Evaluation of head mounted and head down information displays during simulated mine-countermeasures dives to 42 msw

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Scientific Authority: D. Eaton
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Defence R&D Canada - Toronto

Contract Report

DRDC Toronto CR 2008-035

April 2008

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Abstract

Despite recent advancements in diver communications, there is little information on the ability of divers to use a multi-function head down display (HDD) or head mounted display (HMD) for routine underwater tasks. Three information displays (HDD, and a monocular and binocular HMD) were tested by nine mine counter-measures (MCM) divers at the surface and during simulated dives to 42 metres in 6°C water. Divers used the displays to report depth and alarms and to perform navigation, object location and target identification tasks. Task performance was analyzed for speed and accuracy. Subjective data were collected on the usability of the displays in conjunction with other MCM tasks and equipment. Performance was slower and less accurate ($p<0.05$) at 42 msw than at the surface. At 42 msw, response times were faster ($p<0.05$) when using the HDD to report depths and locate objects; otherwise there were no significant differences between displays. Subjective data showed a slight preference for the HDD. Some divers reported eye fatigue or nausea when using a HMD. Although MCM divers were capable of using both the HDD and HMD effectively during dives to 42 msw, each display presented unique design and usability problems.

Résumé

Malgré les avancées récentes dans le domaine des communications des plongeurs, il existe peu de renseignements sur l’aptitude des plongeurs à utiliser un dispositif multifonction de visualisation tête basse (VTB) ou d’un visiocasque pour l’exécution de leurs tâches courantes sous l’eau. Neuf plongeurs de lutte contre les mines ont testé trois dispositifs d’affichage de l’information (un dispositif VTB, un visiocasque à monoculaire et un visiocasque à binoculaire) en surface et pendant des plongées simulées à 42 m dans l’eau à une température de 6 ºC. Les plongeurs ont utilisé les dispositifs d’affichage pour signaler la profondeur et des alarmes et pour effectuer des tâches de navigation, de repérage d’objets et d’identification d’objectifs. On a analysé l’exécution des tâches en fonction de la vitesse et de la précision. Des données subjectives ont été recueillies concernant l’utilisabilité des dispositifs en fonction d’autres tâches et équipement de LCM. La réaction des dispositifs était plus lente et moins précise ($p < 0,05$) à une profondeur de 42 m qu’à la surface. À une profondeur de 42 m, les temps de réaction des dispositifs VTB étaient plus rapides ($p < 0,05$) pour le signalement des profondeurs et le repérage d’objets; dans les autres situations, les écarts entre les dispositifs étaient négligeables. Les données subjectives ont montré une légère préférence pour les dispositifs VTB. Certains plongeurs ont signalé avoir éprouvé une fatigue oculaire ou des nausées avec l’utilisation du visiocasque. Même si les plongeurs de LCM étaient en mesure d’employer efficacement le dispositif VTB et le visiocasque pendant les plongées à une profondeur de 42 m, chacun des dispositifs présentait des problèmes particuliers sur les plans de la conception et de l’utilisabilité.

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Executive summary

Introduction: The advent of portable computers and small screen displays offers new methods of communication and display of information to a diver. Despite the technological developments, there is little empirical information on the ability of divers to use a multi-function head down display (HDD) and head mounted display (HMD) for routine underwater tasks, or whether a HDD, or a monocular or binocular (HMD) is preferred.

Methods: Three modes of information display were tested at the Diving Research Facility of Defence R&D Canada – Toronto. Nine mine counter-measures (MCM) divers used the displays at the surface and during simulated dives in a hyperbaric chamber. Each diver completed three dives to 42 metres while immersed in 6^{o}C water: one dive using a HDD, one using a monocular HMD, and one using a binocular HMD. Divers used the displays to obtain and respond to information, including depth and system alarms, and to perform simulated navigation, object location and target identification tasks. Task performance was measured as response times, task completion times, and accuracy of information retrieval. Subjective data were collected from the divers on the usability of the displays in conjunction with other MCM tasks and equipment.

Results: Task performance was generally slower and less accurate ($p<0.05$) during the simulated dives than at the surface. At 42 msw, response times were faster ($p<0.05$) when using the HDD to report depths and when performing the object location task. Otherwise, there were no significant differences in the measures of task performance between the displays. In subjective reports, 8 divers ranked the HDD first or second overall, 7 ranked the binocular HMD second or third, and 5 divers ranked the monocular HMD last. Some divers reported eye fatigue or nausea when using the HMD.

Significance: Results show that MCM divers are capable of using both HDD and HMD effectively to perform an array of MCM tasks during simulated dives to 42 msw. Divers showed a slight preference for the HDD. Each of the three displays present MCM divers with unique design and usability problems when completing typical MCM underwater tasks.

Sommaire

Introduction. L'avènement des ordinateurs portables et des petits écrans d'affichage offre aux plongeurs de nouvelles méthodes de communication et d'affichage de l'information. Malgré les avancées technologiques, il existe peu d'information empirique sur l'aptitude des plongeurs à utiliser un dispositif multifonction de visualisation tête basse (VTB) ou d'un visiocasque pour l'exécution de leurs tâches courantes sous l'eau, ou à savoir si un dispositif VTB, un visiocasque à monoculaire ou un visiocasque à binoculaire est préférable.

Méthodes. Trois dispositifs d'affichage de l'information ont fait l'objet d'essais à l'Installation de recherche en plongée de RDDC Toronto. Neuf plongeurs de LCM ont utilisé les dispositifs d'affichage en surface et pendant des plongées simulées en chambre hyperbare. Chaque plongeur a effectué trois plongées à une profondeur de 42 m dans une eau à une température de 6 ºC : une plongée avec un dispositif VTB, une avec un visiocasque à monoculaire et une autre avec visiocasque à binoculaire. Les plongeurs ont utilisé les dispositifs d'affichage pour obtenir des informations et y répondre, notamment au sujet de la profondeur et d'alarmes système, et pour effectuer des tâches simulées de navigation, de repérage d'objets et d'identification d'objectifs. L'exécution des tâches (rendement, en anglais *performance* ou p) a été mesurée en fonction des temps de réaction, des temps d'exécution des tâches et de la précision de l'information obtenue. Des données subjectives ont été recueillies des plongeurs concernant l'utilisabilité des dispositifs en fonction d'autres tâches et équipement de LCM.

Résultats. La réaction des dispositifs était généralement plus lente et moins précise ($p < 0,05$) pendant les plongées simulées à une profondeur de 42 m qu'à la surface. À une profondeur de 42 m, les temps de réaction des dispositifs VTB étaient plus rapides ($p < 0,05$) pour le signalement des profondeurs et le repérage d'objets. Dans les autres situations, les écarts d'efficacité entre les différents dispositifs étaient négligeables. Dans les données subjectives recueillies, 8 plongeurs ont classé le dispositif VTB au premier ou au deuxième rang, 7 ont classé le visiocasque à binoculaire au deuxième ou au troisième rang et 5 plongeurs ont classé le visiocasque à monoculaire au dernier rang. Certains plongeurs ont signalé avoir éprouvé une fatigue oculaire ou des nausées avec l'utilisation du visiocasque.

Portée. Les résultats montrent que les plongeurs de LCM sont en mesure d'employer efficacement le dispositif VTB et le visiocasque pour exécuter diverses tâches de LCM pendant des plongées simulées à une profondeur de 42 m. Les plongeurs ont indiqué avoir une légère préférence pour les dispositifs VTB. Chacun des trois dispositifs présente des problèmes particuliers sur les plans de la conception et de l'utilisabilité pendant l'exécution de tâches de LCM sous l'eau.

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Introduction

The main objective of this study was to evaluate the effectiveness of different types of underwater display devices: a head down display (HDD), a monocular and a binocular head mounted display (HMD) in simulated MCM diving conditions. The study also measures the adverse effects of the MCM diving environment on the use of information displays and evaluates the effectiveness of various screen layouts in providing information to MCM divers at each stage of the dive.

Underwater displays are used to provide divers with important information during underwater operations. In the past, the majority of underwater displays have been designed by modifying equipment that was originally designed for the air environment. This process has resulted in displays that are not optimal for diving activities. In general, they lack integration, do not provide the diver with sufficient information, and are inflexible. The limitations in the display technology forced divers to adapt their activities to the limitations of the hardware. Research into the optimal design of displays has been a focus for many industries over the past decade. The majority of the research has been directed towards use of displays in an air environment.

Work to Date

This study is part of a larger project on human factors in MCM diving. The main objectives of the work completed in the first two phases were to optimize the performance and safety of MCM diving procedures and to determine the requirements for communication and display of information in MCM diving. The objectives of Phase 3 are to establish a set of ergonomic design guidelines for underwater information displays and to evaluate new methods of communication and display of information underwater. The work completed to date is outlined below.

In Phase 1 the current operating procedures of the Canadian Forces (CF) MCM divers were documented; ergonomic problems with the existing procedures were identified; and solutions were provided to improve the efficiency and safety of MCM diving (Morrison, Hamilton & Zander, 1997).

In Phase 2 the MCM diving procedures at Fleet Diving Unit (Pacific) and Fleet Diving Unit (Atlantic) were further examined and compared; available technologies were studied; and a set of recommended procedures for MCM diving were produced. The information and display requirements of MCM divers were determined, and a set of ergonomic design guidelines for underwater displays was proposed, together with a summary of missing information (Morrison, Zander & Hamilton, 1998).

The purpose of Phase 3 is to further develop knowledge of ergonomic design guidelines, and to test new communication and display technologies for use in MCM diving through a series of experimental studies conducted at Simon Fraser University (SFU) and at Defence R&D Canada – Toronto (DRDC Toronto).

Other experiments completed in Phase 3 include:

The effects of diving in cold water on manual performance:

- identifying the effects of cold, neoprene gloves, and pressure (40 msw) on grip strength, tactile sensitivity and manual dexterity;
- identifying the effects of cold, pressure (40 msw) and exposure time on finger and hand skin temperature when wearing neoprene gloves;

Design parameters for underwater displays:

- determining appropriate font size for underwater lit displays under varying water conditions
- determining appropriate use of colour and contrast for underwater lit displays in varying water conditions;
- determining the optimal information layout for underwater lit displays for MCM divers.

The experiment described in this paper was completed at DRDC Toronto using Canadian Forces (CF) Clearance Divers. A variety of information display formats were investigated using three different display devices. When designing or evaluating display devices for use in the underwater environment, it is important to consider information processing capabilities in humans in that environment. Research has shown that due to a series of environmental stressors, information processing capabilities are decreased when operating underwater.

Information Processing

Humans have a limited ability to process information (Eriksen and Eriksen, 1974). Many models have been developed to explain information processing and human performance, but the basic components of most of the models are similar. The overview of human information processing is that humans sense information from the environment, store it in sensory memory then attend to and store a limited amount of this information into short term memory (also known as working memory), and then transfer and store some of this information to long term memory for later retrieval.

Sensory memory has a large capacity with very brief retention. It represents the information stimulus in the environment around the person. Visual information is stored for up to 0.5 seconds, and auditory information can be stored for up to 2 seconds (Goodhead, 1999; Wade and Tarvis, 1990). As attention is applied to the sensory stimulus in sensory memory, it is transferred to short term memory. Short term memory has a limited capacity and limited storage time. Information is stored in short term memory for between 7 to 30 seconds (Norman,1982). Short term memory is involved in conscious processing of information. Information may either be used while it is in short term memory or transferred to long term memory. Generally, information that is rehearsed, that is given meaning or that has previous meaning (i.e., is consistent with the existing mental models of the person) can be transferred to long term memory. Long term memory theoretically has an unlimited capacity, and some believe permanent storage, although this is very difficult to test.

Effects of Environmental Stressors on Information Processing

Theoretically, anything such as an environmental stressor that disrupts any stage of the process can decrease the amount or type of information that can be used in short term memory, stored as long term memory or retrieved from long term memory. In the underwater environment there are many stressors that can affect information processing capabilities, and thus impair diver performance when using an underwater display. These include ambient light, hearing, pressure, cold, and anxiety.

