Investigation of button size and spacing for underwater controls

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Abstract

This study was designed to identify the optimal size and spacing of push-button controls for use by divers when wearing neoprene gloves in cold water. Four keypads having different size and spacing of buttons were tested in three environmental conditions. Ten subjects completed two different tests of speed and accuracy in air and in 25°C water with no gloves and in 4°C water with neoprene gloves. Results showed that there were main effects of keypad size and environment on performance and an interaction effect between keypad and environment. Responses were slower and less accurate in 4°C water with gloves than in air or 25°C water ($p<0.05$). Responses were also slower in 25°C water than in air ($p<0.05$). A keypad having 10 mm button size and 20 mm spacing (centre to centre) was found to be optimal when wearing gloves in cold water; there was no significant improvement in performance with larger keypads. Using a stylus to operate a smaller keypad improved accuracy when wearing gloves in 4°C water, but proved impractical without ergonomic design improvements. It is concluded that keypads designed for use in air are not optimal for use underwater.

Résumé

La présente étude visait à déterminer la taille optimale et l'espacement des boutons-poussoirs des commandes utilisées par les plongeurs portant des gants de néoprène en eau froide. Quatre claviers dotés de boutons de taille et d'espacement différents ont fait l'objet d'essais dans trois conditions environnementales. Dix sujets ont effectué deux essais différents de vitesse et de précision dans l'air et dans l'eau à 25 ºC, sans gants, et dans l'eau à 4 ºC, avec gants de néoprène. Les résultats ont montré que la taille du clavier et l'environnement avaient des effets sur le rendement, et qu'il y avait une interaction entre le clavier et l'environnement. Les réactions étaient plus lentes et moins précises dans l'eau à une température 4 ºC, lorsque les sujets portaient des gants, que dans l'air ou dans l'eau à 25 ºC ($p < 0,05$). Les réactions étaient aussi plus lentes dans l'eau à 25 ºC que dans l'air ($p < 0,05$). On a constaté qu'un clavier doté de boutons de 10 mm et espacés de 20 mm (entraxe) constituait la solution optimale pour les plongeurs portant des gants en eau froide; des claviers plus gros n'amélioraient pas le rendement de façon significative. L'emploi d'un stylet avec des claviers plus petits a amélioré la précision des utilisateurs portant des gants dans l'eau à une température de 4 ºC, mais leur emploi ne s'est pas révélé pratique à moins que des améliorations ne soient apportées à l'aspect ergonomique. Il en est conclu que les claviers conçus pour une utilisation dans l'air ne sont pas la solution optimale pour un usage dans des activités sous-marines.

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Executive summary

Introduction: Underwater communications and displays are important issues for divers. The advent of new technology has made more sophisticated communication and display systems available for use underwater. However, these systems often require the diver to operate a complex array of controls. There are many factors in the underwater environment that influence the ability of divers to operate controls. This study forms part of a larger project to provide design guidelines for underwater information displays and controls.

Methods: This study was designed to identify the optimal size and spacing of push-button controls for use by divers when wearing neoprene gloves in cold water. Four keypads having different size and spacing of buttons were tested in three environmental conditions. Ten subjects completed two different tests of speed and accuracy in air, in 25°C water with no gloves and in 4°C water with 3-fingered neoprene gloves.

Results: Results showed that there were main effects of keypad size and environment on performance and an interaction effect between keypad and environment. Response times were slower and less accurate in 4°C water than in air or 25°C water ($p<0.05$). Response times were also slower in 25°C water than in air ($p<0.05$).

Significance: A keypad having 10 mm button size and 20 mm spacing (centre to centre) was found to be optimal when wearing neoprene gloves in cold water; there was no significant improvement in performance with larger keypads. Using a stylus to operate the smallest keypad improved accuracy when wearing gloves in 4°C water, but proved impractical without ergonomic design improvements. It is concluded that keypads designed for use in air are not optimal for use underwater. This information was used to design an underwater keypad for a subsequent study that tested different methods of communicating between the mine countermeasures diver and dive supervisor.

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Sommaire

Introduction. Les moyens de communication et d’affichage sous l’eau sont des questions importantes qui préoccupent les plongeurs. L’arrivée de nouvelles technologies a permis de mettre au point des systèmes de communication et d’affichage plus perfectionnés pouvant être employés dans des activités sous-marines. Toutefois, ces systèmes exigent souvent du plongeur qu’il manipule un ensemble de commandes complexes. De nombreux facteurs dans l’environnement sous-marin influent sur l’aptitude des plongeurs à utiliser les commandes. La présente étude fait partie d’un projet de plus grande envergure visant à présenter des directives pour la conception de dispositifs sous-marins de commande et d’affichage de l’information.

Méthodes. La présente étude visait à déterminer la taille optimale et l’espacement des boutons-poussoirs des commandes utilisées par les plongeurs portant des gants de néoprène en eau froide. Quatre claviers dotés de boutons de taille et d’espacement différents ont fait l’objet d’essais dans trois conditions environnementales. Dix sujets ont effectué deux essais différents de vitesse et de précision dans l’air et dans l’eau à 25 ºC, sans gants, et dans l’eau à 4 ºC, avec gants de néoprène à 3 doigts.

Résultats. Les résultats ont montré que la taille du clavier et l’environnement avaient des effets sur le rendement, et qu’il y avait une interaction entre le clavier et l’environnement. Les réactions étaient plus lentes et moins précises dans l’eau à une température 4 ºC que dans l’air ou dans l’eau à 25 ºC ($p < 0,05$). Les réactions étaient aussi plus lentes dans l’eau à 25 ºC que dans l’air ($p < 0,05$).

Portée. On a constaté qu’un clavier doté de boutons de 10 mm et espacés de 20 mm (entraxe) constituait la solution optimale pour les plongeurs portant des gants en eau froide; des claviers plus gros n’amélioraient pas le rendement de façon significative. L’emploi d’un stylet avec des claviers plus petits a amélioré la précision des utilisateurs portant des gants dans l’eau à une température de 4 ºC, mais leur emploi ne s’est pas révélé pratique à moins que des améliorations ne soient apportées à l’aspect ergonomique. Il en est conclu que les claviers conçus pour une utilisation dans l’air ne sont pas la solution optimale pour un usage dans des activités sous-marines. Ces renseignements ont servi à concevoir un clavier d’usage sous-marin en vue d’une étude subséquente ayant porté sur l’essai de diverses méthodes de communication entre un plongeur de lutte contre les mines et le superviseur de plongée.

