Applied Ergonomics 1986, **17.2**, 143–147

Task performance under water

An evaluation of manual dexterity efficiency in the open ocean underwater environment

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The present review examines studies which have reported on the performance of submerged operators on manual dexterity tasks in the practical arena of the open ocean underwater environment. The previous emphasis on the primacy of the factor situational anxiety, in degrading efficiency, is questioned. The case for environmentally-based factors and performer skill level as potent influences on performance is advanced. In postulating a potential linear relationship between depth of operation and performance decrement for air-breathing divers, the review seeks to stimulate further experimental examination of this important applied issue.

Keywords: Underwater, divers, performance assessment

Introduction

In order to function effectively in the underwater environment, the diver must possess a degree of mastery over a variety of differing skills. One of the most important of these skills is manual dexterity. This ability is necessary for several aspects of commercial, military and recreational diving. Considering the practical importance of this issue, relatively few controlled experimental investigations have been reported in the open literature concerning the relationship between depth of operation and degradation of manual dexterity underwater. Despite the procedural difficulties which accompany such research, studies concerning diver capability have been conducted but much of this information is contained in technical reports and is not always readily accessible. Even with recognition of the results of such investigations, the relative contributions of several different factors which act to affect diver performance have yet to be clearly distinguished (Godden & Baddeley, 1979).

The purpose of the present review is to provide an evaluation of empirical research concerning the performance efficiency, on simple manual dexterity tasks, of the submerged operator in the applied operational setting – the open ocean underwater environment. With respect to this particular category of tasks, it has been suggested that the major influence in retarding performance capability is situational anxiety (Baddeley, 1967; Baddeley & Idzikowski, 1985; Davis *et al*, 1972; Mears & Cleary, 1980). This assertion maintains that as ocean dive conditions become more stressful, through increased depth of operation, reduced water temperature and visibility, dive location or night versus daytime diving, then the level of anxiety rises. As a consequence of this elevated level of anxiety, the time to complete tasks requiring manual dexterity is increased.

Review of literature

The suggestion concerning the influence of anxiety was first made by Baddeley (1967) and emerged from the comparison of results from two empirical studies conducted by Baddeley and his colleagues at two Mediterranean dive locations. In his initial work Baddeley (1966) observed that the mean time for 12 divers to complete a manual dexterity screwplate test increased 28% at 10 ft (3 m) and 49% at 100 ft (30·5 m) ocean depth when compared with equivalent dry land performance. In a subsequent study, conducted prior to Baddeley's (1967) report, Baddeley *et al* (1968) examined the performance of 18 divers on the same screwplate test at equivalent ocean depths. Although finding a compatible percentage increase in completion time at the shallow depth (27·7%), the time to complete the task at 100 ft (30·5 m) was considerably shorter than that reported in the previous experiment – i e, an increase of 35% compared with the earlier 49%.

Requests for reprints should be sent to P.A. Hancock, Department of Safety Science, Institute of Safety and Systems Management, University of Southern California, Los Angeles, CA 90089-0021, USA. An earlier version of a portion of this paper was presented at the Annual Meeting, of the Human Factors Society, Seattle, WA 1982. Note that the original submission of this work was in mid-1983. In a subsequent brief revision, only the recent work of Baddeley and Idzikowski (1985) is included.

0003–6870/86/02 0143–05 $03.00

Baddeley accounted for this discrepancy between these two findings by suggesting that local dive conditions in the earlier experiment generated considerable anxiety when compared with almost perfect diving conditions of the latter experiment. Although anxiety was proposed as the crucial variable, its identification was mostly a *post hoc* procedure and, in consequence, the production of and precise relationship between anxiety and underwater performance remained a largely unexplored proposal.

There is an alternative account of the data presented by Baddeley and his colleagues in the two reports cited. The first point to note is that the initial performance of each of the two groups studied, varied widely. While the 12 original divers completed the screwplate task in 184·75 s, with a standard deviation of 29·39 s, the latter 18 divers completed the same task in 147·2 s, with a standard deviation of 17·0 s. This dry land performance variation does not appear due to a trade of speed for accuracy as the latter experimental group lost only one screw in total during the deeper performance condition.

Rather, the difference in reported decrement at depth is posited as due to the differential skill level of each group, as evidenced by the prior dry land performance capability. This suggestion is supported by some work reported by Brady (1979) in which he stated:

> The effect of level of manual dexterity on . . . underwater performance did not reach a generally acceptable level of significance (p = 0·067) but was of such a magnitude as to suggest that manual ability could be an important factor in the performance of underwater manipulative tasks (p 32).

