Human Factor in Scientific Diving: an Experimental Approach

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Abstract

The most powerful scientific tool available in a scientific diving team is the diver. The ability to quickly address fast-changing situations and the holistic approach to understanding the circumstances are unique traits of humans and represent key factors for gaining valuable scientific evidence during underwater operations. On the other hand, human errors are the primary non-technical cause of diving incidents, highlighting the double-sided aspect of having to rely on the human factor in diving. This study focuses on an analysis of several human factors during training dives performed by professional scientific divers. The goal was not only to address the individual variability in human factors but also to identify how those affect the teamwork. Preliminary results show common score values between the team members for most of the dives and a moderate degree of correlation between some of the stressors and human factors performance.

Keywords: fatigue, situational awareness, teamwork, technical skills

Introduction

Human factors studies focus on the ability of the individuals to cope with the surrounding working environment; errors associated with these factors are very often the root causes of major accidents (FAA, 2008). The impact of human factors failure is even more severe when the operative environment is complex, challenging and dynamic, such as during diving operations (Lo, 2006). Human performance is strictly linked to specific behaviors, identified as skilled, ruled and knowledge based (Rasmussen, 1983). The three behaviors can be placed in a hierarchic organization, starting with the skill-based behavior which is related to sensory-motor performance and requires minimal, if any, conscious control. Swimming is an example of such behavior. Rules are used for more complex tasks, and the boundary between skill and rule based behavior shifts in relation to the level of training of the individual. Over-learned rules can be applied automatically, as in the case of expert divers who are able to apply emergency procedures almost as an instinct. Finally, knowledge based behavior requires rational analysis of the situation and the development of a mental model of the surrounding environment. This is typical of very complex and/or unusual circumstances. Divers confronted with unforeseen and novel events require longer analytical times in order to correctly address the issue. A general reaction of an individual exposed to a problem is to look for solutions based on some kind of rule. If this is not sufficient, a knowledge-based approach will be attempted. More expert operators are able to quickly develop a mental model based on similar, even if not necessarily identical, former experiences in supporting their logical analysis of the situation (Reason, 2006). These behaviors can be grouped into a "mental system" which can be briefly described as the way in which an individual manages mental models and that person's interaction with the environment. For divers, correctly managing the mental system is a key feature for both safety and efficiency while underwater.

Underwater activity relies heavily on technical supports, including scuba gear, dive computers and any other device that is needed for the specific planned task. We refer to such supports as “technical system”. Divers should be able to master their technical system with particular focus on the life-support part, such as gas-management and regulators.

Another element of human factors is situational awareness (SA), which requires being aware of the surrounding environment and its changes. SA is a three-step process starting with the ability of the individual to understand what is happening around them, then relate this understanding to the specific goals of the planned operation and finally be able to predict the likely evolution of the situation (Endsley, 1995). Diving incidents are often associated with a loss of SA that allows for small variances from safe procedures to go unnoticed until their cumulative effect impacts the safety of the dive (Sadler, 2011).

Human behavior is also affected by a variety of stressors originating both from the working environment and from the physical and mental status of the operators. Stressors include cold, workload, and fatigue (Staal, 2004). In a diving situation, cold and poor visibility are the main environmental stressors and fatigue has the greatest physical impact on the diver (O'Connor, 2005).

When stress is increased, the individual tends to better focus on more relevant information until a threshold is reached. Further arousal causes tunneling of attention with potential loss of relevant cues (Kahnerman, 1973). If stress increases to a level above a point that an individual can manage, a drop in performance results (Bougherara et al., 2011). Experts seem to be able to offset the impact of stress, thanks to their higher level of knowledge, skills and former experience in similar situations (Juarez-Espinosa and Gonzalez, 2004).

The personality of the divers also plays a role in how they will behave when exposed to different stimuli. Generally, five traits have been identified as component of personality (Roccas et al., 2002):

- *Neuroticism:* individuals with emotional instability.
- *Extraversion*: socially active individuals who may show some hedonism.
- *Openness:* individuals are open-mined with multiple interests.
- *Agreeableness:* individuals are mostly rules-followers.
- *Conscientiousness:* individuals with strong self-discipline.

Divers scoring high in neuroticism and anxiety show more irresponsible behavior than more emotionally-stable ones (Musa et al., 2010); extraversion and agreeableness traits characterize divers with the most responsible behavior (Ong and Musa, 2012). Assessing the personality of a diver is therefore important to assure smooth and safe dive operations.

