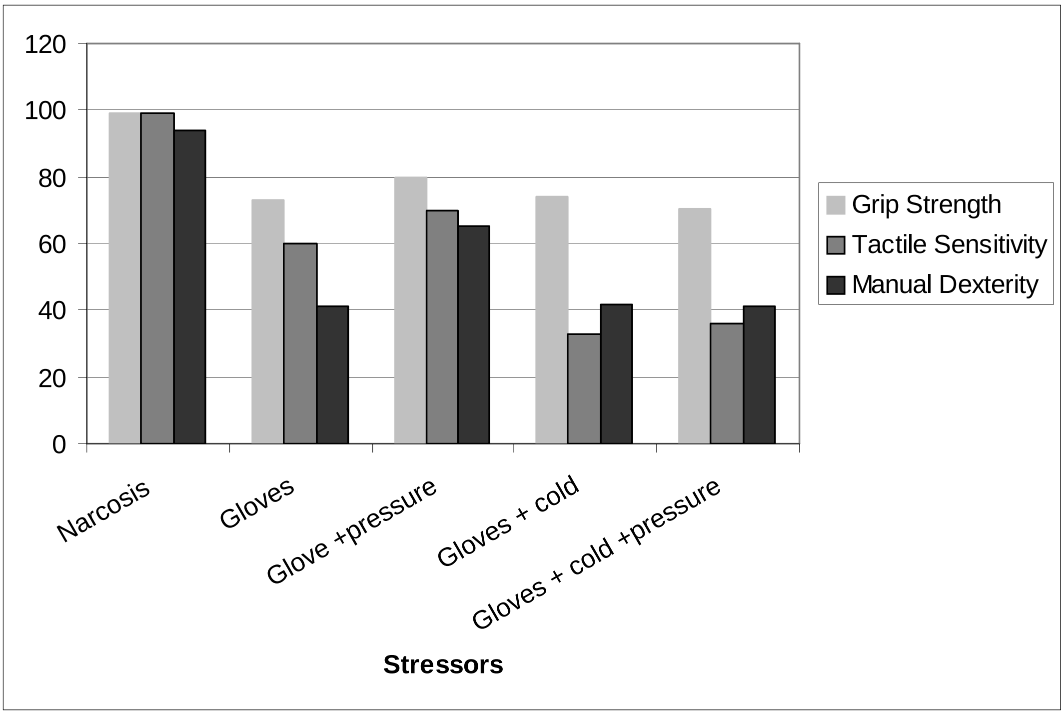


Figure: 16 Independent and Combined effects of Environmental Stressors (% impairment) on Components of Manual Performance.

Figure 16 displays both the independent and combined effects of the environmental stressors on the three components of manual performance. It is clear that the combined effect of stressors is not additive. This can be explained by the antagonistic effects of compression of neoprene and cold.

Of the three components of manual performance, tactile sensitivity likely has the highest dependence on finger temperature. Similarly, the absence of a cold effect on grip strength may be explained by its dependence on deep muscle temperature of the forearm, which will have a slower rate of cooling. In contrast, manual dexterity has the greatest requirement for manipulation, and hence is more susceptible to the resistive effects of the gloves. The component of manual performance that shows the greatest impairment due to cold is tactile sensitivity (Figure 16) whereas manual dexterity is the component that is more impaired by gloves and most enhanced by compression of neoprene.

Figure 16 shows that Condition 5 and 6 (gloves, cold, and pressure,) are associated with the largest decrements in performance, with >60% decrement in tactile sensitivity and manual dexterity. These conditions represent a typical diving environment in Canadian waters. Thus, equipment should be designed to match the capabilities of divers in these conditions.

Design of equipment and controls for use underwater

An underlying goal of this study was to provide insight into the design of controls for use underwater. The finding that grip strength may be reduced to approximately 70% of normal due to the combined effects neoprene gloves and cold should be taken into account in the design of equipment and tools that require activation by the diver. The amount of grip strength required to operate a tool is a function of weight, balance, grip shape, and friction (tenacity) between the tool and glove. Thus, the grip strength required to operate underwater tools can be reduced by designing the tools to be neutrally buoyant, with the hand grip arranged close to the center of mass of the tool. To accommodate the bulkiness of the glove, the handgrip should be larger than recommended in normal ergonomic guidelines for the human hand. Guidelines for appropriate handle design when wearing protective gloves are available in ergonomic literature (Pheasant, 1996). Handgrips should also be designed to provide a high coefficient of friction (tenacity) to the glove to minimize the required grip force. Alternatively, the glove surface could be designed to have a higher tenacity by applying a high friction material to the surface of the glove.