It should be noted that Brady's subjects were engaged in a complex assembly task at a shallow (4·26 m) depth in an indoor swimming pool. The earlier results reported by Baddeley and co-workers (1968) imply that depth of operation and level of manual dexterity may interact and this perhaps accounts for Brady's marginal failure to reach an acceptable level of significance for the factor of manual ability. In addition and in consonance with Brady's observation of a learning effect apparent underwater, the data of Baddeley *et al* (1968) imply that the greater gains in performance are to be had at the greater depth, where absolute completion time on the chosen task was almost equal at the two ocean depths after only one day of practice. These combined observations suggest that, in addition to some impact for the previously identified factor of anxiety, it is the prior skill level of the individual performer that impacts manual dexterity decrement, particularly at depth (see Hancock, 1986).

Effects of breathing different gas mixtures

While situational anxiety and skill level may influence underwater performance, two studies have demonstrated the efficacy of breathing different gas mixtures in the mitigation of simple manual dexterity performance decrement at depth. In 1966, Bowen *et al* reported that divers in the SEALAB II experiment completed a manual dexterity triangle assembly task in 49% greater time with reference to dry land performance. This is the same figure as that given by Baddeley (1966) for air-breathing divers performing at 100 ft (30·5 m) ocean depth. However, divers in the former experiment worked at 205 ft (62·5 m) or over twice the ocean depth (Bowen *et al*, 1966). The major difference between the two studies was that the SEALAB divers used a nitrogen, helium, oxygen mixture rather than compressed air, and this difference between the gas mixtures employed circumvented the progressive degradation in manual task performance efficiency that is predicted at the greater depth of operation.

To test the specific influence of varying breathing mixture, Baddeley and Fleming (1967) compared the performance of divers using compressed air with those breathing a mixture of oxygen and helium at 10 ft (3 m) and 200 ft (61 m) ocean depth. They found that while the oxy-helium-breathing divers worked slightly faster and more accurately than the air-breathing divers, there was still considerable performance decrement at depth even with the use of more appropriate gas mixture. The results of both Bowen and his colleagues (1966) and Baddeley and Fleming (1967), using different gas mixtures, have been incorporated into Fig. 1. The calculation of decrement for the air-breathing divers at 200 ft (61 m) was derived by comparison of figures given by Baddeley and Fleming and the previously reported work of Baddeley (1966).

Effect of fixing the physical base of operation

There are two studies which have produced data concerning the manual performance of air-breathing divers in the open ocean which do not follow the trend illustrated. In two experiments concerning simple manual dexterity in the open ocean, Davis and co-workers (1972) investigated performance on a bench top task in British coastal waters.

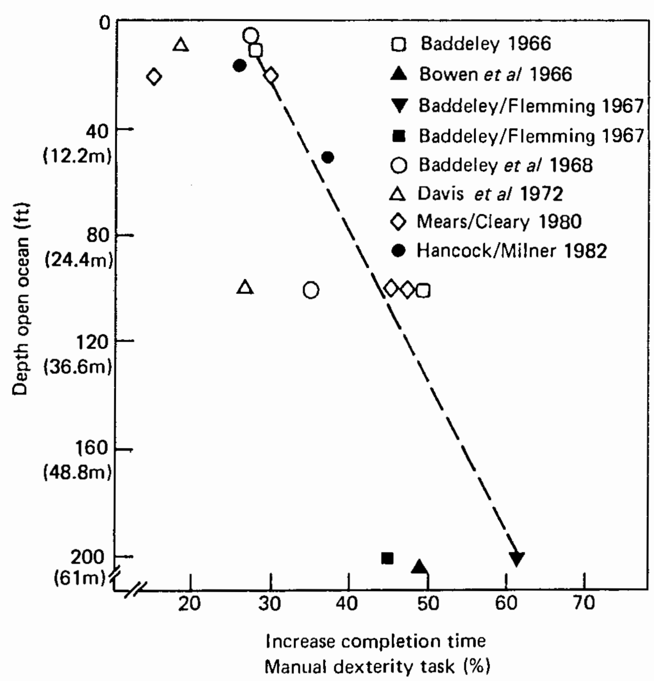

Fig. 1 Percentage increase in manual dexterity task completion time as a function of increasing ocean depth. First Author of cited studies is included in Legend. Note that the work of Bowen *et al* (1966), filled triangle, and Baddeley and Fleming (1967), filled square, represent performance of divers using oxygen-helium and oxygen-helium-nitrogen mixtures, respectively. The axes of the Figure are inverted by intent.

The Bennett Hand Tool Dexterity Task was completed by divers, wearing gloves, at 3 m and 30 m underwater. In the first of two experiments they found an increase of 22% in the time to complete the dexterity task between two depths. In the second experiment they found an increase in completion time of 18% from dry land to 3 m underwater and an identical increase of 18% from 3 m to 30 m underwater.