As scientific divers, we work almost invariably as part of a team. Teamwork is the cornerstone of safe diving and its failure can lead to serious accidents and even fatalities (O'Connor, 2005). The simplest team is composed of two divers; more complex operations require larger teams, including surface support personnel. Good leadership is important, but being a good follower is no less relevant; the team should work as a well-organized unit to reduce the likelihood and impact of human error (Salas et al., 2005). Clear communication within the team is also important to promote correct and complete information transfer and to facilitate shared mental models (Sexton, 2004). This is especially true when more complex underwater tasks, such as those performed by scientific divers, are involved. Several forms of interference can affect successful communication, including environmental noise, distraction, linguistic and cultural barriers. In order to reduce potential misunderstandings, the sender of the message should always ask the receiver for confirmation of having correctly received and understood the information (Sexton, 2004; Salas et al., 2005).

Briefings and de-briefings are important moments during which there is an opportunity for the divers to understand tasks, roles and procedures and then to analyze their performance for future improvement. Moreover, team leaders may use the briefing for contingency planning and team-building (Sexton, 2004).

Training is helpful only for scenarios that have been rehearsed and is therefore very task-specific (Saal, 2004). This highlights the importance of rehearsing diving operations under realistic circumstances similar to those that will be encountered by the divers.

Methods

This study aims to identify the relationship between human factors and performance using an experimental approach. To collect consistent data, a diving journal was used by each diver involved in the experiment in which the narrative part of the dive experience was coupled with a score value (1 to 3) of key parameters such as: situational awareness, fatigue, mental and technical skills. Environmental parameters, including water temperature, visibility and current, were also recorded to investigate their impact on human performance. The divers belonged to a group of experienced professional scientific divers of the Woods Hole Oceanographic Institution (WHOI). The vast majority of the dives were performed in the waters surrounding the Woods Hole village and the island of Martha's Vineyard, MA. As part of the study a standardized briefing form was consistently used for each of the dives. In addition, a practical test aimed at team-building was used as part of the training for new WHOI scientific divers.

Diving journal

Each diver was required to fill out a diving journal at the end of each dive with the following information:

- Date and location of the dive.
- Environmental conditions (water temperature and visibility, estimated current speed, surface weather).
- Objective/goals of the dive.
- Fatigue level (1 to 3).
- Mental system status (1 to 3).
- Technical system status (1 to 3).
- Situational awareness level (1 to 3).
- Description of the dive.
- Decision making processes.
- Specific situational awareness description.
- Communication quality.
- Teamwork activity.
- Leadership/followship.

Temperature and visibility were further categorized in order to produce a numerical output (Table 1). The aim was to have the stressors (cold, poor visibility and fatigue) follow the same numerical ranking, with 1 the less stressful condition and 3 the most adverse one. This helped to provide consistent mathematical elaboration and graphical analysis. In the ranking for SA, mental and technical systems, 1 indicates a poor performance and 3 the best performance.

Table 1: numerical values attributed to stressors

Temperature (^{o}F)	Temperature factor	Visibility (ft)	Visibility factor
< 50	3	0 - 10	3
51 – 70	2	11 – 25	2
> 70	1	> 25	1

The information from the narrative sections of the journal was used to identify specific situations that affected the divers most when drop in performance was indicated. When needed, cross-reference between the journals of diving team members during any specific dive was used to identify common trends.

Briefing form

A good briefing is the cornerstone of a good dive; we developed a standardized form to be used during the briefing by the team leader in order to assure that the diving team received the needed information in a reliable and consistent way. The consistent use of this briefing form allowed for optimized briefing time, clearer information sharing, even in a complex diving operation, and a record of the diving plan for future reference. The provided information included:

- Date and time of the dive.
- Team members.
- Objectives of the dive (primary and secondary).
- Dive plan (a sequential lists of actions).
- Assigned roles (lead diver, specific tasks, buddy pairs).
- Dependencies (minimum is the buddy system).
- What if (contingency plan).
- Feedback (asking the other team members to repeat in their own words the objectives, dive plan, roles and contingency plan).
- Checks (in more complex scenarios, use of written checklists is encouraged).
- After action plan (debriefing).

Practical test

The practical test aimed to challenge the students with a task requiring good pre-dive planning, coordination within the team and dexterity. The divers had to dismantle a flange suspended in mid-water (25 ft of depth) and swap two rubber gaskets at its extremities before reassembling the flange; they had to hover during the operation, be in visual contact with each other at all times and check their air consumption at least every 10 minutes. A time limit of 30 minutes was set. A safety diver was present with the added task of filming the procedure for future reference.