The different physical characteristics of water affect the way that humans are able to function. Water is more dense (80 times), more viscous (600 times) and has a higher thermal conductivity (25 times) than air (Albano, 1970). When divers enter the water, the sensory information they receive is altered.

Ambient Light

Vision provides the viewer with knowledge about the surrounding environment. Viewing objects proves to be a quick source of information about size, shape, colour, location of objects, and also about the viewer's spatial orientation within the environment. Vision is recognized (Adolfson and Berghage, 1974) as being the most important sense in information processing because it provides a lot of information quickly.

In the underwater environment, vision is degraded as light energy is attenuated by absorption, scatter, reflection, and refraction. Even with a mask, vision underwater is not the same as it is in air. The lack of visual stimuli, and low ambient light cause the environment to appear hazy and empty. This effect is referred to as the Ganzfeld effect. The Ganzfeld effect makes it difficult to process information from the visual environment and decreases situational awareness (Adolfson and Berghage, 1974).

Hearing

The degraded hearing capabilities while underwater decreases the amount of information collected in sensory memory by decreasing the auditory stimuli. The increased workload in differentiating between sounds may also impact short term memory. Background noise is likely a factor in distracting the diver from attending to other, important information.

Pressure (narcosis)

Immersion in water increases the ambient pressure of the diving environment and may lead to narcosis. According to Fowler *et al.,* (1985) information processing is slowed at each stage by narcosis (nitrogen and carbon dioxide). It is likely that transferring information from sensory memory to short term memory is degraded because it requires the individual to attend to the information. Transfer from short term memory to long term memory by rehearsing or forming meaningful links, is also likely degraded. The effects of narcosis as a function of depth are well established in the literature (Bennett, 1994; Fothergill, 1988).

Cold

Both peripheral and core cooling can cause decrements in information processing. Peripheral cooling degrades memory by causing distraction; the pain and discomfort of cold demand the attention of the individual making it difficult to attend to other stimuli (Parsons, 2003). Core cooling also causes distraction, but in addition, it degrades the information processing lifecycle (Emmerson, 1986). The results of exposure to cold are decreased ability to recall information, either because it was not initially attended to, or because of a failure during some component of the information processing.

It is difficult to quantify the effects of cold on information processing and the working memory and long term memory components. Previous research has concluded that exposure to cold causes a decrement in information processing and working memory. Coleshaw *et al*. (1983) showed that mild hypothermia was associated with working memory deficits. Drops in core temperature of between 2 to 3°C were associated with amnesia (*Coleshaw et al.,* 1983). Baddeley (1992) showed that drops in rectal temperature of between 0.7 and 1.0°C were associated with significant impairments in information processing. Stang (1970) suggested that, irrespective of core temperature, cutaneous cooling (via 30 to 90 minutes submersion in 6 to10°C water while wearing a wet suit) was associated with significant decrements in information processing. However, these studies do not clearly define how information processing or working memory was isolated from other confounding factors.

Anxiety

Most of the research related to diving and anxiety has focused on manual performance (Hancock and Milner, 1986; Mears and Cleary; 1984; and Baddeley and Idzikowski, 1985). The cognitive decrement associated with anxiety has been generalized from research related to standard air environments. The Yerge-Dodson theory stipulates that each individual will operate at a given level of arousal or stress. Further, each individual will have an optimal arousal or stress level where their mental performance will be maximized. The standard or resting level of arousal differs between individuals. According to Edmonds *et al.,* (1992), divers (in particular military divers) are generally people who require a lot of stimulation, "thrill seekers". These people are thought to generally operate below their optimal arousal level and they require increased stress or anxiety to help them optimize their performance. For these types of divers, some added anxiety caused by deep diving and low light levels may help optimize their performance. However, if the anxiety level increases too much, for example diving on a live mine, performance may be degraded. Similarly, for individuals whose resting arousal level is close to their optimal level, any added anxiety may act to decrease their cognitive performance.

Comparison of Display Types

Visual displays can be categorized into two main groups when considering underwater technologies: head mounted displays (HMD) and head down displays (HDD).

Head Mounted Displays

The purpose of a HMD is to provide the user with a hands-free information display, and thereby to decrease the equipment burden while concurrently providing more information than would otherwise be possible. It has been suggested that as a result of these benefits, user performance can theoretically be improved. However, a review of the literature shows that rather than improving performance, incorporating HMDs may actually degrade user performance.

As already discussed, the visual parameters and related information processing are decreased when operating in the underwater environment. Using a HMD also affects the performance of the visual system and the related visual information processing. The visual parameters that are affected by use of a HMD are outlined below.

An inherent property of a HMD is that it occludes the vision of the user. When viewing the display, the user either cannot see the surrounding environment, or can see only a portion of the surrounding environment. A monocular HMD (which covers only one eye) will occlude less of the viewer's field of view (FOV) than a binocular HMD (which covers both eyes). The decrease in FOV caused by the HMD will affect the diver in a number of ways.

The most obvious result of occlusion is that the user will be unable to obtain visual information directly from the environment. The spatial orientation and situational awareness will be decreased. A diver surveying the environment for contextual information or environmental cues to provide meaning to the information received, will be unable to access much of the visual information that is normally available.

Reduced FOV decreases the amount of peripheral information received. Peripheral information is critical for spatial awareness. Peripheral information uses the ambient information processing system to provide scope to the surrounding environment by detecting objects and movement relative to the objects. Continual sampling of the ambient information processing system allows the viewer to place himself within the environment, and allows him to move within that environment. The ambient information processing system does not use active attention, so it does not add to the workload of the short term memory system. Fast eye movements are also used to detect and focus on objects in the environment; this uses the foveal visual system. Using the foveal visual system does use active attention and adds to the information processing workload of the diver. A diver wearing a mask with a HMD will lose the majority of peripheral vision and the HMD will partly occlude the foveal vision. By reducing the visual field the viewer must use more head and eye movements to view the surrounding environment and rely more heavily on the remaining foveal visual system. These types of head and eye movements can cause the information displayed to momentarily blur or lag, resulting in increased workload, frustration, and even motion sickness (Hockey, 1986). Alternatively, the diver must move the HMD out of the FOV in order to gather information about the environment, thus losing some of the advantage of the HMD as hands-free display that is continuously in view.

Depth perception is decreased when using a HMD. When using monocular HMDs it is not possible to use accommodation and convergence (two visual parameters that aid in depth perception) because the two eyes are viewing different stimuli. Visual rivalry becomes a problem as focus alternates between the two eyes, which is very fatiguing (Williamson, 2000). Binocular HMDs may also be affected by visual rivalry depending on the FOV. Other visual cues such as stereopsis, interposition, size, perspective, and motion parallax are also decreased by using both monocular and binocular HMDs, further decreasing depth perception capabilities (Williamson, 2000; 1995; Tovee, 1996, Keller and Colucci, 1998). Since depth perception is already degraded by operating underwater and wearing a mask, the HMD may decrease the depth perception to a point where the diver is unable to operate effectively.

Head Down Displays

Head down displays can refer to any type of a visual display that is not linked to the diver's FOV. Computer display screens, gauges and watches are types of head down displays. In the underwater environment a HDD does not provide a completely hands-free method of providing information like a HMD; the diver must either wear or carry the display.

HDD do not affect the visual information processing system in that they do not occlude the FOV. If the diver does not want to look at the display, he can avert his gaze. This can be a problem when using a HDD: the diver may not see relevant information when it is required. There are two main types of head down displays currently used in diving operations: wrist mounted; and hand-held display (whip-mounted).

Wrist mounted displays

Wrist mounted displays present a number of ergonomic problems. Divers frequently wear several wrist-mounted displays, which makes finding information more difficult and time consuming. Display size can also be problematic, depending on the amount of information being presented in a small space. Designing for the wrist introduces a space limitation, although the wrist mounted display can be significantly larger than a traditional watch.

Considering only the location of the display, a single, well-designed, integrated display on the wrist offers several ergonomic advantages. A wrist-mounted display is relatively hands free, in that it does not burden the diver with equipment that must be hand-held during operations. However, it is not a truly hands-free option because the user must hold the arm in position for viewing, and use the other hand to operate any controls on the display.

Most dive watches are wrist-mounted, as well as some depth gauges and some decompression computers. Many of these wrist-mounted displays use too small a screen either due to space limitation or poor ergonomic design. The size and layout of the display are often not adequate for operating in the underwater environment, particularly in turbid water. The development of a well designed multi-function wrist display would eliminate most of the ergonomic problems of display information size, layout and equipment burden associated with single-function displays.

Hand-held (whip-mounted) displays

Hand held displays are commonly mounted in a rubber boot that is attached to the breathing apparatus or vest by a line (whip). This category also includes instruments that may be hand-held by the diver, and are attached to the wrist via a line. There are several ergonomic problems with hand held displays: access, tangling, burdening the diver, and efficiency.

The display can be difficult to access quickly as the whip may be trailing the diver or tangled in his equipment. The diver must find the origin of the whip and trace it to the display before moving the display into his field of view, and the display must be held in the divers hand during viewing. Accessing the display is further complicated when the diver has multiple whips or other equipment that impedes movement.

A whip presents a tangling hazard for divers working in confined spaces or diving on a life line. Becoming tangled is a serious hazard as it is difficult to remove tangles underwater. Buoyancy makes it difficult to maintain position or exert force, and poor visibility makes it difficult or impossible to see the origin of the tangle.

The hand held display requires the divers to have a free hand to access and hold the display while it is being viewed. If the display is required repeatedly throughout the dive, the diver must make a decision to either hold the display continually, or spend time accessing the display again when the information is next required.

The time required to access and view the information decreases diving efficiency. When a diver requires information from his displays, the diving operation is often stopped until the information is received (Morrison *et al.,* 1998). For the majority of diving operations, time is a premium because of the limited bottom times in many diving operations.

Most pressure gauges and many depth gauges, compasses, and decompression computers are whip-mounted. If all gauges are integrated into a single whip, the risk of tangling is decreased and accessing the display is easier. The problem with fitting several gauges on one whip is the size of the display module. Incompatibility between gauges can also be a problem if the same company does not design all of the displays. However, this can be rectified by a single multifunctional display that can be controlled by the diver.

Displays currently used in underwater operations

There are many head down displays currently available to divers. Some are single-function while others integrate a number of functions, such as providing time, depth, gas pressure and navigation information. However, integrated displays mainly comprise a group of single function displays, or readouts. They are not truly multi-functional in the sense that the diver (or diver supervisor) can select or change the information to be displayed by indexing through different screens.

Most decompression computers have an integrated display that provides depth, maximum depth, dive time, and a decompression profile for the diver. Some decompression computers attach to diver's breathing gas supply to provide information on gas pressure. Decompression computers can be either whip-mounted or wrist mounted.

New Technology

A number of new technologies are under development are designed to provide the diver with a multi-function display that will allow the diver, or dive supervisor, to select display information that is pertinent to each phase of the dive. This includes depth, time, equipment status, navigation information, decompression, and information about the work task to be completed by the diver. These developments are summarized below.

Sea PC: a lap-top computer re-designed for the underwater environment by Nautronix and WetPC. The computer is designed to be hand-held, with one hand on either side of the screen. The display can provide the diver with a multitude of information including detailed navigation information, and includes a data collection system to enable the diver to record information. Each handle is equipped with buttons, and the system is designed with Kordit™ technology, a chordic keyboard that provides multiple command choices by depressing different button combinations. The system is under development (not commercially available at time of writing), but presumably could be programmed to integrate all of the display requirements into a single interface. This is a stand- alone system and does not require a hard link to the surface. The same companies also make a wearable (head-mounted) version called the Wet PC.

Wet PC: a miniature computer that mounts to the divers' air tank and connects to a head-mounted display on the divers' mask. The display features are controlled by a single handed Kord Pad ™ (using a chordic keyboard). The Wet PC offers the same features as the Sea PC, but is still in the testing phases, and is not yet commercially available.