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Introduction

Underwater communications and displays are important considerations for divers. In many cases, the only link between the diver and the surface is via communications equipment. Ideally, the diver should be provided with well designed communications and displays for accessing information about his environment and his equipment, and for communicating information to the surface personnel. The communication and display system should be equipped with appropriate controls that allow the diver to operate the system easily and efficiently. The main objective of this study was to identify the optimal size and spacing of push-button controls for underwater use.

Recent advances in technology have seen the development of multi-function head-down displays (HDD) and helmet-mounted displays (HMD). These systems include a number of controls that allow the diver to adjust and select the information displayed. Controls range from simple push buttons, used in the US Navy monocular and binocular head mounted displays, to more complex keyboard systems used in the Sea PC and the Kongberg Simrad PC (Morrison and Zander, 2005a). Previous research has shown that there are significant impairments of tactile sensitivity and manual dexterity when diving in cold water and wearing protective neoprene gloves (Morrison and Zander, 2005b). It is unrealistic, therefore, to expect a diver working in cold water to be able to operate the controls of a communication system that is designed for use in an air environment. If the diver is to operate efficiently, the communication system must have controls that are designed specifically for his environment.

Review of the literature suggests that push-buttons used in conjunction with legend switches are the optimal control choice for use underwater (US Mil. Std. 1472C, 1999). Legend switches include the use of indicator lights to show when buttons have been depressed successfully and/or the status of the function or output that the button controls. Push buttons are used where a control or array of controls requires momentary contact to activate a response (US Mil. Std. 1472C, 1999). Push-buttons are generally used when each button represents a separate response, but can also be used to cycle through options (Rodgers & Eggleton, 1983). For optimal efficiency, push-buttons should be accompanied by a legend switch, or other form of display such as HDD or HMD, that shows the response to the operator. Additional positive feedback, such as legend switches, is recommended for situations where the operator must know immediately if the system is malfunctioning.

In a pilot study (Zander, 1999) it was determined that when using push-buttons in an underwater environment, cues and positive feedback are critical to the usability of the system. Users reported that poor visibility and reduced tactile sensitivity when wearing gloves made operating push-button controls more difficult underwater compared to an air environment. Push-buttons with high visibility against the background colour of the control pad were preferred to low-contrast control pads. Push-buttons with physical feedback, such as an obvious click, or a tactile sensation such as a definite stop at the bottom position that could be physically felt through the gloves were preferred to push-buttons without an obvious physical cue to indicate proper activation.

Human factors guidelines may be consulted in the design of underwater controls, but they must be interpreted relative to the operational environment. There are many factors that are not present in a normal air environment that influence the ability of the diver to operate controls while underwater. The main factors that degrade the manual performance of the diver are: cold; narcosis; the use of protective gloves; decreased visibility; buoyancy in water; and pressure (Fowler *et al.*, 1985; Heus *et al*. 1995; Morrison & Zander, 2005b,c; Parsons and Eggerton, 1985). Some of these factors affect the diver directly (for example cold directly affects the manual performance capabilities of the diver) while others such as pressure act indirectly by increasing narcosis and changing the physical properties of the gloves. Morrison & Zander, 2005b measured a 60% impairment of manual dexterity when diving in cold water and wearing neoprene gloves.

Hancock and Milner (1986) and Baddeley and Idzikowski (1985) have both estimated that there is a decrement in manual performance (measured as the ability to use a Purdue Peg Board or Screw-plate Test) related to operating in the underwater environment. Baddeley and Idzikowski (1985) estimate that the decrement is approximately 15%, thus, scores of speed and efficiency decrease appropriately 15% just because they are completed underwater. These tests were completed in controlled environments; they do not reflect the decrement in performance due to protective clothing, degraded vision, cold, anxiety or pressure.

In a separate study (Morrison and Zander 2005d) the authors investigated three different signaling systems for diver-to-supervisor communication. These included traditional rope pulls, an electronic push-button using the same coding as rope pulls, and a twelve-button keypad and HDD with which text messages were relayed between the diver and supervisor as a series of acronyms displayed on a HDD. In order to design a suitable keypad for these experiments it was necessary first to determine the optimal button size that divers could operate when wearing three-fingered neoprene gloves in cold water, while at the same time minimizing the keyboard size. The present study was initiated to determine the optimum button size and spacing for underwater keyboards and control pads.

Objectives

This study had three main objectives:

1. To identify the effect of the underwater environment on the ability of divers to operate a push-button keyboard;

2. To identify the optimal push-button size and spacing for operation in realistic cold water diving conditions;

3. To determine if it is practical to use a stylus to operate a small keypad when wearing neoprene gloves in cold water diving conditions.

Methods

Subjects

Eleven male and female subjects between the ages of 20 to 40 years participated in the experiment. Each subject was provided with a description of experimental procedures and of any risks as well as the potential benefits derived from this research. Subjects signed an informed consent form prior to participation. Experimental procedures used in this experiment were approved by the Ethics Review Committee of Simon Fraser University.

Environmental Conditions

There were three environmental conditions for this experiment:

1. bare hands in 21 ±1°C air

2. bare hands in 25 ±1°C water; and

3. gloved hands (3 finger neoprene gloves) in 4°C water.

The conditions were selected to represent realistic diving operations. The first condition, bare hands in 21°C air, was used to collect baseline data.

Condition 2, bare hands in 25°C water, represented tropical diving conditions, where divers did not wear protective gloves. By comparing the baseline data to data collected in condition 2, it was possible to identify the water effect on ability to operate push-buttons.