Training site

A training site has been developed along the WHOI Iselin Pier using cave-diving derived procedures, including fixed and temporary guide-lines, light signals during the dive and swimming techniques aimed to minimize stirring up the seafloor sediments. The diving site extends along the pier boundary with some lines running below it; this provides a good simulation of a cave environment in terms of light, without the risks associated with a real overhead environment, since it was possible to surface below the pier at any time during the dive and, if needed, surface swim towards one of the pier exits. A few lines run off the pier to concrete blocks on the seafloor (Figure 1). When swimming along these lines, attention must be given to commercial ferry traffic which approaches run above the diving area. To minimize risk, dives are planned to not overlap with ferry arrival/departure times. The maximum depth of the area is about 70 ft with an average depth of 45 ft; the water temperature ranges from 30 ^{o}F in winter to 77 ^{o}F in summer. Visibility can drop to almost zero. Strong tidal currents develop and accurate planning of the dive time is necessary in order to assure that the operations will happen during slack water. The main advantage of such a training site is that it allows the divers to operate in a challenging but controlled environment; this is of great help to both novice divers, who can progressively build experience, and to more expert divers who may rehearse complex dive plans.

The diving area is also served by good logistic support, with divers having access to a dedicated locker and storage area, warm showers and an office space with multimedia equipment available for classroom and discussions. Moreover, divers in training can borrow most diving gear, including wet and dry suits. A compressor, able to produce both air and nitrox (up to 32%), is available and nitrox is used on most of the dives. A safety advantage is that the maximum depth of the training area is shallower than the MOD for the used nitrox, making it impossible to exceed the planned maximum oxygen partial pressure. A limited number of dives are also performed using closed circuit rebreathers (CCRs) by certified scientific divers; during these dives, a safety diver using open circuit is always present, and a bailout rig is mandatory for the CCR divers.

Figure 1. Training site around the WHOI Iselin Pier.

Results

The study of the journal entries of 103 dives allowed us to identify the impact of various stressors on the divers' performance and to assess behavioral status in terms of human factors. Of the stressors considered in this study, temperature and visibility have the same values for all the divers on any given dive whereas fatigue shows variability linked to the personal status of each diver. Other stressors do not have a numerical score but can be identified through an analysis of the diving journal. These elements include: high workload, new diving gear being used/tested, and diving with less skilled and/or less familiar divers.

Visibility
Bad visibility affects the capacity of divers to operate, causing tunneling of vision, reduced spatial awareness and increased likelihood of being separated from the diving buddies. On 103 cumulative dives, visibility was generally poor, with a median factor value of 2; very bad visibility (factor 3) affected 54% of the dives. No dives with factor 1 visibility were recorded.

Temperature
Cold is another important physical stressor affecting mostly dexterity and, to some degree, mental alertness (Stang and Wiener, 1970). The water temperature in the training area remains below 70°F for most of the year, with the exception of the late summer (Figure 2). This stressor therefore scores a value of 3 for about 60% of the dives (considering a period from January to July 2017).

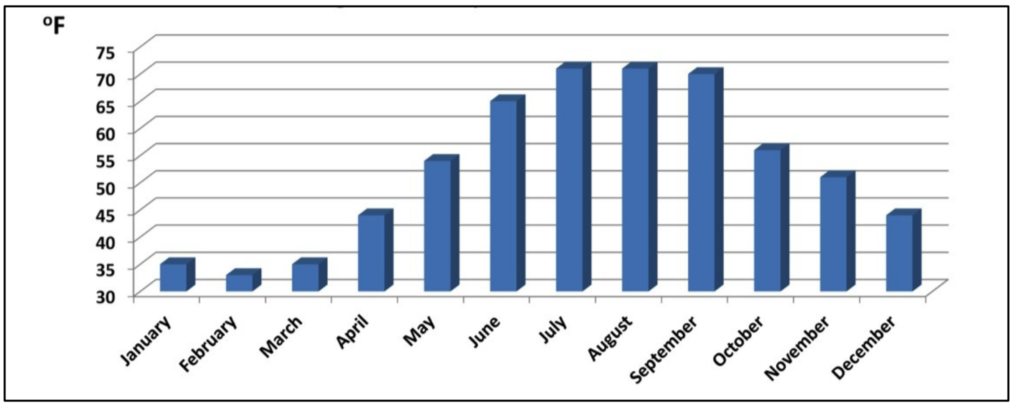

Figure 2. Average annual temperature trend at WHOI Iselin Pier (data from NOAA 2014 modified)

Current
Because of the strong tidal current that may develop, the dives are planned during slack tide; despite the planning, some strong current was met during a few dives. Its impact caused deterioration in performance, mostly when specific operations were to be performed. In particular, it adversely affected the deployment of a new line, causing one of the largest observed drops in SA and technical and mental systems.