Underwater Microprocessor (UMP): Kongsberg Simrad developed an hand held computer for divers. The unit houses a microprocessor, a LCD and controls in a rugged design. The display can be controlled by the diver by using push-buttons and a joystick. This unit differs from the SeaPC in its design. The SeaPC uses a flat screen with handles on either side. The handles hold the control push-buttons. The UMP is designed like a modified lap top computer. The screen is offset at a fixed angle to the control pad, which houses the push-buttons and joy stick. Development of this display has been discontinued.

Royal Navy HMD (monocular): The Royal Navy has developed a prototype for a head mounted display that provides the diver with a monocular display that can be moved out of the field of view if required. The system requires the diver to be attached to the surface via an umbilical. The diver is provided with real- time working images through the umbilical. The display can be coupled to a hand-held sonar in order to provide the diver with images for sonar navigation in dark or low visibility environments.

Kongberg Simrad helmet-mounted display (monocular): Kongsberg Simrad has recently manufactured a HMD originally designed for military operations. The helmet provides a video link, light source and eyepiece for the working diver.

Divex Cyclops Integral Diver Viewing System (monocular): Divex has manufactured a helmet mounted display that provides an internally mounted monitor and eyepiece within a diving helmet. The system is designed to provide active video images, non-destructive testing /oscilloscope images and photographic images to the working diver. Drawings or instructions can be provided to the diver during the operation. The diving helmet is fitted with a light source, and a video camera that is attached to a control unit on the surface via an umbilical. At the surface there is an inspection probe display, a video camera (for recording images to be sent to the diver), an image processing or enhancement package, a computer aided design (CAD) package, a virtual reality package and the display control unit. All of the equipment topside feeds information through a common umbilical to the diver. As a result, the diver is connected to the surface by two umbilical lines, one to send and one to receive information.

The eyepiece is mounted inside of the helmet, but it is possible to move it outside of the field of view by manipulating an adjustment on the outside of the helmet.

Cochran mask mounted HUD: Cochran industries has advertised a mask-mounted Head-up display that projects dive information from the divers mask to the area within the divers' field of view. This technology did not seem to progress past the concept stage, and is no longer advertised. It is not known if a working prototype was ever achieved, or if further research and development is being conducted in this area.

US Navy HMDs: The devices consist of a head mounted liquid crystal display (LCD) that attaches to the external of the diver's mask (AGA Divator Mk II). There is both a monocular and a binocular version. The monocular display is positioned over the right eye of the diver, and the binocular display is positioned over both eyes. The display can be rotated out of the divers field of view if the diver wishes to view the surroundings.

The display attaches via an umbilical to a source computer on the surface. The display system provides information one-way: from the surface to the diver.

General ergonomic problems with underwater displays relate to difficulty in accessing the display (display location); reading the display (readability); understanding the information (information layout); and occlusion of the field of view. Head down and head mounted displays both have unique advantages and disadvantages in ergonomic design. Lack of knowledge about which type of display is most effective in the underwater environment lead to the initiation of this study.

Objectives

The objectives of the study are:

1. To determine which type of underwater display (HDD or HMD) is most appropriate for MCM diving.

2. To measure the performance decrement in accuracy and speed of information retrieval due to the adverse conditions of cold water diving to 42 msw.

3. To determine whether the design of information display considered by the MCM divers to provide the optimal amount of information on the surface, is still optimal when working underwater.

4. To determine whether the best type of display is dependent on the particular stage of the dive.

5. To determine whether the information displayed to the diver at any stage of the dive causes information overload, measured as number of errors and response times.

Methods

Subjects

Nine male volunteer divers between the ages of 21 and 55 participated as subjects in the experiment (age range selected as standard age range of military divers at DRDC Toronto). All divers were CF trained Clearance Divers or ex-Clearance Divers with current diving medical examinations and were experienced in diving with full-face mask and a dry suit. Divers supplied medical documentation that they were fit to dive. Divers were informed fully of the details, discomforts and risks associated with the protocol and were required to sign consent forms before being allowed to participate in the experiments. All divers were certified medically fit before commencing each dive. The study was approved by the ethics review boards of Simon Fraser University and DRDC Toronto.

Experimental Procedures

Experiments took place in the Diving Research Facility (DRF) at DRDC Toronto. Three information display devices were tested by MCM divers: a head down display (HDD), a monocular head mounted display (HMD mono), and a binocular head mounted display (HMD bino). Each diver tested each display device in two environmental conditions: at the surface in air at room temperature, and in a hyperbaric chamber during a simulated dive to 42 msw (521 kPa) in 6^{o}C water while breathing air from a demand regulator fitted to a full-facemask. All three display devices incorporated similar information transfer between the diver and researcher. By ensuring that the information displayed was similar, the potential benefits and limitations of each system were measured. Nine male MCM divers completed the dive series, consisting of three surface trials, and three dives to 42 msw.

The experiment was designed as a 2 (environmental condition) x 3 (display device) repeated measures factorial design. Each diver used each display device once at the surface and once at 42 msw, i.e., six experimental sessions. The diver was expected to use the display as required throughout the dive, and to respond to warnings and alarms. The diver was measured on response time and number of errors when using or reading the display information during the dive. The diver was asked to complete an interview after each experimental condition to identify problems of usability with each type of display and to determine diver preference.

Divers were trained on the use of each display to control for a learning effect. The divers were split into three balanced groups (with three divers in each group) each with a different dive order to control for order effects. The surface and depth conditions were also balanced for order effects. Table 3 shows the dive order for the three groups in each environmental condition.

Table 1: Dive Order

Group	HMD mono	HMD bino	HDD
Surface Condition			
#1	dive 1	dive 2	dive 3
#2	dive 2	dive 3	dive 1
#3	dive 3	dive 1	dive 2
Depth Condition			
#1	dive 2	dive 3	dive 1
#2	dive 3	dive 1	dive 2
#3	dive 1	dive 2	dive 3

Apparatus

The same experimental apparatus was used in both conditions (surface air, and 42 msw), with slight modifications as indicated. The apparatus consisted of a laptop computer and an underwater display. The apparatus was designed to provide visual stimuli to the diver, who then reacted by providing verbal feedback. The basic layout of the apparatus is shown in Figure 1. The underwater display acted as a remote monitor that displayed the information output of the laptop computer. The display was either a HDD, positioned approximately 40 cm from the diver’s eyes, within their line of sight, or a HMD which was mounted to the upper rim of a full face mask (AGA Divator Mk II) worn by the diver. The researcher viewed the same information on the computer display as the diver viewed on the underwater display. During the experiment, the diver was also linked to the researchers and operations crew via audio communications.

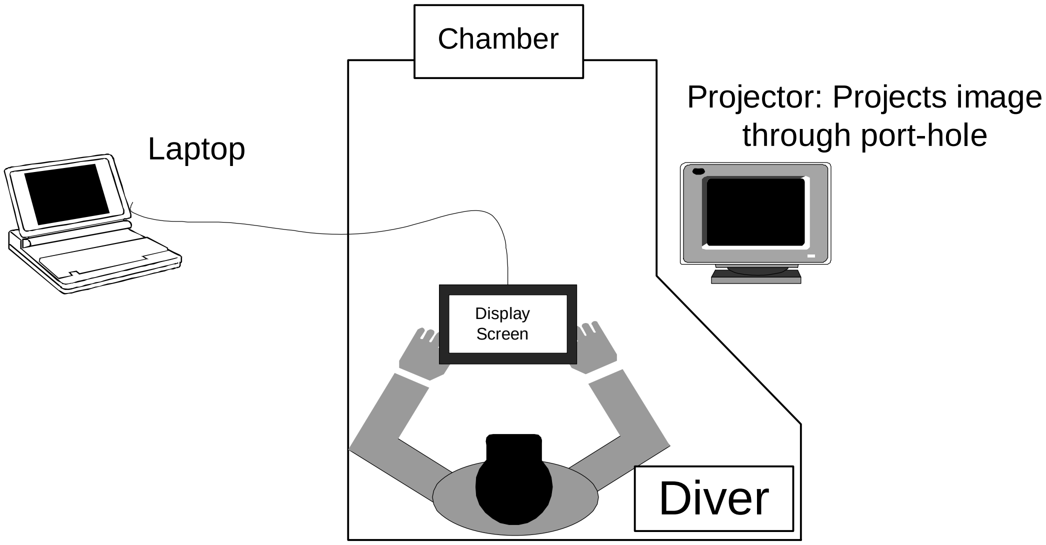


Figure 1: Experimental apparatus and data collection system

A secondary display screen was used to provide the diver with a detailed image of a mine-like object. The object consisted of a basic shape with ancillary attachments and lettering or symbols on the main body. Each object was viewed and matched to one of a series of images shown on either the HDD or HMD. In the surface condition, a secondary computer screen, controlled by the researcher, was used to show these images. The divers were asked to view the secondary computer screen as required during the trial. In the depth condition, images were projected through the DRF Wet Chamber viewport onto a screen in the wet section of the chamber. The diver was asked to view the screen as required during the dive.

Underwater Displays

The purpose of each type of display was to provide the MCM divers with information regarding their (simulated) surroundings, position, depth, time, navigation, targets, and decompression. Each display also provided the diver with alarm information on their equipment status (oxygen and carbon dioxide partial pressures (PO2 & PCO2), breathing apparatus gas supply pressures). In this study, all of the displayed information was simulated, except that depth and time followed the actual dive profile. All three displays were programmed to provide the same screen resolution (480 x 234 pixels) which was the maximum resolution of the head down display. Although the maximum resolution capability of the head mounted displays was higher, the resolution was set to match that of the HDD.

Head Mounted Displays

The HMDs were developed as prototypes by the US Navy. They have been used in field use in a number of operations including the recovery of debris from the space shuttle Columbia. The devices consist of a head mounted liquid crystal display (LCD) that attaches to the mask of the diver (AGA Divator Mk II). The HMD was hard-wired via a through hull connector to a laptop computer that was operated by the research team outside the hyperbaric chamber. The HMD was connected to the laptop's video output and to a 12 volt DC power supply. In this study the HMD was tested in two versions: a monocular display and a binocular display.

The monocular display was positioned over the right eye of the diver and the binocular display is positioned over both eyes. The HMD was rotated into the diver's field of view when the displayed information was required and can be rotated upwards, out of the diver's field of view, when the diver wishes to view his surroundings. The diver was in control of the position of the HMD display for the duration of the dive.

Figure 2. Diver wearing Monocular HMD.

Head Down Display

The HDD provided the diver with the same information displayed on the HMD. The system consisted of a hand-held LCD (Audiovox LCD Model No. LCM-5600 (Display 5.6" diagonal (114 x 83 mm) with 480 x 234 resolution) housed in a clear acrylic, pressure and waterproof case designed by Shearwater Human Engineering and manufactured by Dimension-3 Plastics. Details of the Audiovox LCD and pressure housing are provided in Appendix 1. The pressure proof case was designed to an ultimate strength of approximately 1.5 MPa (150 msw) and pressure tested to 100 msw. The HDD was hard-wired via an underwater cable and through hull connector to the laptop computer operated by the research team external to the hyperbaric chamber. The display was connected to the laptop's video output and a 12 volt DC power supply.

Diver equipment

The divers and the standby diver breathed compressed air and oxygen from the in-service CF full-facemask and open-circuit demand regulator (Interspiro AGA with Divator Mk II regulator) connected to the DRF Built in Breathing System (BIBS). Divers wore CF in-service neoprene dry suits with Thinsulate® underwear, a neoprene hood, neoprene three-fingered gloves and weight belt. Divers were also equipped with voice communications and one of the three underwater displays connected via an umbilical cable.