The difference in the change of percentage decrement on task performance at the shallow exposure – i e, 18% in these experiments compared with 28% in previous work (Baddeley, 1966; Baddeley *et al,* 1968) – was in part attributed to the nature of the task. While the screwplate test is hand held by the divers, the Bennett Hand Tool Task is fixed to a firm working base with a bench top surround to further facilitate work conditions. With this more stable working surface, deterioration of performance was closer to Mosby's (1967) observation of 15% drop in work efficiency with submersion. The reduction in performance decrement was apparently due to the mitigation of the problem of bodily instability and weightlessness in task performance, as previously noted on the screwplate test by Baddeley and Fleming (1967).

Davis *et al* (1972) utilised the comparison of performance between 3 m and 30 m to support the position that elevated anxiety, from more stressful dive conditions in British coastal waters, was responsible for a larger increase in percentage task completion time at depth when compared with 'perfect' dive conditions encountered in a Mediterranean location (Baddeley *et al,* 1968). In previous work, increase in completion time had been calculated with reference to equivalent dry land performance. This is difficult with the work of Davis and his colleagues in that they report two comparisons, one between land and 3 m and the other between 3 m and 30 m. In the latter comparison, one subject failed to complete the test in the deeper condition while another was excluded due to a marked learning effect on the task which resulted from a congenital manual deformity. Consequently, the comparison of times between land and 30 m may only be made on the basis of the mean completion time of groups differing in number. When this calculation is performed, however, the difference in decrement – which was 27% in the Davis study compared with 35% in the land to 30 m comparison for Baddeley *et al* (1968) – does not support a simple anxiety notion. Unfortunately, the 10% difference in group mean performance time at 3 m (see Davis *et al* Tables II and III) is quite large and leaves the suggestion of less percentage decrement somewhat equivocal from the data reported. The major practical point to emerge from this research, however, appears to be that fixing the base of operation can significantly reduce open ocean performance decrement on manual dexterity tasks.

Differences in night vs daytime diving

Recently, Mears and Cleary (1980) have reported on the effect of night and daytime diving at 6 and 30 m on a metric version of the screwplate test. Using a four-group design, they found a 14% increase in completion time at 6 m during a daytime dive and a 30% increase at 6 m during a night-time descent. The two 30 m groups exhibited a compatible change, being 45% decrement during the day and 47% at night.

They compare their finding of 14% during daytime diving at 6 m, erroneously, with some previous work of Bowen (1968). In his work, Bowen utilised a tank and quarry location and found a 21% decrement in the screwplate test at a comparable temperature – i e, 61°F (16·1°C) (Mears and Cleary, 1980), 62°F (16·7°C) (Bowen, 1968). Bowen noted that a battery of manipulative function tests exhibited a 25% general decrement at this water temperature. However, he achieved manipulation of water temperature, through varying the depth of the work platform at the quarry site. He observed that results from the 62°F (16·7°C) exposure accrue from only the quarry locale, where to obtain such a temperature the platform was suspended only 3 ft (0·9 m) below the surface. This depth was measured from surface to the level of the diver's chest. Consequently, his findings, whether 21% for the actual screwplate test or 25% for the total manual task battery, fall more in line with the present trend shown in Fig. 1 and do not constitute support for the results of Mears and Cleary as was implied. Parenthetically, Bowen's results are not considered directly in this work due to the test locales – i e, quarry and tank exposures – compared to performance in the open ocean which forms the focus of the current review.

Mears and Cleary (1980) sought to examine directly the role of anxiety in underwater performance by manipulating the conditions of diving by depth and time of day. Night diving was suggested as inducing greater anxiety. They reported that the general trend in their data, which includes alternate performance task measures, affirmed the proposed relationship between anxiety and underwater work performance. However, the results from the main dexterity task do not support this assertion. Clearly, it is intrinsic to their position that both depth and night serve to increase anxiety. Consequently, it may be expected that an interaction between these two factors would result. This combined effect should have produced the greatest decrement at night/30 m, with the difference between night/30 m and day/30 m being greater than or at least equivalent to the difference between night/6 m and day/6 m. This does not occur. Rather, decrement is highly similar at 30 m for both night and day, and the atypical observation appears to be at 6 m during the day exposure. Although this may be due to the problem of allocating novice divers only to the 6 m group, it seems more parsimonious to suggest that the dry land performance of the 6 m daylight group was in some way depressed, with respect to all other groups (see Mears and Cleary, Fig. 1a). In some of our own work (Hancock & Milner, 1982) we examined the performance of experienced divers in near optimal ocean dive conditions. We found a 25·8% increase in simple dexterity task completion time at 4·6 m and 36·8% increase at 15·3 m. These results follow the relationship expressed in Fig. 1, despite the lack of situational anxiety as reported by the divers.