Fatigue
In the analyzed dives, the median value for fatigue level is 2, with 3 reported for 23 dives. A direct link between fatigue and drop in performance is indicated in four dives only.

Other factors
Nineteen dives showing relevant drops in SA and/or technical and mental systems were selected for further analysis. In five dives, the testing of a new CCR was indicated as the main stressor, and in a dive requiring the replacement of complex new underwater sensors with a new dive buddy, loss of SA and reduced control of the mental system was recorded. Diving with novice divers is also cause of reduced performance.

Dive 1: The diver was acting as safety diver assisting a CCR diver. Due to a poor briefing from the CCR diver, some specific information about critical elements of the CCR management were missing. This caused a loss of SA and limited assistance capacity. This event highlights the importance of a comprehensive briefing and good communication between the team members. The safety diver was not properly informed of all the technical aspects of the CCR and therefore his/her assistance ability in case of need was compromised.

Dives 2 and 11: During the replacement of a guide-line in the training area under strong current and extremely low visibility, a temporary loss of orientation was experienced. The job was interrupted and the divers returned safely to the exit point. In this case, the current developed sooner than expected based on the tide charts. This highlights that even good planning can be hampered by unforeseen events and that divers have to be ready to terminate the dive if the changed conditions do not allow for a safe continuation of the operation.

Dive 3: The diver experienced an unusually high level of fatigue with a general sense of uneasiness leading to increased psychological stress and discomfort. In this case, no specific cause for the observed drop in performance was identified, it was just a "bad day".

Dive 4: The diver was acting as supervisor and safety diver for a novice diver with potential panic issues. Moreover, the dive followed multiple dives in the same day. We can identify multiple sources of stress, including diving fatigue from multiple dives and apprehension for a potential panic situation to be managed.

Dive 5: The diver had difficulty focusing on the tasks at hand because of some anxiety regarding a deeper and more complex dive planned for the next day. In this case the psychological factor was predominant in affecting the mental system.

Dive 6 to 10: During these five dives, the diver was using a new CCR that was an updated version of a model previously used by the diver. During each of the dives, specific drills were planned. Multi-tasking and need to focus on a new life-support system caused increased stress, affecting SA and mental and technical system management.

Dive12: This dive was aimed at replacing underwater instruments in shallow (18 ft) water. The instruments were to be positioned over a beam connected to an observation tower 1 mile offshore from Martha's Vineyard. The diver was performing this operation for the first time even if he/she had experience on similar tasks. The dive buddy was new; the two divers had dived together only one time before this operation and not in a job-related dive. SA, mental and technical systems were lower than usual throughout the dive. The task was successfully concluded in spite of this. Multiple stressors are involved in this dive, including new tasks, diving with a new buddy and professional pressure to complete the job.

Dive 13: During this dive, the diver experienced colder conditions than usual and had some buoyancy issues because he/she was under-weighted. Both events caused a feeling of discomfort, and the difficulties in controlling buoyancy caused reduction in technical system control. Environmental factors and technical issues had a negative synergic effect on the diver's proficiency.

Dive 14: Spatial disorientation occurred due to very bad visibility. There was an issue with a 3-diver team; one diver was separated at the beginning of the descent and the team had to surface and restart.

Dive 15: Bad visibility and an unfamiliar equipment configuration, along with a new complex job to be performed caused a loss in performance.

Dive 16: Loss of SA and poor management of the technical system was caused by a very tiring dive plus by the failure to realize that the BCD was leaking and taking water in the bladder.

Dive 17: Difficulties in using a new piece of equipment for a working dive caused reduction of performance.

Dive 18: Loss of spatial awareness was due to maintaining a continuous inverted position needed for maintenance operations. High level of fatigue was experienced during the dive.

Dive 19: Loss of efficiency was caused by underestimating air needs and using a partially full cylinder. The job was interrupted to replace the cylinder.

Standardized briefing

The systematic use of a standardized briefing form helped to improve consistency in the information provided to the divers before any dive. In particular, the tasks of the dive were clearly identified, allowing for more efficient resource planning. Moreover, the divers were well informed on the contingency procedures, enhancing the safety of the operation. To ensure clear communication and avoid any misunderstanding, it was standard procedure to ask the divers to rephrase in their own words the key points of the briefing. We adopted this approach following a mishap in which there was confusion about a specific procedure that caused diver separation. Since implementing this briefing format, the divers have a better understanding of even complex operations and more confidence in the dive to be performed. We also noticed that the use of a standard form optimizes time usage, with briefings that are concise and efficient, independent from the attitude of the person providing the briefing. Repetitions, convoluted expressions or lack of key information are avoided.