Experimental Conditions

Surface Condition

The surface conditions were completed in an air environment in the DRF. The HDD was immersed in clear water in a glass aquarium. The diver viewed the display through a facemask mounted to the side of the aquarium. The glass of the facemask was removed and the glass wall of the aquarium acted as its replacement (i.e., the air-water interface). The distance between the diver's eye and the display was 40 cm.

The diver provided feedback to the researcher verbally, while viewing and processing information displayed on the screen. The researcher viewed the same information on the laptop display that the diver viewed on the underwater display.

To view the HMDs (monocular and binocular) in surface air conditions, the diver was asked to wear the full-facemask (Interspiro AGA) from which the demand regulator was removed so that the diver was breathing room air. A HMD was mounted to the top rim of the full-facemask to position the display directly in the diver's field of view.

When viewing each display, the diver was dressed in normal work clothing and was seated in an upright position.

Depth Condition (42 msw).

The depth condition was completed in an underwater environment (at 6^{o}C water temperature) in the Dive Chamber of the Diving Research Facility at DRDC Toronto. Each dive team consisted of two divers (subjects), a standby diver and a team leader. One type of display was provided for each subject in each dive. The divers were also equipped with an underwater voice communications system (each on a separate channel) that allowed them to converse with a researcher and with the chamber operators outside the hyperbaric chamber. Each diver was in communication with a separate researcher, who controlled the information on the display screen through a laptop computer. The diver was expected to respond to visual stimuli on the display screens verbally. Table 2 shows the dive conditions.

Table 2: Diving depths and times for experiments (*Based on CF Decompression Table 2*)

Gas	Depth (msw)	Bottom Time (min)	Total Time (min)	Remarks
Air	42	35	73	3 dives per diver
Air	0	N/A	20	3 trials per diver

Dive Scenarios

In each condition, the diver completed a simulated dive scenario. The tasks performed in each condition were similar but the information displayed was not the same. Each dive scenario required the diver to recognize and respond to information about the stage of the dive. The diver was verbally directed to find specific types of information on the display. For example, the diver was asked to report his depth, dive time, or navigational heading. The diver was also expected to respond appropriately to information that was displayed. If an alarm was shown at any time during the dive, the diver was expected to report the alarm verbally as well as the appropriate course of action to respond to the alarm. Each diver received four alarm signals at random times; two during descent and two during bottom time.

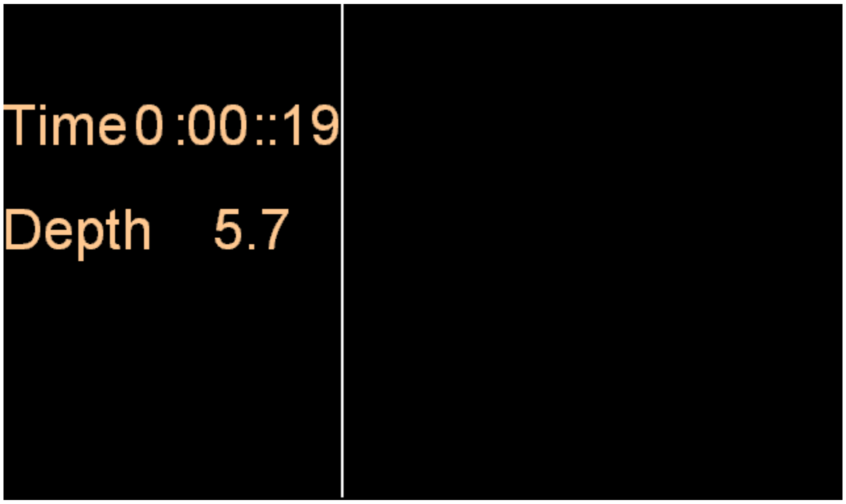
The display of information and data collection was subdivided into five stages of the dive with each stage involving a different task. The method of data collection and the type of information that was displayed in each stage of the dive are presented below.

Stage 1: Compression/ Descent

As the diver was compressed the display screen provided simulated information on the diver status. A typical sample screen and the information to be displayed are shown in figure 3. The diver was expected to respond to this information verbally. In the air environment, compression was simulated without change of depth by changing the information displayed on the screen. During the descent phase, the depth and time displayed on the diver's screen was incremented in real time. The diver was required to monitor the display and report his depth at every three-metre depth increment. The diver also had to respond to two systems alarm conditions that appeared in the display at random time intervals during the descent. The researcher activated a button connected to the computer immediately the diver responded. Depth, time, and response time data were automatically collected by the computer program.

Information to be displayed to the diver

- Depth
- Time



Time 0 :00::19

Depth 5.7

Figure 3: Sample of screen layout and information to be displayed

Stage 2: On the bottom, simulated navigation task

The diver was asked to view a navigation screen and to identify diver location and the location of three targets. A sample of the screen layout and the information to be displayed is shown in figure 4. Data on distance, bearing, and time were logged automatically by the computer program. The target that the diver was required to navigate to was highlighted in a brighter colour than the two other targets. The diver started the navigation task from the shot (a weight that secures the line down which the diver descends). The diver was asked to report information verbally on the distance and bearing from the diver to the first target. The researcher entered the distance and bearing into the computer and the display moved the diver's location to that position. If the new position did not coincide with the target location, the diver was asked to provide a new distance and bearing until the diver's position coincided with the target. The diver then provided a new distance and bearing to the next target. This procedure was repeated until all three targets had been successfully located. The diver's ability to navigate through the simulated navigation task was measured for speed and accuracy (number of steps).

Information to be displayed to the diver

- Depth
- Compass bearings
- Position of diver
- Identification of strongest target
- Time
- Position of shot
- Positions of targets
- Distance to target(s)

Figure 4: Sample of navigation screen and information to be displayed

Stage 3: On the bottom, simulated sonar target location task

The purpose of this task was to present the diver with a display in which the information to be identified is merged with background noise. This type of display, in which a diver has to recognize shapes that are indistinct or partly hidden, is more typical of a sonar visual display. The display contained a number of shapes, some of which were abstract, and some of which were geometrical. The shapes were superimposed on an uneven background with low contrast between the shapes and the background. A sample of the screen layout is shown in figure 5. The display provided a simulated "diver's eye view" of the seabed as viewed from a hand-held sonar.

Level 1: The diver was asked to identify the geometric objects within the display screen, describe their shape and features, and provide their distance and bearing from cues on the screen. The diver was allocated a score based on the number of objects correctly identified and the correct information provided about the object. The number of targets displayed varied between 4 and 6. Therefore, the score was normalized by dividing the total score by the number of objects. A second score was allocated for the accuracy with which the diver was able to locate the objects (position expressed as a heading (degrees) and distance (m)).

Level 2: The display was then changed to zoom in on a specific target. The diver was required to provide a detailed description of the target, including the new distance and bearing. This zoom process was repeated for three of the geometric shapes. The diver was allocated a score for the amount of correct information (detail) reported about each object. A second score was allocated for the accuracy with which the diver was able to locate the objects (heading and distance) on the zoom screens. The time taken for the task was logged automatically by the computer. The description, heading and distance of each object were logged by the researcher.

Information to be displayed to the diver

- Depth
- Simulated sonar image of seabed
- Range (m) of field of view
- Time
- Obstacles denoted by change in contrast and shadow
- Compass headings

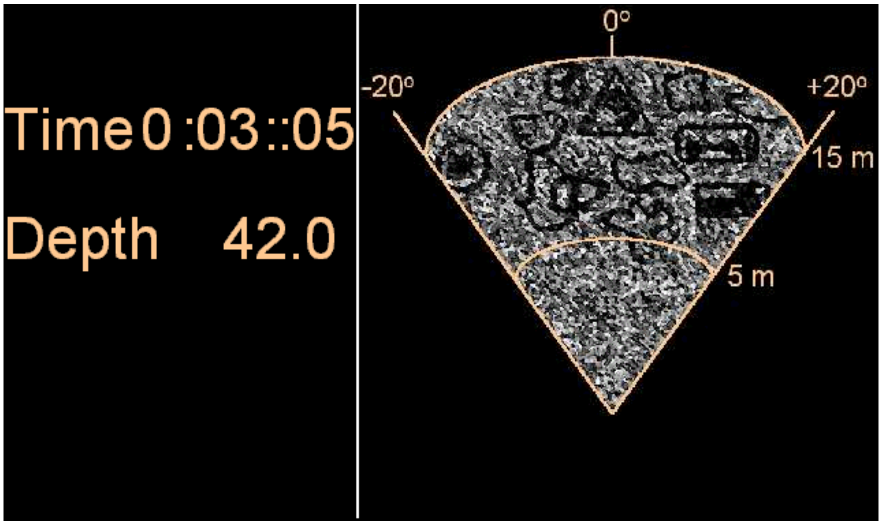


Figure 5: Sample of sonar target location screen and information to be displayed

Stage 4: On the bottom, target identification

An image of a simulated mine-like-object was viewed by the diver either on a secondary computer screen (surface) or on a secondary underwater screen in the chamber (42 msw). A sample of the screen layout is shown in figure 6. The diver was required to proceed through a series of display screens in order to match the target to the correct image contained in a shape library of twenty seven images stored in the computer. The first series of display screens provided the lowest level of detail. The diver proceeded through three display screens showing different outline shapes of the “mine”. The diver selected the basic “mine” shape from this series of screens.

The second series of screens used the correct outline shape, and added detail to the “mine”. The diver viewed three screens that showed the same outline shape, with different types of attachments. The diver attempted to select the correct configuration of attachments from this series of screens.

The third series of screens added specific numbering and lettering information to the selected “mine”. The diver viewed three screens with the same attachments, but different types of alphanumeric information. The diver attempted to select the correct “mine” information from this series of screens. The time taken to complete the task was logged automatically by the computer program.

Information to be displayed to the diver

- Depth
- Target shape
- Alphanumeric data
- Target orientation
- Time
- Target attachments
- Target identification number

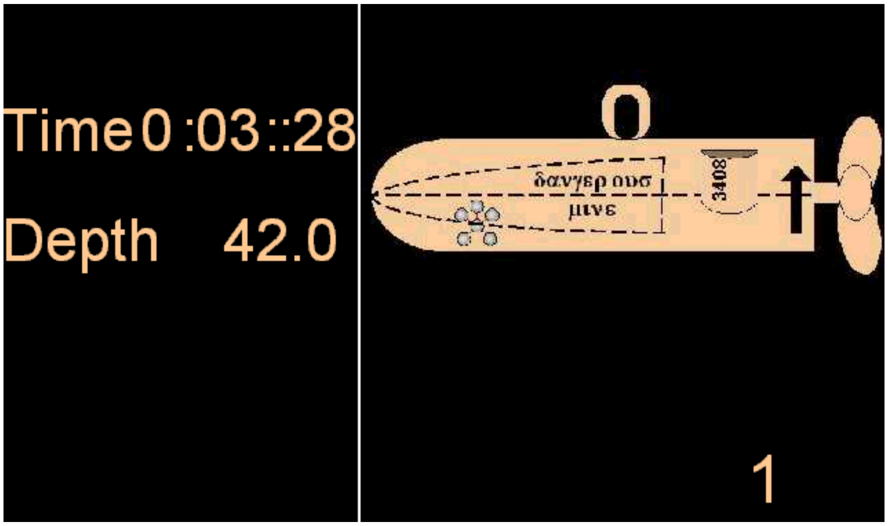


Figure 6: Sample of target identification screen and information to be displayed

Alarms

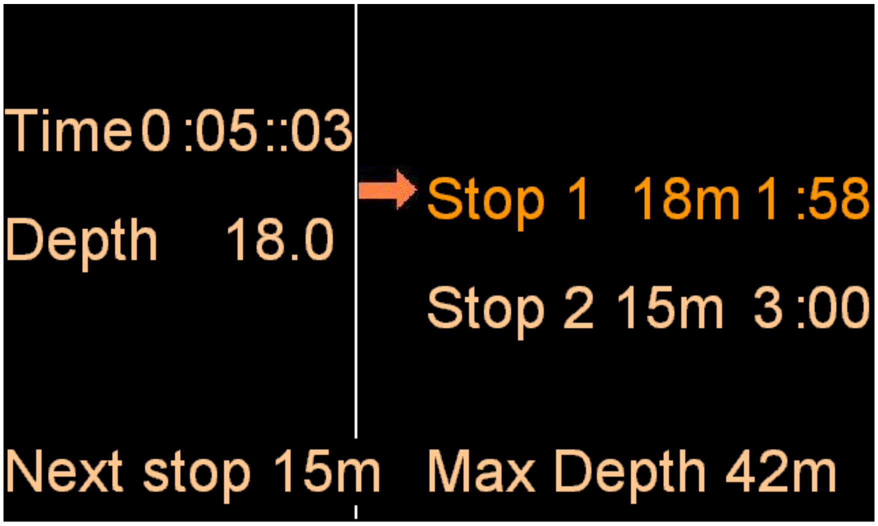
The diver also had to respond immediately to any systems alarm condition that appeared in the display during the bottom time (stages 2 through 4). Two system alarms were generated during the bottom time. Timing of the alarms was randomly assigned, but did not occur during other task assignments in order to avoid conflict with objective measures of task times. The researcher activated a button connected to the computer immediately the diver responded.