The third condition, wearing three-fingered neoprene gloves in 4°C water represented typical Canadian diving conditions. The effect of cold on manual performance when wearing protective gloves is known to be time dependent (Morrison and Zander, 2005c). Therefore, subjects had their gloved hands immersed in 4°C water for approximately 20 minutes prior to collecting data for the third condition. Comparing conditions 2 and 3 provided information on the ability to operate push buttons in different diving conditions. Data from conditions 2 and 3 were used to identify the optimal push-button size and spacing configuration for diving equipment.

Apparatus

The apparatus consisted of a laptop computer, an underwater head-down display and a twelve-button keypad. The keypad was selected from a set of four, each having a different button size and spacing. The display acted as a remote monitor controlled by output from the laptop computer, and is described in Morrison and Zander (2005a). The twelve-button keypad acted as a remote keyboard to the laptop computer and was attached to the computer via a USB port. The display was positioned approximately 40 cm from the subject's eyes, within their line of sight, and immediately above the keypad at a viewing angle of approximately 45 degrees below horizontal. The apparatus used by the subjects was similar in appearance to a miniature computer with a keypad and a screen. The layout of the apparatus is shown in figure 1. The apparatus was designed to provide visual stimulus to the user, who then reacted by depressing a specific button(s) on the keypad.

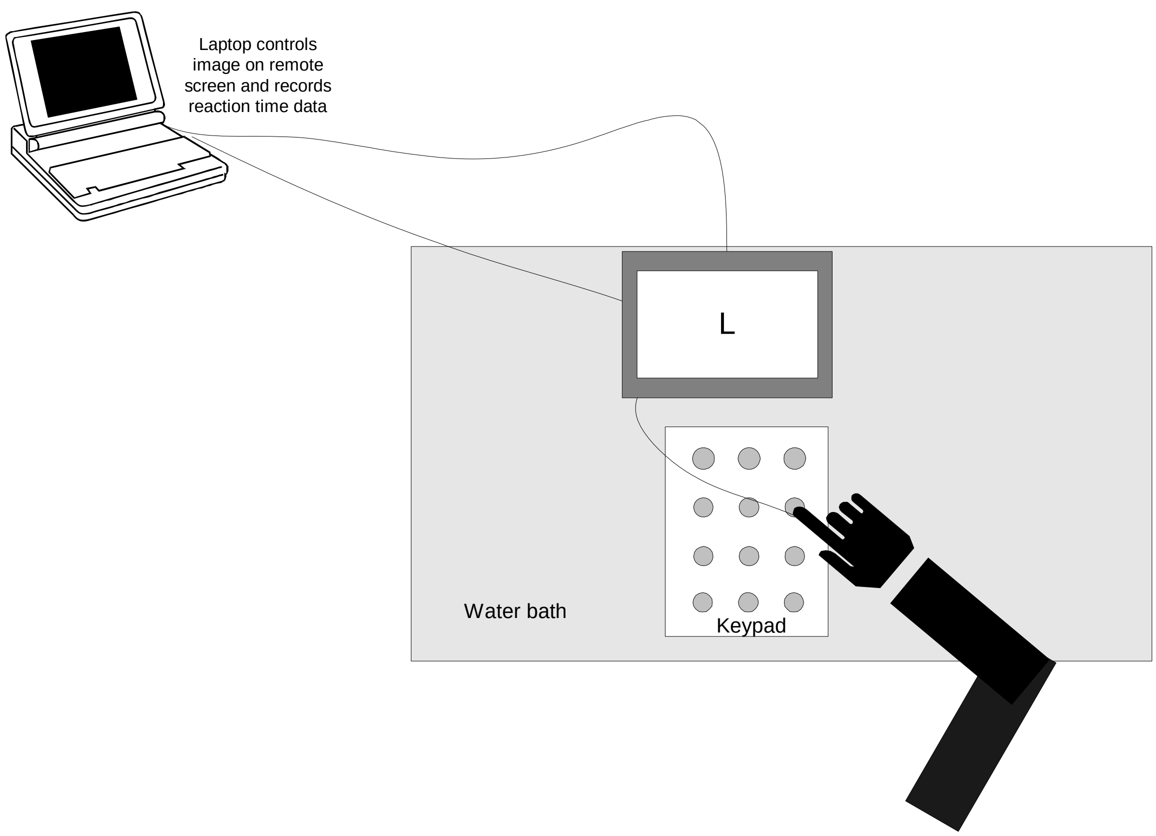

Figure 1: Experimental apparatus

In condition 1 the entire apparatus was out of the water. For conditions 2 and 3, the screen was out of the water, but the keypad and the subject's hands were immersed in a water filled glass tank (0.3 m width x 0.9 m length x 0.3 m depth). The subject was seated on a high stool and the tank was mounted on a surface chosen so that the water level was at approximately elbow height of the seated subject. The subject's arms were unsupported with the forearms angled downwards and hands immersed in water. The posture of the subject, keyboard height and display viewing angle were adjusted to approximate those of condition 1. In condition 3, the subjects wore 3-fingered neoprene gloves. The gloves were manufactured from 7 mm thick, Rubatex ® G-231-N neoprene, and were similar to those worn by Canadian forces MCM divers.

Each keypad shared the same design, the difference being the size and spacing of the push-buttons. Each keypad had 12 buttons, organized in four rows of three buttons. All four keypads had the same button size to space (separation distance) ratio. The size to space ratio was chosen because of its successful application in emergency equipment designed for an air environment (US Mil. Std. 1472C, 1999). These standards state that for emergency or alarm buttons, the diameter of the button should be at least 26 mm with 51 mm separation between the centers of adjacent buttons, roughly a 1:2 ratio.

When designing a multiple push-button portable control panel for divers, 26 mm push-buttons may not provide optimal performance, particularly when multiple controls are required. For example, a keypad for communication purposes could potentially have ten to twenty keys for data entry. 52 mm spacing will result in a cumbersome console that cannot be readily integrated with a diver's equipment. Ideally the keypad should be miniaturized and designed either to mount on the diver's wrist or forearm or to be a hand-held console that can be retrieved from a docking device (or pocket) on the diver's suit. This experiment was designed to identify the optimum size of push-buttons, maintaining the 1:2 button size to space ratio. As the size to space ratio has been shown to be successful for emergency conditions in an air environment, it is believed to be adequate for non-emergency functions in the underwater environment. Pilot testing indicated that this ratio is comfortable in the underwater environment, provided that the buttons are of adequate size (Zander, 1999).