Tactile sensitivity is particularly important to the capabilities of divers when operating multi-function controls such as keypads. In this study, the ability of divers to differentiate the embossed tabs in the Braille character set is, to an extent, analogous to the ability to differentiate between keys on a keypad. For this reason, the analysis of tactile sensitivity was focused on identifying the smallest tab and character size that divers could accurately differentiate. Results showed that divers achieved the highest score for the two largest Braille character sizes. At 40 msw the largest character size (11 mm tabs by 28 mm spacing between tabs) showed no gain in speed or accuracy over the second largest (6.5 mm by 16 mm spacing). The larger size presents a greater ergonomic burden in the form of a large control pad. Regression analysis of performance data suggests an optimum size of 8 to 10 mm. However, subjective data indicated that the divers preferred the tab size and spacing of the second largest row. It is recommended that underwater controls should have minimum size and spacing characteristics not less than those of the second largest character set (6.5 mm tabs x 16 mm spacing). Hence, when designing a keypad for underwater use, the minimum size of each key or control should be 6.5 mm, but ideally should be 8 to 10 mm, and the minimum space between two keys should be at least 16mm. It is proposed that this recommendation should be tested in a separate study to evaluate the optimum size and spacing of underwater keypads.

This study used manual dexterity to measure the ability of divers to pick up and manipulate small objects. Results showed almost a 60% decrement in manual dexterity due to exposure to narcosis, compression of neoprene gloves, and cold. This relates to the divers ability to manipulate controls and equipment; however, the extent of the decrement in manual dexterity reported should be used with caution when designing controls as it is likely to be a function of control size. In this study, divers were manipulating 11mm (7/16 inch) nuts and bolts; for controls having a smaller footprint it is likely that the performance decrement would be considerably larger. Therefore, it is suggested that equipment controls (or other tools or objects that must be manipulated by the diver) should have a minimum dimension of 12 mm (1/2 inch). Controls that have to be activated in emergency situations, should be substantially larger (2 to 4 times) than the minimum dimension of 12 mm. This recommendation is in good agreement with the US Mil. Std. (1999), that emergency buttons should be at least 26 mm diameter with 52 mm spacing.

Results also show that when wearing neoprene gloves and diving to 40 msw in 4^{o}C water, the effects of compression of neoprene and loss of insulation are antagonistic on manual performance. Hence, there were no changes in the three components of performance between 0.4 msw and 40 msw. This suggests that testing of equipment and controls in cold water at surface pressure can provide a good prediction of performance at depth. This finding simplifies the environmental requirements for initial ergonomic testing of prototypes of underwater equipment and controls.

The overall findings of this study show that the manual performance capabilities of divers operating in cold waters are impaired by up to 60%. When new equipment and controls are designed for divers, these decrements should be considered and incorporated into a user centered design and usability testing process that includes the appropriate environmental stressors to which the divers are exposed.

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(U) With the introduction of new communications and display technologies, the ability of divers to operate complex controls becomes an important factor in systems design. This study evaluates the effects of pressure, gloves, and cold on three components of manual performance: grip strength, tactile sensitivity and manual dexterity. Performance was evaluated at 0.4 and 40 msw: with and without gloves in 25oC water, and with gloves in 4oC water. Results show that narcosis did not affect manual performance at 40 msw ($p>0.05$). In 25 oC water, three fingered neoprene gloves caused a significant impairment of grip strength (23%), tactile sensitivity (35%) and manual dexterity (45%). There was an interaction effect between gloves and pressure, with the compression of neoprene providing an improvement in grip strength and manual dexterity at 40 msw. Tactile sensitivity and manual dexterity were both affected by cold at 40 msw when wearing gloves ($p < 0.05$). The combined effects of gloves, pressure and cold water resulted in a 30% decrement in grip strength and a 60% decrement in tactile sensitivity and manual dexterity. Based on these findings, ergonomic recommendations are made for design and usability testing of underwater equipment and controls.

(U) L'arrivée de nouvelles technologies de communication et d'affichage fait en sorte que l'aptitude des plongeurs à utiliser des systèmes de commande complexes constitue un facteur important de la conception des systèmes. La présente étude évalue les effets de la pression, des gants et du froid sur les trois composantes de la dextérité, soit : la force de préhension, la sensibilité tactile et la dextérité proprement dite. Le rendement (en anglais performance ou p) a été évalué à des profondeurs de 0,4 m et de 40 m : avec et sans gants dans l'eau à une température de 25 ºC et avec gants dans l'eau à une température de 4 ºC. Les résultats montrent que « l'engourdissement » n'avait pas d'incidence sur la dextérité à une profondeur de 40 m ($p > 0,05$). Dans l'eau à 25 ºC, les gants en néoprène à 3 doigts ont entraîné une diminution significative de la force de préhension (23 %), de la sensibilité tactile (35 %) et de la dextérité (45 %). On a relevé une interaction entre les gants et la pression, la compression du néoprène améliorant la force de préhension et la dextérité à une profondeur de 40 m. Chez les plongeurs portant les gants à une profondeur de 40 m, le froid a diminué la sensibilité tactile et la dextérité ($p < 0,05$). Les effets combinés des gants, de la pression et de l'eau froide ont entraîné une diminution 30 % de la force de préhension et de 60 % de la sensibilité tactile et de la dextérité. Comte tenu de ces résultats, des recommandations en matière d'ergonomie ont été faites en vue de soumettre à des essais de conception et d'utilisabilité les commandes et l'équipement de plongée.

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(U) underwater; diving; divers; immersion; dexterity; skin temperature; hyperbaric; grip strength; tactile sensitivity; gloves; hand; narcosis; ergonomic