Stage 5: Decompression/ Ascent

As the diver was decompressed the display screen provided information on the dive status. A sample screen is shown in figure 7. The diver was expected to respond to this information by reporting verbally the depth at three-meter increments, arrival at decompression stop, and stop time. In the air environment, decompression was simulated without physically changing the depth. Only the depth on the display changed. The response times were recorded automatically to the computer by the researcher using a single button keypad.

Information to be displayed to the diver

- Depth
- Decompression stops
- Next stop
- Time
- Time remaining at current stop
- Maximum depth



Time 0 :05::03

Depth 18.0

→ Stop 1 18m 1 :58

Stop 2 15m 3 :00

Next stop 15m

Max Depth 42m

Figure 7: Sample of decompression screen and information to be displayed

Measurements

Objective Measures

The objective measures used to compare the three types of underwater display were the speed and accuracy with which the divers could recognise, process and make decisions on information provided by each display.

Accuracy

The number and type of errors made with each type of display were recorded. Errors provide information about the difficulties that a diver may have when using the different types of displays. The type of errors and the tasks in which the errors were made also provide information about the divers' abilities to use the displays effectively and for improving the design of each display system. Types of error can be categorized as:

1. Missed information. Display cues that were not noticed or reported by the diver. (For example, three-metre depth increment not reported on descent.)

2. Incorrect information. Errors in interpreting the information displayed. (For example, incorrectly identified object when asked to find specific information during sonar location task).

3. Execution errors. Errors in using the display. (For example, the number of extra steps required to complete the navigation task.)

Some errors are more hazardous than others. Missing an alarm notification has more serious consequences than misjudging a target position cue that can be corrected. For this reason, errors are categorized and reported separately for each task.

Speed

Speed is an important factor in using an underwater display. The diver should not be required to spend an excessive amount of time searching for or responding to information. It is difficult to find a meaningful measure of speed because there were no data that suggest an optimal operating speed for the use of underwater displays. For instance, the difference between 0.5 and 1.0 second to respond to a message may or may not be meaningful. Therefore, speed was used as an analytical tool to determine whether the times taken by the divers to complete specific tasks using the three displays were significantly different. Speed (response time or task time) was measured by the computer program as the time from which a message was first displayed to the time of response.

Subjective Measures

The divers were interviewed upon completion of the dive series. The interviews were designed to collect specific information from the divers on their preferences for type of display and methods of displaying information for MCM diving. This included the characteristics of the display layouts provided to the divers during each phase of the dive, such as amount of information on the screen, method of presentation, location of information, analog versus digital data, etc. Information was also collected on the characteristics of the three display types, including usability of the display, comfort, integration and/or interference with other MCM tasks and equipment, and ease of accessing and interpreting information displayed.

Analysis

The experiment consisted of a 2 (condition) x 3 (display) repeated measures factorial design. The conditions were: surface, dry, breathing room air at room temperature; and 42 msw, immersed in 6^{o}C water, breathing compressed air from a demand regulator. Each stage of the experiment was treated in a separate analysis. Objective data (accuracy, speed) were analyzed for main effects of environment and type of display using one-way analysis of variance. Significant differences were determined at the $p<0.5$ level.

Subjective data were analyzed to determine differences in diver perception of the three display devices. This included the usability of the display, comfort, integration and/or interference with other MCM tasks and equipment, perceived information overload, and ease of accessing and interpreting the information displayed.

In addition, the objective and subjective information collected from each of the five phases of the dive was further analyzed to determine whether the best display device is task dependent or diver dependent.

Results

Descent and Ascent

The data collected during the descent and ascent stages of the dive are similar, and are therefore presented together. The data are presented in four separate analyses shown in tables 3, 4, 5 and 6. These tables show the following results:

- Descent mean reaction time: the mean time (seconds) for the diver to report each of 13 depth increments (three-meter increment in depth) when descending;
- Descent misses: the number of descent depth increments that the diver did not report;
- Ascent mean reaction time: the mean time (seconds) for the diver to report each of 8 depth increments when ascending;
- Ascent misses: the number of ascent depth increments that the diver did not report.

Table 3: Mean reaction times for reporting depth cues when descending

Descent: mean reaction time (s) ± standard deviation (n=9)		
Display	0 msw	42 msw
HDD	1.0 ±0.3	1.1±0.3
HMD mono	1.4±0.8	1.4±0.5
HMD bino	1.1±0.3	1.7±0.8

Statistics			
	F	Sig.	Power
Environment	2.9	0.1	0.3
Display	1.8	0.2	0.3
Environment x Display	6.1	0.01	0.8

Results in table 3 indicate that there were no main effects of environment and display type on reaction time when reporting depth cues during the descent phase of the dive. However, there was an interaction effect between environment and display. Diver reaction times when using the binocular HMD during the 42 msw dive were approximately 50% slower than at the surface, whereas reaction times of the other two displays were unchanged. Diver reaction times when using the binocular HMD were also approximately 50% slower than when using the HDD during the 42 msw dive.

Table 4: Number of misses when reporting depth cues during descent

<table>
<tr><th colspan="4">Descent: mean misses ± standard deviation (n=9)</th></tr>
<tr><td>Display</td><td>0 msw</td><td colspan="2">42 msw</td></tr>
<tr><td>HDD</td><td>0.2±0.4</td><td colspan="2">1.0±1.5</td></tr>
<tr><td>HMD mono</td><td>1.1±0.3</td><td colspan="2">0.6±0.7</td></tr>
<tr><td>HMD bino</td><td>0.1±0.3</td><td colspan="2">0.9±1.6</td></tr>
<tr><th colspan="4">Statistics</th></tr>
<tr><td></td><td>F</td><td>Sig.</td><td>Power</td></tr>
<tr><td>Environment</td><td>2.2</td><td>0.2</td><td>0.3</td></tr>
<tr><td>Display</td><td>0.4</td><td>0.7</td><td>0.1</td></tr>
<tr><td>Environment x Display</td><td>2.1</td><td>0.2</td><td>0.4</td></tr>
</table>

Results in table 4 indicate that there were no significant effects of environment and display type on the number of missed depth cues during the descent phase of the dive. Divers missed on average one or less of the 13 depth increments when using all three display types in both environments. This represents less than a 10% error (missed information) rate.

Table 5: Mean reaction times for reporting depth cue when ascending

<table>
<tr><th colspan="4">Ascent: mean reaction time (s) ± standard deviation (n=7)</th></tr>
<tr><td>Display</td><td>0 msw</td><td colspan="2">42 msw</td></tr>
<tr><td>HDD</td><td>1.7±0.5</td><td colspan="2">1.3±0.5</td></tr>
<tr><td>HMD mono</td><td>1.8±0.2</td><td colspan="2">1.9±0.3</td></tr>
<tr><td>HMD bino</td><td>1.6±0.4</td><td colspan="2">2.1±0.3</td></tr>
<tr><th colspan="4">Statistics</th></tr>
<tr><td></td><td>F</td><td>Sig.</td><td>Power</td></tr>
<tr><td>Environment</td><td>1.5</td><td>0.3</td><td>0.2</td></tr>
<tr><td>Display</td><td>4.2</td><td>0.04</td><td>0.6</td></tr>
<tr><td>Environment x Display</td><td>5.3</td><td>0.02</td><td>0.7</td></tr>
</table>

Two divers did not complete the ascent phase of the experiment due to equipment malfunction. As a result, the sample size decreased to 7 for the ascent phase. Results in table 5 show that there was a main effect of display type (F=4.2, p=0.04) on diver reaction time when reporting depth increments on ascent. There was also a significant interaction effect between display and environmental condition (F=5.3, p=0.02). There were no differences in reaction times between displays at the surface. However, at 42 msw scores were approximately 50% slower when using a HMD (either mono or bino) when compared with a HDD.

Table 6: Number of Misses when reporting depth cues during ascent

Ascent: mean misses ± standard deviation (n=7)			
Display	0 msw	42 msw	
HDD	0.1±0.4	0.4±0.8	
HMD mono	0.1±0.4	0.7±1.3	
HMD bino	0.1±0.4	0.9±1.6	
Statistics			
	F	Sig.	Power
Environment	2.5	0.2	0.3
Display	0.2	0.8	0.08
Environment x Display	0.3	0.7	0.09

Results shown in table 6 indicate that there were no significant effects of environment and display type on the number of missed depth cues during the ascent phase of the dive. When using all three display types, divers missed on average one or less of the 8 depth increments during the ascent from the 42 msw dive, and almost none of the depth increments in the surface condition.

Alarms

Alarm data were analyzed in three categories:

1. Descent alarms: mean reaction time (seconds) to report each of two alarms that occurred randomly during the descent phase of the dive;

2. Bottom alarms: mean reaction time (seconds) to report each of two alarms that occurred randomly during the bottom time of the dive;

3. Number of misses: total number of missed alarms during the dives.

Table 7: Mean reaction times for reporting alarms when descending

Alarms: reaction time (s) during descent (n=9)			
Display	0 msw	42 msw	
HDD	0.2±0.0	2.1±0.6	
HMD mono	0.3±0.4	2.0±0.6	
HMD bino	0.2±0.1	3.6±1.4	
Statistics			
	F	Sig.	Power
Environment	127.4	0.000	1.0
Display	7.2	0.006	0.9
Environment x Display	10.2	0.001	1.0

There was a main effect of environment (F=127.4, p=0.000) and of display type (F=7.2, p=0.006) on diver reaction time to alarms (table 7). There was also an interaction effect between environment and display. The difference in reaction time between the surface and the 42 msw condition can be explained by a difference in the experimental technique. The divers operated a response button at the surface, so that reaction times represent the time divers took to see the alarm. During the 42 msw dive, the researcher activated the response button. Therefore, reaction times represent the time taken for the diver to see and verbally report the alarm. There was no significant difference in diver reaction times when using the different displays at the surface condition. Reaction times (including reporting) were slower when using the binocular HMD compared with the other two displays when descending to 42 msw (F=10.2, p=0.001).

Table 8: Mean reaction times for reporting alarms when on bottom

Alarms: reaction time (s) during bottom time (n=9)			
Display	0 msw	42 msw	
HDD	2.3±0.8	2.5±0.2	
HMD mono	3.2±1.3	2.3±0.3	
HMD bino	2.8±1.0	2.0±0.3	
Statistics			
	F	Sig.	Power
Environment	3.2	0.1	0.4
Display	1.4	0.3	0.2
Environment x Display	3.8	0.05	0.6

Results shown in table 8 indicate that there were no main effects of environment and display type on reaction time for alarms during the bottom time of the dive. However, there was an interaction effect between environment and display type on reaction time. When using both types of HMD, reaction times were shorter at 42 msw than at the surface.