The button size and space configurations used in this experiment are outlined in Table 1. The button sizes selected were based on pilot data collected to determine the approximate minimum and maximum size limits for an underwater keypad. The smallest button size was determined as the size at which a diver wearing gloves may select and depress a single button within an array. The largest button size was determined as the size beyond which there was no obvious gain in performance, and at which the equipment burden would become problematic to the diver (based on a 12 button keypad). It was hypothesized that as size and spacing increases beyond a certain limit, the ease and speed of selection will be offset by the travel time between buttons in multi-button keypads. Thus, as button size increases from small through large it might be expected that the performance would improve, plateau, and then eventually decrease, providing a U-shaped curve for response-time v. button size. In contrast, accuracy might be expected to improve and then plateau as button size increases. As the design constraints generally dictate that the control pad should be as small as possible, the experiment was designed to capture the increase and plateau in performance as a function of button size. The actual button sizes shown below were selected based on the closest match to the goal size that was commercially available, with the restraint that each button size should have a similar tactile design, travel and stiffness.

Table 1: Size and spacing for push-buttons

Keypad	Button Size (diameter, mm)	Button Spacing (center to center, mm)
1	5	10
2	10	20
3	15	30
4	22.5	45

Procedures

To avoid order effects (practice effect or fatigue effect) the order of the environmental conditions, and keypads within each condition, was varied across subjects. To avoid a learning effect, subjects were provided with adequate training time both in an air environment and in the water. Subjects were acclimatized to approximately 21°C room temperature (in an air environment) for 30 minutes prior to data collection. This time was used to brief the subject and provide time to practice the performance tests.

Subjects were asked to complete one set of Random Location Reaction Time (RLRT) and one set of Multiple Digit Commands (MCD) performance tests on each of the four keypads in all three environmental conditions. The performance tests are described in detail in the following section. The subjects completed the performance measures twice on keypad 1 (the smallest keypad), once using the index finger and once using a stylus to operate the buttons. The stylus was tested only on the smallest button configuration, as that represents its most realistic operational use. The subjects were seated, with both hands available for operating the keypad. Subjects required approximately 2 minutes to complete both the RLRT and MDC tests on one keypad. Performance tests using all five keypad options in each of the three environmental conditions were completed during a single experimental session.

The order of performance measure (i.e., RLRT and MDC) was consistent throughout all conditions. This was not considered to be a problem since the results of each test are independent and are not compared.

Performance Measures

1. Random Location Reaction Time (RLRT): A random location reaction time test was performed to measure the time required to locate and depress the appropriate button on a 12 button keypad. The keypad was fitted with an overlay that labeled each key with either a letter or a command. Nine of the keys were fitted with a subset of letters, in alphabetical order; the other three keys were labeled with control keys (enter, up, and down).
   The screen randomly displayed a single letter (or code key) to stimulate the subject to depress the corresponding button. As soon as any button was depressed, the stimulus disappeared from the screen. Twenty letters were displayed at random intervals. Response times and number of errors were measured and recorded by the laptop computer.

2. Multiple Digit Commands (MDC), Limited Keypad: For this test, the keypad was fitted with the same label overlay that was used in the random location reaction time test.

The screen displayed a four letter command as a stimulus. The subject was required to replicate the command by depressing the four appropriately labeled buttons. The stimulus command disappeared when any four buttons were depressed. Ten commands were shown at randomized intervals. Response time and number of errors were recorded by the laptop computer.

Subjective Measures

After completing all three conditions, subjects were asked to complete a questionnaire indicating their keypad preference in each environment, the effect of neoprene gloves and cold on their ability to use the keypads, and the benefit (if any) of using a stylus.

Statistical Analysis

Statistical analysis was used to identify the differences in performance among the four keypads when operated with the index finger, and when using a stylus to operate the smallest keypad. A 3 (environmental condition) x 5 (keypad condition) factorial design with repeated measures on both factors was completed for each performance measure. ANOVA was used to analyze results for response time and accuracy in order to identify main effects for the environment and for the keypad size, and interactions between the two. Data were tested for significant differences at the $p \leq 0.05$. Figure 2 shows a diagram of the experimental design.

	Control Pad #1 (Stylus)		Control Pad #1 (Finger)		Control Pad #2 (Finger)		Control Pad #3 (Finger)		Control Pad #4 (Finger)	
25 C air no gloves	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC
25 C water no gloves	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC
4 C water gloves	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC	RLRT	MDC

Figure 2: Experimental design for control pads

Results

The data of two subjects were found to be incomplete due to technical problems with the underwater switches and connectors used in design of the keypads. Thus, the results reported are based on 10 subjects, except for multiple digit command data which are based on the results of 9 subjects.

Random Location Reaction Time (RLRT) Test

Table 2: Descriptive data and statistical analysis of random location reaction times

Reaction Time (ms): Mean ± SD (n=10)				
Keypad	Air	Water (25°C)	Water (4°C)	*Means*
1 (stylus)	9.4 ± 1.4	12.3 ± 1.3	12.7 ± 0.8	*11.5*
1 (finger)	8.3 ± 3.5	11.1 ± 1.7	13.1 ±1.6	*10.9*
2 (finger)	9.3 ± 1.7	10.1 ± 1.5	11.5 ± 1.8	*10.3*
3 (finger)	9.8 ± 1.5	10.1 ± 1.5	11.1 ± 1.1	*10.3*
4 (finger)	9.1 ± 0.9	11.1 ± 3.6	12.0 ± 0.9	*10.7*
Means	*9.2*	*10.9*	*12.1*	

Statistics			
	F	Sig.	Power
Keypad	3.2	0.03	0.77
Environment	24.5	0.000	1.00
Keypad x Environment	2.0	0.05	0.80

Results in Table 2 show that there was a significant difference in reaction time when comparing the 5 keypad conditions (F=3.2, p=0.03). There was also a difference in the mean reaction times between environmental conditions (F=24.5, p=0.000). Comparing marginal means shows that RLRT was approximately 32% slower when wearing gloves in 4^{o}C water than in air (no gloves) and 11% slower than in 25^{o}C water (no gloves) (p<0.05). There was also a significant interaction between environmental condition and keypad (F=2.0, p=0.05), showing that gloves and immersion in water did not affect all keypads equally. For example, in air, reaction time was fastest with keypad 1 (finger) and slowest with keypad 3, whereas in 4^{o}C water, reaction time was slowest with keypad 1 and fastest with keypad 3.