Team formation and practical test

During the training for new WHOI scientific divers, specific attention was focused on the formation of the diving teams. When possible, the psychological attitude of the divers was considered in order to enhance the quality of the interpersonal relationships within the team. In this way, weaknesses within the team were largely offset by their strengths.

In total, five pairs of divers completed the flange test with 100% success rate within the time limit of 30 min. One diver lost a washer, one diver put two washers on the same bolt and one diver lost a bolt. Most of the divers decided to split the task and work on the two extremities of the flange at the same time. On average, this allowed the divers to achieve the goal faster, but with a higher risk of losing some parts. Outcomes of these tests are given in table 2.

Table 2. Details of the practical test results.

Team	Time (min)	Split vs. Together	Item lost/misplaced
1	25	Together	washer
2	15	Split	1 bolt
3	30	Together	0
5	21	Split	washer
5	11	Split	0

Discussion

The training area was very appropriate to build up experience and provide good rehearsal of diving operations in a challenging but controlled environment. Both novice divers and more expert ones benefitted from the use of the facility. The logistical support allowed for a year-round diving season and for a dedicated space for divers to plan their dives and discuss the results.

The limited impact of poor visibility on the divers' performance can be explained by the fact that the local divers are used to operating in such environments and therefore manage to mitigate the consequences of diving in reduced visibility. This explanation is supported by comments from newly arrived divers, some of them with very good diving experience, who experienced a variable degree of spatial disorientation when diving for the first time under poor visibility conditions. Similarly, the relatively moderate effect of low temperatures is likely due to the good thermal insulation used, as diving with a dry suit is mandatory during the winter months, and to being accustomed to cold water. These results highlight the importance of progressively building experience to manage challenging diving conditions.

Current is generally not an issue at this site, mostly because of good planning aimed to operate during slack water. Nevertheless, in at least one situation, divers experienced a stronger than foreseen current that interfered negatively with the tasks of the dive, even preventing the completion of some of them. This highlights the need for accurate environmental assessment, mostly in areas where particular natural events, such as high tides, currents or quick changes in meteorological conditions, can affect the diving operations.

Fatigue is often the source of loss of SA and potential accidents (Smith et al., 2006). Its impact on diving performance is also severe, being one of the leading causes of diving accidents (O'Connor, 2005). The feeling of fatigue can be very subjective, with different individuals having different thresholds of resistance; motivation plays a mitigating role (Staal, 2004). Fatigue seems to have a limited impact on routine dives but can reduce performance on dives requiring more complex or less usual operations. Being well rested before demanding dives is a key factor. If multiple dives and/or multiple diving days are planned, adequate rest breaks should be considered.

Much larger adverse effects result from diving with new/unfamiliar diving gear, having a new dive buddy and having to perform novel and unfamiliar tasks. The use of new diving gear likely caused some degree of working memory overload, because the diver cannot rely on automated skills in managing the unfamiliar equipment. To reduce the impact of this stressor, some training dives should be dedicated to acquiring confidence in the use of the new equipment. In addition, having more gadgets does not result in better and safer divers; simplicity should be the main guideline for diving configuration.

Diving with a new buddy always generates some degree of psychological stress. Team building is a process that requires time. Therefore, newly formed teams should not be rushed into working dives, but instead given time to develop interpersonal confidence. From the experience gained during the training for new WHOI scientific divers, the use of a test requiring good teamwork and coordination was instrumental to this process; it is also evident that novice divers improve faster when diving with more experienced ones. Moreover, assessing the main personality traits of the divers fostered better inter-personal relationships, allowing for building better teams.

The use of a standardized dive briefing form assured that all the key information was properly transmitted to the diving teams in a reliable and consistent way. An improved understanding of the dive plan and of the operational targets followed the routine use of such a format. Asking the divers to repeat, in their own words, the key points of the briefing, was important to assure correct communication.

This study is the first attempt to objectively quantify the impact of human factors on the proficiency of professional scientific divers. Through a standardized diving journal, it was possible to acquire consistent and reliable data across different divers and dives, The main result is that progressively acquiring experience is the key for developing safer and more proficient divers. The limit of this study is the relatively low number of divers and dives involved and one of the future targets is to involve a larger community of scientific divers for a more extensive data collection.

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