Table 9: Number of misses in reporting four alarms throughout dive

Alarms: number of misses (n=9)		
Display	0 msw	42 msw
HDD	0.0±0.0	0.3±0.7
HMD mono	0.0±0.0	0.3±0.5
HMD bino	0.0±0.0	0.6±0.9

Statistics			
	F	Sig.	Power
Environment	11.3	0.01	0.8
Display	0.3	0.8	0.08
Environment x Display	0.3	0.8	0.08

Results in table 9 show a main effect of environment on the number of missed alarms (F=11.3, p=0.01). Divers did not miss any alarms during the surface condition, but missed an average of 10% of alarm cues during the simulated wet dive to 42 msw.

Navigation

Results of the navigation task are presented in three separate analyses:

1. Total navigation time: mean time (in seconds) to complete the navigation task;
2. Number of steps: mean number of steps (distance and heading) required to navigate to targets displayed on the screen;
3. Distance off target: the distance by which the diver missed the target. This was calculated as the error between the actual target location and the location reported by the diver.

Table 10: Total navigation time

Navigation: mean total navigation time (s) + SD (n=8)		
Display	0 msw	42 msw
HDD	51.4±18.3	57.1±23.8
HMD mono	56.9±25.8	64.5±19.3
HMD bino	46.6±13.2	84.5±34.5

Statistics			
	F	Sig.	Power
Environment	8.3	0.02	0.7
Display	2.7	0.1	0.4
Environment x Display	1.6	0.2	0.3

Results in table 10 show that there was a main effect of environment (F=8.3, p=0.02) on the time taken to complete the navigation task. Divers were approximately 33% slower at 42 msw than the surface.

Table 11: Navigation: number of steps

Navigation: number of steps (n=8)		
Display	0 msw	42 msw
HDD	5.1±1.4	4.9±1.5
HMD mono	5.3±1.8	5.3±1.6
HMD bino	4.6±1.1	5.8±2.2

Statistics			
	F	Sig.	Power
Environment	1.5	0.3	0.2
Display	0.3	0.7	0.09
Environment x Display	0.5	0.6	0.1

Table 11 shows that there were no significant effects of environment or display on the number of steps required in order to navigate to the three targets.

Table 12: Cumulative error in location of three targets

Navigation: cumulative error distance (n=8)		
Display	0 msw	42 msw
HDD	66.9±64.6	31.2±27.1
HMD mono	74.4±65.1	76.3±97.0
HMD bino	41.3±40.9	73.8±69.7

Statistics			
	F	Sig.	Power
Environment	0.00	1.0	0.1
Display	1.1	0.4	0.2
Environment x Display	0.9	0.4	0.2

Results in table 12 show the cumulative error in calculating the positions of the targets. To calculate these values, the minimum distance required to move to all three targets was subtracted from the actual distance moved. Results show that when navigating to the three targets there were no significant effects of environment or display on the total of position errors.

Sonar target location

Results of the sonar target location task are presented in five separate analyses:

1. Total time for sonar location task: the total time taken by the diver to locate and identify all the relevant information at both the expanded and zoomed views of the simulated sonar screens. Time is reported in minutes.

2. Target location score for level #1: the score for correctly identifying the targets on the expanded view of the sonar screen;

3. Position score level #1: the accuracy in reporting position of the targets; scored as a fraction where the maximum score equals 1

4. Score for level #2 (zoom): the sum of scores for identifying the shapes and details of each shape in each of the three zoom screens. Each zoom screen was first scored as a percentage, then converted to a score out of 1 (i.e., 80%=0.8). The scores were then added for a total zoom score out of 3.

5. Position score for level #2 (zoom): the cumulative score for accuracy in reporting position of the target at each of the zooms. Measured as a score out of 1. The scores were then added for a total zoom score out of 3.

Table 13: Sonar target location: total time

Sonar target location time (min) (n=9)		
Display	0 msw	42 msw
HDD	3.1±0.8	3.4±1.0
HMD mono	3.4±1.4	4.3±1.0
HMD bino	3.7±1.2	4.8±1.2

Statistics			
	F	Sig.	Power
Environment	14.3	0.005	0.9
Display	5.4	0.02	0.8
Environment x Display	0.7	0.5	0.2

Results of table 13 show main effects of environment (F=14.3, p=0.005) and display (F=5.4, p=0.02). Time to complete the sonar navigation task was on average 23% slower at 42 msw than at the surface. During the dive to 42 msw, the time to complete the task was fastest (3.4 min) for the HDD compared to 4.2 min when using the HMD (mono), and 4.8 min when using the HMD (bino).

Table 14: Sonar target identification score for level 1

Sonar target identification score (n=9)		
Display	0 msw	42 msw
HDD	49.0±27.3	38.0±33.0
HMD mono	58.9±26.2	26.7±224.1
HMD bino	48.9±23.1	32.2±36.3

Statistics			
	F	Sig.	Power
Environment	8.8	0.02	0.7
Display	0.06	0.9	0.7
Environment x Display	1.4	0.3	0.3

Results in table 14 show that there was a main effect of environment (F=8.8, p=0.02) on sonar target location scores. Divers were approximately 38% less accurate in identifying shapes at 42 msw than at the surface. There was no significant effect of display on score.

Table 15: Accuracy in reporting target position: level 1

Accuracy of target location: score (/1) (n=9)		
Display	0 msw	42 msw
HDD	0.5±0.2	0.5±0.3
HMD mono	0.7±0.3	0.3±0.3
HMD bino	0.5±0.3	0.4±0.3

Statistics			
	F	Sig.	Power
Environment	8.3	0.02	0.7
Display	0.1	0.9	0.06
Environment x Display	1.7	0.2	0.3

Results in table 15 show that there was a main effect of environment (F=8.3, p=0.02) on the accuracy with which the divers were able to locate (position) objects on the screen. Divers were approximately 28% less accurate in reporting the heading and distance of targets at 42 msw than at the surface. There was no significant effect of display on ability to judge position.

Table 16: Sonar target identification score for level 2 (zoom)

Sonar target identification score (/3) (n=9)		
Display	0 msw	42 msw
HDD	2.3±0.7	2.3±0.6
HMD mono	2.2±0.7	1.6±1.0
HMD bino	2.3+0.8	1.7±0.8

Statistics			
	F	Sig.	Power
Environment	5.9	0.04	0.6
Display	1.1	0.4	0.2
Environment x Display	1.2	0.3	0.2

Table 16 shows a main effect of environment on the ability of divers to accurately discern the information contained in the identified target. The scores for accuracy of detailed information were approximately 28% lower at 42 msw than at the surface (F=5.9, p=0.04). The type of display had no significant effect on accuracy.

Table 17: Accuracy in reporting target position: level 2 (zoom)

Accuracy of target location: score (/3) (n=9)		
Display	0 msw	42 msw
HDD	2.7±0.4	2.9±0.2
HMD mono	2.6±0.6	2.3±1.1
HMD bino	2.9±0.3	2.5±0.4

Statistics			
	F	Sig.	Power
Environment	1.0	0.3	0.1
Display	2.6	0.1	0.4
Environment x Display	1.2	0.3	0.2

There were no main effects of environment or display on the accuracy with which the divers reported the position of the three targets when viewed in the zoom mode.

Target Identification

The target identification task was scored as the total time required for the diver to match the target image that was projected into the chamber or on the secondary computer with the matching target image on his display. In cases where the diver was either unable to find a match or where he made an error, a miss was recorded. There were not enough errors to warrant statistical analysis.

Table 18: Target Identification: Total time to identify a target

Time (s) to identify target (n=8)		
Display	0 msw	42 msw
HDD	34.5±22.2	31.9±12.7
HMD mono	32.8±18.1	32.4±12.2
HMD bino	28.5±6.1	31.1±12.9

Statistics			
	F	Sig.	Power
Environment	0.001	1.0	0.05
Display	0.4	0.7	0.1
Environment x Display	0.2	0.8	0.07

Results shown in table 18 indicate that there were no main effects of environment or display on the time required to identify a target.

Subjective Data

To compliment the objective data, divers were asked to provide subjective data on the usability of each of the displays. Divers were also asked to provide their display preferences for the different phases of the dive, as well as explanations of their likes and dislikes. Results of the subjective questionnaire were collated and are summarized in tables 19 to 22. The following section outlines the major subjective findings.

Table 19 shows the ranking of each display by diver preference. Although there was no consistent preference for a particular display, it is notable that 8 of 9 divers ranked the HDD first or second, while 7 divers ranked the HMD (bino) second or third, and five divers ranked the HMD (mono) last.

Table 20 summarizes the divers' subjective reports of the strengths and weaknesses of each of the three types of display.

Table 21 summarizes the divers' comments on the comfort, effectiveness, ease, or difficulty of using the three different display types to complete each task. Divers were also asked to rank the display within each stage (or task) of the dive. There were no changes from the overall rankings except in the navigation task where one diver, who preferred the HMD bino overall, preferred the HDD for the navigation task.

Table 22 provides the design changes suggested by the MCM divers that are required to improve the effectiveness and usability of each display type.

Table 19: Subjective data on usability of display type

Factor	**Response**		
Overall Rank of Display	HDD	Mono	Bino
Rank #1	4	3	2
Rank #2	4	1	4
Rank #3	1	5	3

Table 20: Strengths and weaknesses of the three display types Comments

	Strengths	Weaknesses
HDD	Display is clear and easy to get information Easy to see, can look at it when need it, but don't have to look at it. Seemed less fatiguing Could concentrate on surroundings	Display housing is too large, and too buoyant. Display needs to be hands-free (i.e., wrist mounted).
HMD Mono	Can "look through" display. Can view display without covering entire field of view. Easy to swim with	Caused eye fatigue. Disorienting for some divers (n=4), in some cases caused nausea (n=3). Hard to concentrate on surroundings
HMD Bino	Can see entire display at once. Easier to focus on information (compared to mono). Easy to swim with	Covers entire FOV. Had to concentrate on display all the time. Difficult to monitor surroundings. Caused eye fatigue. Disorienting for some divers (n=4), in some cases caused nausea (n=3). One diver reported transient loss of vision after removing HMD (bino): lasted less than 5 seconds.

Table 21: Task specific comments on three displays types.

Dive Scenario	Comments
Descent	No difference to overall rank Buoyancy of HDD was problematic during descent (added to cognitive load of divers).
Alarms	No difference to overall rank Most divers reported that they were not noticing the LED that triggered them to look for an alarm when wearing the HMDs but did notice them when using the HDD.
Navigation	One change to overall rank. Diver who preferred HMD bino overall found the HDD preferable for navigation. Divers who preferred the HDD reported that reading navigation with a plan display is easier: this may be a result of training Could see more information, and judge distance more accurately using a HDD. Most divers (n=8) reported that the HDD was a good option (even if not the favourite) for navigation. One diver reported that he thought the HMD options would be preferred for navigation since he wouldn't have to look at his wrist while swimming with a HMD.
Sonar Navigation	No differences to overall rank HMD mono particularly difficult for some divers for sonar navigation because display was too complex for single-eye vision. Some divers (n=4) reported that they had to close one eye for entire Sonar Navigation task to see display properly.
Target ID	No differences to overall rank Divers reported that one strength of the HMD mono during this phase was the ability to view both the target and the display at the same time. Divers reported that a disadvantage of the HMD bino was that the display was in the way of viewing the target, and it was inconvenient to keep moving the display out of the way
Ascent	No differences to overall rank Ascent phase of the diver was more difficult than the descent phase: may be due to fatigue.