Table 3: Descriptive data and statistical analysis for accuracy of RLRT

Accuracy (/10): Mean ± SD (n=10)				
Keypad	Air	Water (25°C)	Water (4°C)	*Means*
1 (stylus)	8.9 ± 1.0	8.7 ±2.4	8.4 ± 1.2	*8.7*
1 (finger)	8.8 ± 1.2	9.2 ± 0.8	7.1 ± 2.3	*8.4*
2 (finger)	9.9 ±0.3	9.7 ±0.5	9.1± 1.0	*9.6*
3 (finger)	9.6 ± 0.5	9.2 ± 0.8	9.2 ± 0.9	*9.3*
4 (finger)	9.8 ± 0.4	9.3 ±0.8	9.4 ± 0.8	*9.5*
Means	*9.4*	*9.2*	*8.6*	

Statistics			
	F	Sig.	Power
Keypad	11.2	0.001	0.96
Environment	6.1	0.001	0.98
Keypad x Environment	1.5	0.18	0.62

Results in table 3 show that accuracy was significantly affected by the type of keypad ($F=11.2$, $p=0.001$), and the environment ($F=6.1$, $p=0.001$). Overall, keypad #1 (finger) received the lowest accuracy scores (8.4) and keypad # 2 was associated with the highest scores (9.6). The accuracy of RLRT responses, measured across all keypads, was significantly lower in 4^{o}C water when wearing gloves (8.6) than in air (9.4) or in 25^{o}C water without gloves (9.2) ($p<0.05$). However, there was no significant difference in accuracy between air and 25^{o}C water. There was no interaction effect between keyboard and environment; the mean accuracy score across all five keyboards was consistently lower when moving from air to 4^{o}C water with gloves.

Environmental condition 3 (three-finger neoprene gloves in 4°C water) had the slowest reaction times and lowest accuracy scores for the RLRT test. Post hoc analyses of these data were conducted to identify which keypad configuration(s) performed best in this environment.

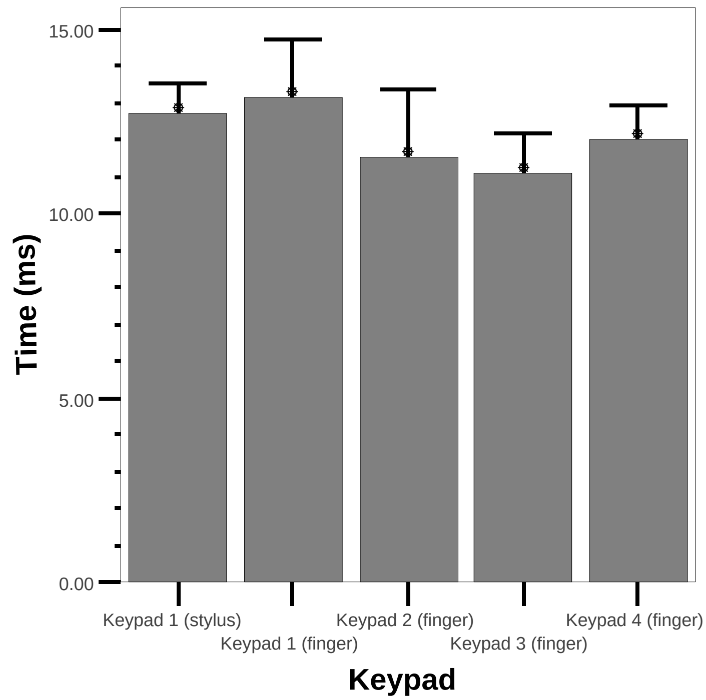

Figure 3: Random location reaction times when wearing gloves in 4^{o}C water

Figure 3 shows the RLRT for environmental condition 3. Tukey's post hoc analysis found no significant difference between the two modes of activation for keypad 1 (finger versus stylus) when considering reaction time. There were no significant differences between the reaction times for keypads 2 through 4. However, keypads 2 (p=0.05) and 3 (p=0.009) were significantly faster than keypad 1 (finger activation only). In contrast, no significant difference was found between keypad 1 (stylus) and keypads 2, 3 or 4.

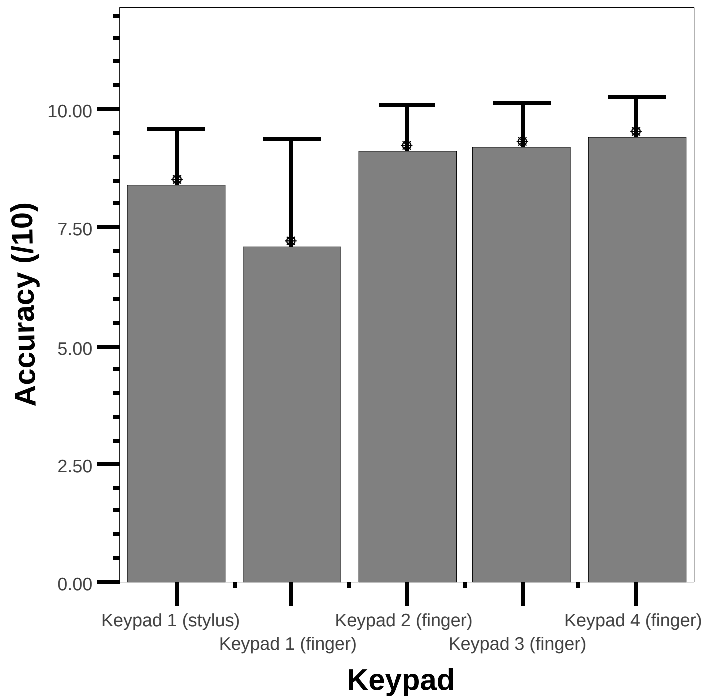

Figure 4: Accuracy of random location reactions when wearing gloves in 4^{o}C water

Figure 4 shows the RLRT accuracy scores for the 5 keypads used in Condition 3. The figure suggests that when using the index finger with neoprene gloves, accuracy tends to plateau at keypad 2. Tukey's post hoc analysis showed that accuracy scores for keypads 2 ($p=0.02$), 3 ($p=0.01$) and 4 ($p=0.004$) were higher than keypad 1 (finger activation). Keypads 2 through 4 were not significantly different from each other. In addition, no significant difference was found between keypad 1 (stylus) and the other keypads.

Multiple Digit Commands (MDC)

Table 4: Descriptive data and statistical analysis of multiple digit command response times

Response Time (s): Mean ± SD (n=9)				
Keypad	Air	Water (25°C)	Water (4°C)	*/Means*
1 (stylus)	34.8 ± 5.4	40.9 ± 3.3	41.8 ± 4.2	*39.2*
1 (finger)	33.9 ± 4.5	40.5 ± 4.1	48.5 ± 5.2	*41.0*
2 (finger)	28.1 ± 4.6	35.1 ± 4.2	41.0 ± 5.3	*34.7*
3 (finger)	34.1 ± 4.0	31.9 ± 9.3	40.4 ± 5.6	*35.5*
4 (finger)	35.2 ± 8.4	39.9 ± 5.2	39.8 ± 5.3	*38.3*
Means	*33.2*	*37.7*	*42.3*	

Statistics			
	F	Sig.	Power
Keypad	7.9	0.000	1.00
Environment	37.8	0.000	1.00
Keypad x Environment	4.6	0.000	1.00

Results in Table 4 show that the reaction time for depressing a combination of keys was affected by both keypad (F=7.9, p=0.000) and environment (F=37.8, p=0.000). The marginal means suggest a U-shaped relationship across all three environments; keypad 2 was associated with the fastest response time (34.7 ms) and keypad 1 was associated with the slowest response time (41.0 ms) when activated with the finger. Marginal means also show that, across all keypads, environment 3 (4^{o}C water with gloves) was associated with the slowest response times: approximately 12% slower than in 25^{o}C water (no gloves) and 27% slower than in air (p<0.05). Mean response times in 25^{o}C water were also 14% slower than in air (p<0.05). There was an interaction effect between keypad and environment (F=4.6, p=0.000) indicating that the environmental condition affected reaction times differently depending on the keypad. Thus, although reaction times increase from environment 1 to environment 3, the degree of change varies among the keypads.

Table 5: Descriptive data and statistical analysis for accuracy of MDC

Accuracy (/10) Mean ± SD (n=9)				
Keypad	Air	Water (25°C)	Water (4°C)	*Means*
1 (stylus)	7.9 ± 1.7	7.1 ± 2.2	6.8 ± 1.7	*7.3*
1 (finger)	6.9 ± 2.3	7.0 ± 2.0	3.6 ± 2.7	*5.8*
2 (finger)	9.5 ± 1.3	9.3 ± 1.1	8.7 ± 1.6	*9.2*
3 (finger)	8.1 ± 2.0	8.5 ± 1.5	8.6 ± 1.5	*8.4*
4 (finger)	9.7 ± 0.5	9.7 ± 0.7	8.5 ± 2.0	*9.3*
Means	*8.4*	*8.3*	*7.2*	

Statistics			
	F	Sig.	Power
Keypad	14.4	0.000	1.00
Environment	10.6	0.001	0.97
Keypad x Environment	2.5	0.02	0.87

Table 5 shows that the accuracy of multiple digit commands was significantly affected by keypad (F=14.4, p=0.000), and environment (F=10.6, p=0.001). Marginal means show that across all three environments keypad 1 (finger) was the least accurate (5.8), and keypad 4 was the most accurate (9.3). The accuracy of MDC responses, measured across all keypads, was significantly lower in 4°C water when wearing gloves (7.2) than in air (8.4) or in 25°C water without gloves (8.3) ($p<0.05$). However, there was no significant difference in accuracy between air and 25°C water. There was an interaction effect between keypad and environment (F=2.5, p=0.02).

Additional analyses were conducted to determine the most appropriate keypad for use in 4°C water when wearing three fingered neoprene gloves (environment 3).

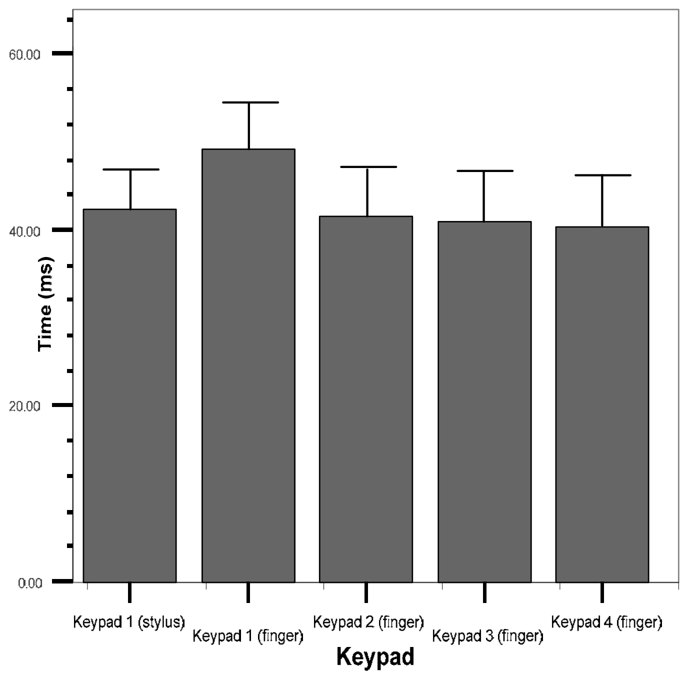

Figure 5: Response times for multiple digit commands when wearing gloves in 4^{o}C water

Figure 5 shows the MDC response times for environmental condition 3. Tukey's post hoc analysis showed that keypad 1 (finger) was significantly slower than all of the other keypad options ($p<0.05$). There were no significant differences between the response times of keypads 2, 3 and 4 and keypad 1 (stylus).