Table 22: Design changes recommended by MCM divers

Factor	Comments/Suggestions
Changes to improve HDD	HDD should be hands-free (i.e., wrist mounted). HDD should be smaller: screen size is good, but the housing was too large (see diagram in appendix 1). HDD buoyancy was a problem.
Changes to improve HMD mono	HMD mono should be smaller, and less heavy on the head. The housing around the screen should be smaller.
Changes to improve HMD bino	HMD bino should be smaller, and less heavy on the head. The housing around the screens should be smaller. Adjustment of the display should be easier, improve ability to move display out of FOV.
Changes to improve user interface (U.I.)	Generally divers liked the U.I. Information was easy to find and read (n=8). Liked how similar information was grouped together (n=8). Liked use of darker colour to denote importance/ alarm states (n=9). Some divers (n=3), thought more information (bearing information) could be provided on the screen in navigation phases (both standard and sonar navigation). Font size could have been larger on the HMD mono (this may be related to visual acuity).
Resolution	Most divers (n=7) reported that the resolution that was used (480 x 234 for all displays) was adequate. Some divers (n=4) reported that the resolution seemed to be worse for the HMDs, in particular the HMD mono. All divers (n=9) reported that the resolution should be as high as possible.
Underwater Effect	Most divers (n=7) reported that performing the experiment, and using the displays, was more difficult in the water for reasons including narcosis; Higher cognitive load due to concentrating on safety of dive, dive procedures, adjusting buoyancy, clearing ears; Higher stress load during the dive than on surface; More problems with mask fogging during dive. Two divers reported that it was harder to concentrate when on the surface due to distractions in the environment.

Discussion

To determine which type of underwater display is most appropriate for MCM diving, MCM diving tasks were simulated in a controlled environment. Both objective and subjective data were collected to compare a HDD with a monocular and a binocular HMD. Results show that no display type is consistently superior in terms of performance.

Information Layout

Prior to designing the screen layouts used in this study, separate experiments were conducted to determine the optimum font size, colours and contrasts to be used in an underwater display and the preferred amount of information to be displayed to the diver in a single screen (Morrison & Zander, 1998; Morrison & Zander, 2005b). In general, divers reported that they found the design of the display easy to read and use. Divers reported that the font sizes were appropriate, the use of colour was clear and easily differentiated, and that the amount of information on the screen was appropriate for the task, with one exception. Divers reported that the sonar navigation screen was too complex, and the image was difficult to interpret. Diver performance when interpreting the sonar navigation images was consistently degraded when comparing the diving condition to the surface condition. It is possible that the combination of environmental stressors degraded the information processing capabilities to the point that the diver experienced information overload when viewing the sonar navigation screens.

Effect of environment on performance

There were significant performance decrements associated with using all three displays at 42 msw. Six measures showed a main effect of environment, with decrements in performance at 42 msw ranging from 10 to 38%. Three other measures showed no main effect of environment, but an interaction effect with one or two of the displays associated with a decrement in performance at 42 msw. The interaction effect shows that the performance on a given display is affected differently from the others by the environment. These results confirm that it is important to test underwater displays in the appropriate environment to accurately predict diver performance. The interaction effects in particular highlight how difficult it is to predict the effects of the operational environment on diver performance, when using a new device.

The performance decrements at 42 msw may be associated with the environmental stressors discussed in the introduction. In post-dive debriefs, divers reported that they believed that buoyancy, equipment burden, and narcosis all made completing the tasks more difficult in the water compared to the air. They also reported that they did not believe that cold, vision or hearing affected their performance at all. Because the experiment was conducted in clear water in the chamber, and the divers were equipped with through water communications, it is reasonable to believe that neither vision nor hearing were factors in this experiment. When asked about the cold water post-dive, most divers reported that they had not noticed the cold. Since the divers were equipped with dry suits, and immersion in 6°C water was limited to less than 30 minutes, core cooling was not likely a factor. Although peripheral (hand) cooling is a factor in cold water diving, the manual components of the tasks in this study were small and hence unlikely to affect performance. When asked about their anxiety level, divers reported that although the cognitive and stress loads were higher during the dive, they did not believe they were unduly stressed (i.e. they did not experience anxiety), but instead were more focused when diving. In this experiment, it is likely that any increase in stress associated with diving increased arousal levels only to a point that it countered some (but not all) of the negative effects of narcosis and equipment burden. If anxiety becomes a factor when diving in open water and on a live mine, the diver's arousal level may increase to the point that it has a negative effect on diver performance. Hence, the performance decrements seen at 42 msw in this study may underestimate those of open water and live MCM diving activities.

Comparison of displays

To determine the effect of display type, both objective and subjective data were analyzed. When analyzing the objective data, three of sixteen measures showed a main effect of display type. Two of these measures also showed an interaction between environment and display, with no difference between displays at the surface but a significant difference at 42 msw. In all three cases, the HDD was associated with the best performance at 42 msw. Two measures showed no main effect of display, but an interaction effect between environment and display. In one case the HMD bino was significantly worse than the HDD at 42 msw; in the other case performance of both the HMDs showed improvement at depth. Thus, the statistical data suggests that differences in performance between displays are few, with the HDD performing better in a limited number of measures at 42 msw. Alternatively, the lack of significant findings may be because of the small number of subjects, and/or that the measures used in this study were not adequately sensitive to identify differences in performance between the displays. In many cases the the statistical analysis showed low power due to a limited number of subjects (n=9) and a considerable variance in the data. In this study the subject pool was limited by availability of trained MCM divers.

When analyzing the subjective data, results again showed that there was no consistent preference. However, the HDD was ranked first or second, by the majority of divers. Results of the subjective data showed that there are some strengths and weaknesses in each type of display. Subjective results also suggest that differences between displays may be subject specific, with some subjects having a greater aptitude to work with a given display than others. This observation was particularly notable with regard to the HMD mono (due to left-right differences in visual acuity and differences in ability to focus on the screen while observing the surrounding environment with the other eye).

There are two ways to interpret the mixed objective and subjective findings. First, that there truly is no significant difference in display type: thus it does not matter which type of display is chosen. Second, that despite the lack of overwhelming evidence, the HDD was shown to be the superior display overall for MCM diving. Both of these ideas are discussed further.

Benefits and limitations of HDD

The HDD also had limitations that were identified by the divers during the questionnaire components of the experiment. The main limitations of the HDD were related to its physical design: it was too large and bulky, had too much buoyancy, and had to be hand held. The HDD was a prototype designed by the experimenters. It consisted of a commercially available small screen display, housed in a 19 mm (¾ inch) thick acrylic box that was both pressure and waterproof. The goal of this prototype was to identify if a HDD was a feasible choice for an underwater display. Although the prototype was sufficient for this purpose, it was not an ideal design. The use of the prototype in the experiment did identify design requirements for the next generation of diving HDDs. The HDD must be smaller, and neutrally buoyant, and the display must be mounted to the diver: ideally to his wrist or forearm, but possibly to a piece of equipment such as the sonar system.

Benefits and limitations of HMDs

Research on HMDs has shown that while there are some obvious benefits of HMDs, there are also some risks associated with using a HMD in an operational environment. Benefits of using a HMD include easy access to the information screen: the user merely has to adjust the focus of his eyes. Because the display is hands-free it allows the wearer to use his hands to hold tools, operate equipment controls, or to complete work.

Our results showed no improvement in diver performance when using a HMD. Even for reporting alarms, a task that theoretically should have been easier with a HMD since the diver did not have to adjust his gaze to the display to notice the alarm, performance with the HMDs was not better than performance with a HDD. In fact, when reporting alarms during the descent, diver's performance was approximately 76% slower when using the binocular HMD compared with either the HDD or the monocular HMD.

The decreased performance when using the binocular HMD may be related to information overload: that the divers were receiving too much visual stimuli by having a constantly changing display within their FOV for the duration of the descent. With the monocular display, divers were able to move their attention to the eye that was not viewing the display, but with the binocular display, the diver was constantly viewing the display.

Another potential advantage of the HMD is the fact that it is hands free, and allows the diver to use his hands for other purposes. This is a clear benefit for MCM divers who already have a high equipment burden, and who rely on their hands throughout the dive to hold and carry tools, manage lines, adjust equipment, and manipulate their orientation in the water. In the questionnaire portion of the experiment, divers did report that the hands-free characteristic of the HMD was appealing, and would be an advantage in MCM diving.

The risks of using a HMD are outlined in more detail in the introduction, and include decreased spatial awareness, inability to attend to the operational environment, lack of depth perception (particularly with monocular displays), eye fatigue, nausea and transient blindness. In addition, if the diver needs to view something in the environment, the HMD (particularly the binocular version) would have to be moved out of the FOV, during which time important information, such as alarms, may be missed. Both our objective and subjective results confirm several of these important and poorly researched issues.

People have a limited capacity to attend to and process information, even in an air environment. They are not necessarily able to attend to both the operational environment and the display information at the same time. Having a coloured, lit, dynamic display within the diver's FOV, may attract his attention away from the operational environment, and cause him to miss important cues. In one practice dive, one diver completely missed the reference target in the target identification task: the diver was intent on viewing the HMD screen before his eyes, forgot to look for the reference target in the surrounding environment, and as a result failed to complete the task. Narcosis and lack of training may also have been contributing factors in this result. The consequence of missing information from the surroundings can be fatal in MCM diving. Thus, further study of this type of event, the ability of divers to attend to the display information and the operational environment simultaneously, and the threshold at which information overload occurs is required in order to establish whether these factors represent significant problems in HMD design.

Many divers reported eye fatigue when using the HMD. Two out of nine divers reported some nausea, and one diver reported a short period of transient blindness upon removal of the HMD. These factors are recognised as possible side effects to using HMDs, but are not well documented and cannot currently be controlled by modifying the design of the display.

Comparison of displays in each stage of the dive

Data were also analyzed to determine if one type of display was more appropriate for particular MCM diving scenarios (i.e., stage of the dive). There was no significant difference in subjective ranking of displays for different stages of the dive; however, there were some interesting findings related to diver performance at the different stages of the dive.

During the descent and ascent phases of the dive, divers were asked to view the display screen and report change in depth every 3 metres. For both descent and ascent, data showed a significant interaction effect between environment and display type. In the surface condition, there were no differences in performance between display types. In the 42 msw dive, the HDD was associated with the fastest reaction times for both descent and ascent followed by the monocular then the binocular displays.

Both the descent and ascent phases of the dives are high activity times for MCM divers; they must manage their buoyancy, adjust their equipment, and attend to the depth changes displayed. The display was designed to show real-time depth information that changed with every 0.1 msw change in depth. Movement on the screen attracted attention, and it is possible that the dynamic screen design caused the divers to experience information overload or to suffer from eye fatigue, particularly during ascent towards the end of the dive. Other factors are the ability to switch attention between the display and the operational environment, and the partial occlusion of environment by the HMDs. It is easier to look away from and back to the screen when using the HDD, and to a lesser extent the monocular HMD, than when using the binocular HMD.

The binocular HMD was also associated with slower reaction times for reporting alarms during the descent phase of the dive to 42 msw. It is likely that alarm reaction times were slower with the binocular HMD for the same reasons as when reporting depth cues (described above). It is interesting to note that the effect of dive condition on alarm reaction times was different during the bottom phase of the dive (table 8) from that during the descent phase (table 7). At 42 msw, the binocular HMD was associated with the fastest reaction times, whereas the HDD was associated with the slowest times (there was no significant difference in times at the surface condition). One difference between viewing alarms on descent and on the bottom was that divers were viewing a dynamic display during descent, but a more static display (except for time) on the bottom. In addition, the diver had to attend to his equipment frequently during descent, whereas he could concentrate more carefully on the display during the bottom phase, and had less confounding information to deal with (alarms were not given when performing other tasks). It is possible that performance using the binocular HMD and the HDD responds differently to these factors (for example, when using an HMD the diver may be more sensitive to information overload).

One reason that the alarms were sometimes missed may be that the alarm trigger was via a LED outside of the useful FOV (UFOV). The alarm message itself was shown as coloured text on the screen. Other cues, such as flashing (to attract attention) or alternate use of colour may improve the visibility of alarms. For HMDs, alarms should be positioned near the bottom of the screen to ensure it is within the UFOV.