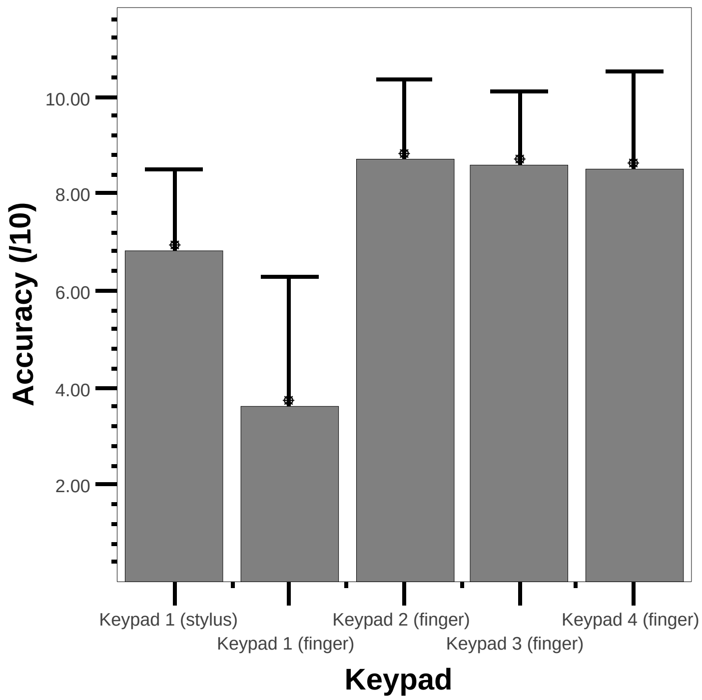

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Figure 6: Accuracy for multiple digit commands when wearing gloves in 4ºC water

Figure 6 shows the accuracy score of all 5 keypads when completing the MDC test in environmental condition 3. Post hoc analysis showed that accuracy of keypad 1 (finger) was significantly lower than all other keypad conditions ($p<0.05$). Subjects achieved only 36% accuracy with this keypad, which was less than half the accuracy of keypads 2, 3 and 4. There were no significant differences in accuracy between any of the other keypads.

Subjective Data

The results of that questionnaire are provided below in Table6.

Table 6: Responses to questionnaire

Which keypad did you prefer in the air environment?	6/10 preferred keypad 1 (finger) 4/10 preferred keypad 2 (finger)
Which keypad did you prefer in 25^{o}C water	7/10 preferred keypad 2 (finger) 3/10 preferred keypad 1 (finger)

Which keypad did you prefer in the 4°C water when wearing gloves?	4/10 preferred keypad 2 4/10 preferred keypad 4 2/10 preferred keypad 3
If you had to choose one keypad for use underwater (with or without gloves), which would you choose?	6/10 preferred keypad 2 2/10 preferred keypad 4 2/10 preferred keypad 3
Did wearing three fingered neoprene gloves affect your ability to operate the keypad?	All subjects reported that the gloves affected their ability to use the keypads. Reasons are listed below: 10/10 subjects reported that the gloves obstructed their view of the keys and decreased their confidence that they were hitting the targeted key. 10/10 subjects reported that the gloves seemed to cause the most difficulty on the smallest keypad, and the least difficulty on the largest keypad. 7/10 subjects were not confident that they were hitting the correct button (even though in most cases they were). 5/10 subjects reported that it was difficult and uncomfortable to hold the stylus when wearing gloves. 2 subjects reported that their hand started to cramp when holding the stylus.
Did your hands feel cold when wearing gloves in 4°C water?	8/10 subjects reported that their hands felt cold.
Did the cold affect your ability to use the keypad?	6/10 subjects thought the cold did not affect their ability to complete the button pushing tasks. 2 subjects thought that the cold affected them, more through distraction than through decreased ability to depress specific buttons.
Did you find the stylus helped or hindered you when using the smallest keypad?	All subjects were able to use the stylus for depressing the buttons. All subjects (10/10) reported some level of dissatisfaction when using the stylus. All subjects were skeptical at the thought of using a stylus when diving: they believed that they would drop or lose the stylus, in particular that it would get in the way. 5 subjects reported hand discomfort (2 hand cramps).

Discussion

Results were analyzed to identify the effect of immersion of the hands in water, and cold, on the ability to use a keypad, the optimal keypad size for use in cold water diving conditions, and to identify if a stylus was an appropriate option for use in the underwater environment.

Underwater Effect

This study showed that performance when using a keypad was impaired by immersion in water. Response times were significantly slower and the accuracy of responses was lower when wearing gloves in 4^oC water than in air. These results are in general agreement with the previous findings of Morrison and Zander (2005b), although the magnitude of impairment reported in this study is smaller. This is likely due to differences in the design of the manual performance tests between the two studies. For example, the dimensions of the buttons used in this study are generally larger (5 to 22.5 mm) than the dimensions of the embossed tabs (3.5 to 11 mm) used by Morrison and Zander (2005b) to test tactile sensitivity. The interaction effect between keyboard and environment found in the results of this study suggest that there is a (button) size effect on the degree of performance impairment in cold water. The performance impairment when using keypad 1 (finger) in 4^oC water with gloves was generally greater than that when using the larger keypads. In addition, response time data tended to show the expected U-shaped relationship to button size, with the minimum response times moving from keypads 1 (RLRT) and 2 (MDC) in air, to keypads 3 (RLRT) and 4 (MDC) in cold water with gloves. However, statistical results found that in cold water, differences between keypads 2, 3 and 4 were generally not significant at the $p<0.5$ level.

The effect of immersion of the hands in 25^oC water, without gloves, on the ability to operate a keypad is less marked than in 4^oC water with neoprene gloves. RLRT and MDC response times were 18% and 14% slower than in air respectively ($p<0.05$) but accuracy was not significantly affected. Results in 25^oC water are in agreement with the findings of Hancock and Milner (1986) and Baddeley and Idzikowski (1985), that immersion alone is a factor in impairment of manual performance, independent of other stressors such as narcosis, cold and gloves. The aetiology of impairment due to immersion is unclear, but may include such factors as refraction, absorption, and scatter of light, the affect of water viscosity, friction, and drag on manual dexterity and tactile sensitivity, buoyancy of the fingers and hands, and local skin temperature effects.

The interaction effect between environmental condition and keypad size suggests that it is not possible to predict underwater performance from measurements made when using a keypad in an air environment. Thus when designing underwater equipment, it is essential to measure the performance of the equipment in realistic environmental conditions.

Optimal Button Size and Spacing for Underwater Control Pads

Results indicate that for both RLRT and MDC, responses when using keypad 2 in cold water with neoprene gloves were significantly faster and more accurate ($p<0.05$) than keypad 1. In addition, results show that no significant improvement in either speed or accuracy of response was obtained by increasing the button size and spacing (keypads

3 and 4) beyond the dimensions of keypad 2. Hence, it is concluded that 10 mm keys with 20 mm spacing (centre to centre) are optimal for the design of control pads that are to be operated when wearing three-fingered neoprene gloves in cold water. These results are in good agreement with the previous recommendations of Morrison and Zander (2005b) based on testing of tactile sensitivity and manual dexterity.

Use of a Stylus for Keypad Control

This study also evaluated the potential of using a stylus to operate a smaller control pad than can be operated using a gloved finger in 4^oC water. Results were not conclusive. When using a stylus with keypad 1, RLRT response times were intermediate between those of keypad 1 (finger), and keypad 2. Thus, although results with the stylus were not significantly different from keypad 2, they were generally lower, and were not significantly better than when operating keypad 1 with the index finger. The lack of significance in this test indicates that the analysis was not sensitive enough to determine, to the level of significance required ($p \leq 0.05$), whether response times using the stylus were truly faster than using the index finger with keypad 1, or slower than using keypad 2. In contrast, when using the stylus, MDC response times were faster than when using the index finger on keypad 1, and not significantly different from keypads 2, 3 and 4. Results also showed that the stylus was significantly more accurate than the index finger, and not significantly different from the other keypads (2, 3 and 4), when performing the RLRT and MDC tests.

In contrast to the generally positive objective data, subjective data indicated that the stylus was uncomfortable to hold, easy to drop, and that subjects were skeptical about its usability in the underwater environment. However, the subjects were not used to operating a stylus with gloves. The design of stylus used had not been tested in usability trials and most probably was not an optimal design. It is possible that an ergonomically designed stylus that incorporated a method of attachment, and improved comfort and control, would allow for further miniaturization of underwater keypads.

Conclusions

It is concluded that a push-button size of approximately 10 mm and spacing of 20 mm is optimal for underwater control pads that are to be used with neoprene gloves in cold water. If a control pad having smaller dimensions is required then accuracy will be reduced and response times increased. The use of a stylus with a smaller keypad has the potential to improve accuracy and response times and may be helpful if suitably designed. However, based on the results of this study, a smaller stylus operated keypad cannot be recommended as an optimum design without further ergonomic design and usability testing.

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(U) This study was designed to identify the optimal size and spacing of push−button controls for use by divers when wearing neoprene gloves in cold water. Four keypads having different size and spacing of buttons were tested in three environmental conditions. Ten subjects completed two different tests of speed and accuracy in air and in 25C water with no gloves and in 4C water with neoprene gloves. Results showed that there were main effects of keypad size and environment on performance and an interaction effect between keypad and environment. Responses were slower and less accurate in 4C water with gloves than in air or 25C water ($p<0.05$). Responses were also slower in 25C water than in air ($p<0.05$). A keypad having 10 mm button size and 20 mm spacing (centre to centre) was found to be optimal when wearing gloves in cold water; there was no significant improvement in performance with larger keypads. Using a stylus to operate a smaller keypad improved accuracy when wearing gloves in 4C water, but proved impractical without ergonomic design improvements. It is concluded that keypads designed for use in air are not optimal for use underwater.

(U) La présente étude visait à déterminer la taille optimale et l’espacement des boutons−poussoirs des commandes utilisées par les plongeurs portant des gants de néoprène en eau froide. Quatre claviers dotés de boutons de taille et d’espacement différents ont fait l’objet d’essais dans trois conditions environnementales. Dix sujets ont effectué deux essais différents de vitesse et de précision dans l’air et dans l’eau à 25 ºC, sans gants, et dans l’eau à 4 ºC, avec gants de néoprène. Les résultats ont montré que la taille du clavier et l’environnement avaient des effets sur le rendement, et qu’il y avait une interaction entre le clavier et l’environnement. Les réactions étaient plus lentes et moins précises dans l’eau à une température 4 ºC, lorsque les sujets portaient des gants, que dans l’air ou dans l’eau à 25 ºC ($p < 0,05$). Les réactions étaient aussi plus lentes dans l’eau à 25 ºC que dans l’air ($p < 0,05$). On a constaté qu’un clavier doté de boutons de 10 mm et espacés de 20 mm (entraxe) constituait la solution optimale pour les plongeurs portant des gants en eau froide; des claviers plus gros n’amélioraient pas le rendement de façon significative. L’emploi d’un stylet avec des claviers plus petits a amélioré la précision des utilisateurs portant des gants dans l’eau à une température de 4 ºC, mais leur emploi ne s’est pas révélé pratique à moins que des améliorations ne soient apportées à l’aspect ergonomique. Il en est conclu que les claviers conçus pour une utilisation dans l’air ne sont pas la solution optimale pour un usage dans des activités sous−marines.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

(U) ergonomics; human engineering; underwater; diving; divers; immersion; hyperbaric; tactile sensitivity; gloves; speed; accuracy; human performance; keypad; cold water; warm water; stylus; human systems interaction; HSI