For the navigation phase of the dive, performance was 33% slower in the 42 msw condition compared with the surface, but there were no main effects for display types. The design of the display for the navigation phase of the dive was critiqued by the divers during the questionnaire component of the experiment, and divers reported that they found the display to be clear, concise, easy to read and fairly easy to interpret. However, it is important to note that due to the constraints of completing the experiment in a hyperbaric chamber, it was not possible for the divers to swim the navigation course. Most divers reported that they believed the display would have been even easier to interpret if they had been swimming the course and receiving their relative position on the display in real time.

Four tasks within the sonar target location phase showed significantly decreased performance at 42 msw. Further, at 42 msw the HDD had the best score in all sonar target location tasks, and the binocular HMD was generally associated with the worst score, although results were not significant. This trend was not evident in the surface condition. The sonar target location is a phase of the dive where the diver may have been experiencing information overload. The sonar navigation screen showed a complex image with low contrast that had to be attended to and interpreted by the diver. It is possible that the more complex or visually demanding the information, the poorer the performance when using a HMD display, particularly a binocular HMD.

Conclusions

MCM divers currently do not use any type of integrated information display. Instead, they rely on a combination of wrist and whip mounted analogue gauges, coloured HMD LEDs and lines in the water to gather information during each dive. To introduce an integrated display into the MCM diver’s equipment will be an expensive and technically difficult task: the diver's display must be water-proof, pressure-proof, and magnetically clean, in addition to being ergonomically designed. Once introduced into the system, the divers must maintain the display.

HDDs have been used in many different environments for many years while HMDs are a relatively new technology that is relatively untried in the underwater environment. To justify moving towards a HMD, the HMD would have to be significantly better than a HDD for the speed and accuracy of information retrieval, and this is not supported by the results of this study.

However, the study does offer some evidence for the HDD (and against the HMDs) as the preferred choice for MCM diving. Both the objective and subjective data show a tendency towards the HDD having the best performance in relation to completing MCM diving tasks. Most, but not all, of the limitations of the HDD are related to the physical design of the display, and as such, can be eliminated through improved design. In contrast, the limitations that were identified with the HMD are related to the technology of HMDs, and are not limitations that can be readily fixed by modifying the design. These include interference with field of view, impairment of spatial orientation, loss of situational awareness, nausea, fatigue and temporary blindness.

It is concluded from the findings of this experiment that there is inadequate evidence to recommend conclusively the implementation of any one of the three designs tested as the optimum design for MCM diving. However, based on the results of this experiment, it seems likely that a HDD is the most appropriate design solution for MCM diving for the near future. If HMDs are to be considered, more research is required to improve and validate the performance of the display in underwater operations. The current HMD technology that is used for underwater operations is not considered by the authors to be adequate for MCM divers.

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Appendix 1: Dimensions of LCD Display and underwater housing.

Audiovox Active Matrix LCD Monitor

Model No. LCM-5600
Cabinet dimensions: 160x115x29 mm (WxHxD)
Display Screen: 5.6” diagonal (114 x 83 mm)
Resolution: 480 (W) x 234 (H) dot
    Total 112320 dot
Power source: 12 VDC
    Consumption: 11 W
Operating Temperature: 0 ^{o}C to 40 ^{o}C
Weight: 500g
Video Format: PAL, NTSC

Underwater housing

Dimensions: 195x160x73 mm (WxHxD)
Thickness: 19 mm
Design Strength: 1.5 MPa (150 metres seawater equivalent depth)
Tested to: 1.0 MPa (100 metres seawater equivalent depth)

Figure A1: LCD Monitor in pressure proof underwater housing

Figure A2: Diver holding display underwater

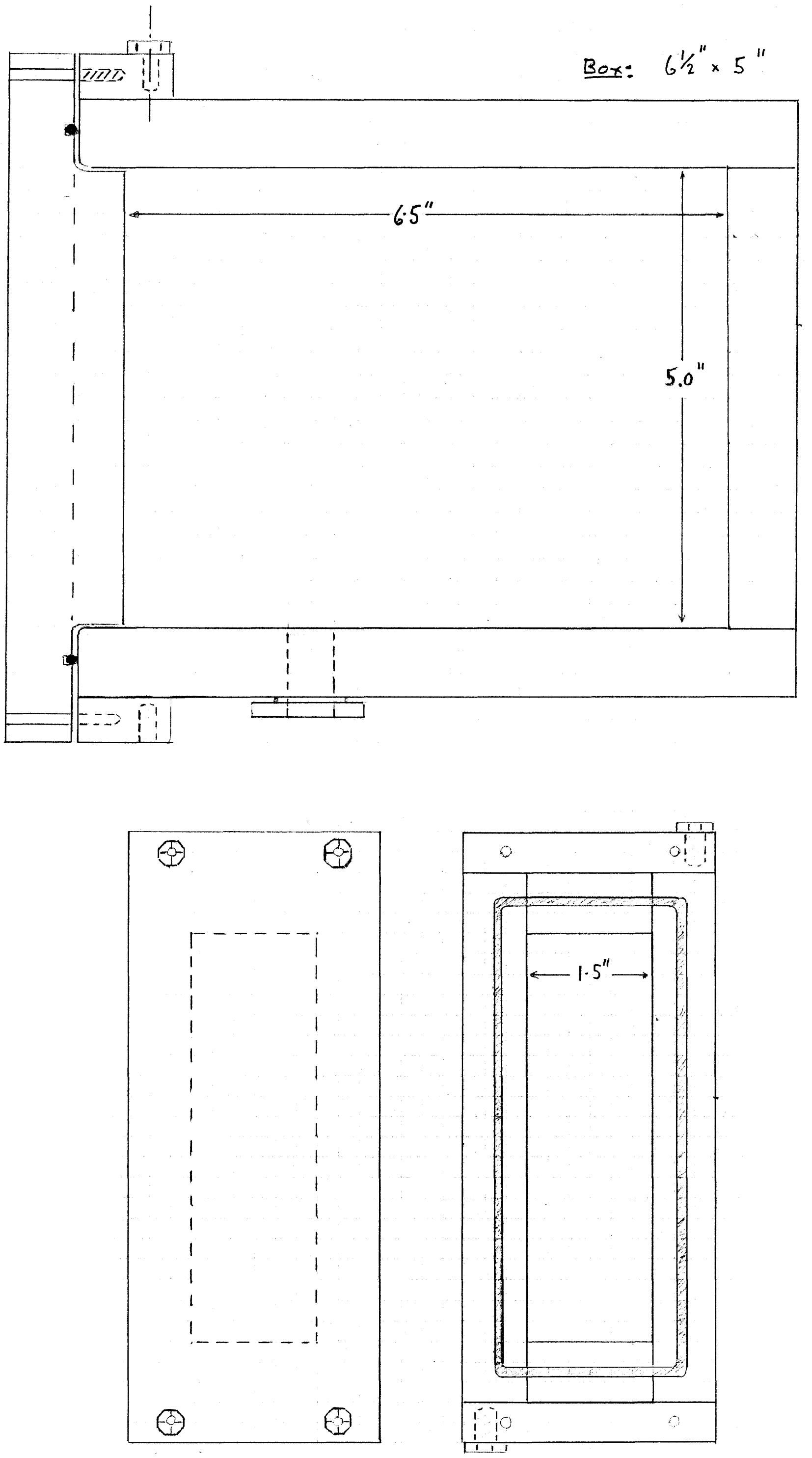

Figure A3: Schematic of pressure proof underwater display housing
Top: Front elevation showing Housing with Lid in place;
Bottom Left: End elevation of Lid for housing;
Bottom Right: End elevation of housing with lid removed, showing O-ring seal.

DOCUMENT CONTROL DATA

(Security classification of the title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (The name and address of the organization preparing the document, Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's document, or tasking agency, are entered in section 8.)

Publishing: DRDC Toronto

Performing: Shearwater Human Engineering, 438 Felton Place, North Vancouver, BC

Monitoring:

Contracting:

2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)

UNCLASSIFIED

3. TITLE (The complete document title as indicated on the title page. Its classification is indicated by the appropriate abbreviation (S, C, R, or U) in parenthesis at the end of the title)

Evaluation of head mounted and head down information displays during simulated mine−countermeasures dives to 42 msw (U)
Évaluation de dispositifs d’affichage d’information de type visiocasque ou de visualisation tête basse pendant des plongées simulées de lutte contre les mines à une profondeur de 42 m (U)

4. AUTHORS (First name, middle initial and last name. If military, show rank, e.g. Maj. John E. Doe.)

J.B. Morrison; J.K. Zander

5. DATE OF PUBLICATION (Month and year of publication of document.)

April 2008

6a NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)

55

6b. NO. OF REFS (Total cited in document.)

26

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of document, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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8. SPONSORING ACTIVITY (The names of the department project office or laboratory sponsoring the research and development − include address.)

Sponsoring:

Tasking:

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant under which the document was written. Please specify whether project or grant.)

16i

9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)

W7711−997606

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document)

DRDC Toronto CR 2008−035

10b. OTHER DOCUMENT NO(s). (Any other numbers under which may be assigned this document either by the originator or by the sponsor.)

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(U) Despite recent advancements in diver communications, there is little information on the ability of divers to use a multi−function head down display (HDD) or head mounted display (HMD) for routine underwater tasks. Three information displays (HDD, and a monocular and binocular HMD) were tested by nine mine counter−measures (MCM) divers at the surface and during simulated dives to 42 metres in 6oC water. Divers used the displays to report depth and alarms and to perform navigation, object location and target identification tasks. Task performance was analyzed for speed and accuracy. Subjective data were collected on the usability of the displays in conjunction with other MCM tasks and equipment. Performance was slower and less accurate ($p<0.05$) at 42 msw than at the surface. At 42 msw, response times were faster ($p<0.05$) when using the HDD to report depths and locate objects; otherwise there were no significant differences between displays. Subjective data showed a slight preference for the HDD. Some divers reported eye fatigue or nausea when using a HMD. Although MCM divers were capable of using both the HDD and HMD effectively during dives to 42 msw, each display presented unique design and usability problems.

(U) Malgré les avancées récentes dans le domaine des communications des plongeurs, il existe peu de renseignements sur l’aptitude des plongeurs à utiliser un dispositif multifonction de visualisation tête basse (VTB) ou d’un visiocasque pour l’exécution de leurs tâches courantes sous l’eau. Neuf plongeurs de lutte contre les mines ont testé trois dispositifs d’affichage de l’information (un dispositif VTB, un visiocasque à monoculaire et un visiocasque à binoculaire) en surface et pendant des plongées simulées à 42 m dans l’eau à une température de 6 ºC. Les plongeurs ont utilisé les dispositifs d’affichage pour signaler la profondeur et des alarmes et pour effectuer des tâches de navigation, de repérage d’objets et d’identification d’objectifs. On a analysé l’exécution des tâches en fonction de la vitesse et de la précision. Des données subjectives ont été recueillies concernant l’utilisabilité des dispositifs en fonction d’autres tâches et équipement de LCM. La réaction des dispositifs était plus lente et moins précise ($p < 0,05$) à une profondeur de 42 m qu’à la surface. À une profondeur de 42 m, les temps de réaction des dispositifs VTB étaient plus rapides ($p < 0,05$) pour le signalement des profondeurs et le repérage d’objets; dans les autres situations, les écarts entre les dispositifs étaient négligeables. Les données subjectives ont montré une légère préférence pour les dispositifs VTB. Certains plongeurs ont signalé avoir éprouvé une fatigue oculaire ou des nausées avec l’utilisation du visiocasque. Même si les plongeurs de LCM étaient en mesure d’employer efficacement le dispositif VTB et le visiocasque pendant les plongées à une profondeur de 42 m, chacun des dispositifs présentait des problèmes particuliers sur les plans de la conception et de l’utilisabilité.

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(U) ergonomics; human engineering; underwater; diving; divers; immersion; hyperbaric; human systems interaction; HSI; information display; human performance; speed; accuracy; eye fatigue; nausea; mine−like objects; mine counter measures; MCM; navigation