Anxiety and motor efficiency

Most recently, Baddeley and Idzikowski (1985) have sought to elaborate upon the anxiety position. They tested 32 novice performers immediately prior to diving and at an alternate time when a dive was not imminent. Despite the fact that no underwater observations were made, Baddeley and Idzikowski derived some data of importance with respect to the present review. They noted an increase of 6·4% in completion time on the screwplate test when diving was imminent compared with the no-dive control test. They concluded that, although the magnitude of the anxiety effect was not great, it did confirm their previous overall position concerning the impact of anxiety on underwater performance.

There are several aspects of this study which require some examination. Not all the subjects exhibited a tendency toward slowing under the pre-dive condition. Nine of the 32 participants actually completed the task more quickly, as noted by the original authors, in the higher anxiety pre-dive condition. Baddeley and Idzikowski rightly maximised the probability of obtaining a positive result through the selection of novice divers about to encounter their first ocean dive under somewhat adverse conditions (see Baddeley & Idzikowski, 1985, p 1477). However, despite the use of this preselected sample, the mean effect was still only some 6·4% change. Subjects appeared to receive limited practice on the performance task (Baddeley & Idzikowski, 1985, p 1478) and there is a variety of potential problems that may be encountered when testing for the impact of a stressor while a subject has yet to reach a performance asymptote.

In this and other studies, completion speed was taken as the measure of performance and details of performance accuracy were not recorded. Although it is probable that accuracy was held constant, other experiments using the screwplate task have given some overall accuracy estimate; for example, in terms of screws lost by the performing diver. This is important in that in setting performance and safety standards for work underwater there is a need to recognise the considerable penalty for mistakes in accuracy. This information should be incorporated with the more commonly used temporal criteria such as work completion time and bottom time. It should be noted that conclusions derived from the present review are based solely upon the data for completion speed and therefore the picture, as represented in Fig. 1, reflects only one aspect of overall performance. Consequently, any inferences drawn from this illustration should be treated with particular caution.

Most importantly, the work of Baddeley and Idzikowski does not present direct evidence on underwater performance. This is particularly detrimental to the argument being proposed by the authors in that, as they themselves suggest, it is probably the case that level of anxiety produced prior to diving is not the same as that actually *in situ*. This suggested interaction would certainly favour the notion of greater performance decrement in the actual work environment.

Although anxiety has been identified as a prominent variable in the production of performance decrement underwater, the concept has remained largely undeveloped in those studies invoking its potency. The linear trend between increasing depth of operation and increased percentage in task completion time demands that anxiety be responsive only to depth and the 'state' anxiety be the direct cause of decreased motor efficiency. Neither of these assertions appears tenable in light of research concerning anxiety and motor performance (Martens, 1971).

Davis *et al* (1972) introduced physiological measures of anxiety; however, they failed to differentiate between 'state' and 'trait' anxiety (Speilberger, 1966). It is implicit in each of these studies that 'trait' anxiety, or that acquired behavioural disposition toward the perception of non-dangerous situations as potentially threatening, is low in diving populations. However, differences within individual divers in terms of anxiety have been shown by Biersner *et al* (1980). Thus, the suggestion that situational anxiety, or 'state' anxiety – the subjective consciously perceived feelings of apprehension and tension – is the major responsible agent in performance degradation in manual dexterity tasks underwater is too simple and cannot account for the current consensus of the data. One aspect of the anxiety notion, which has yet to be fully explored, is the notion of inter-individual performance variability. According to an anxiety account, there should be a direct relationship between individually perceived anxiety level and manual dexterity performance decrement underwater. This strong prediction from the anxiety position remains as yet largely untested.

In the light of present understanding it is more parsimonious to propose that the trend depicted in Fig. 1 is reflective of the physical stressors associated with increasing depth. This attribution of a lesser role to situational anxiety is also made with the recognition of the potentially potent effect of difference in diver manual ability, particularly with respect to mitigation of performance decrement at depth (Brady, 1979; Baddeley *et al,* 1968). The relationship in Fig. 1 represents performance on relatively simple manual dexterity and does not incorporate data from studies which have examined more complex underwater assembly (Brady, 1979; Egstrom & Weltman, 1974; Streimer, 1972; Weltman *et al,* 1970) where factors such as problem solving may play an important role.

Discussion

There are many factors that impact on an individual diver's capability in task completion in an underwater environment. These may be generally divided into environmental factors and individual factors. Previous accounts of manual dexterity have emphasised the primacy of one individual factor, namely situational anxiety as a final conduit through which performance decrement is mediated. In this work we have suggested that the linear trend between depth of ocean operation and reduction in performance efficiency implies a greater role for the physical stresses directly associated with the environment.

There are several points about Fig. 1 that should be noted. First, it is unlikely that more complete experimental evidence would continue to favour a simple linear interpretation. Indeed, we have suggested elsewhere that progressive failure under stress is more likely to exhibit non-linear trends (Hancock & Chignell, 1985). However, the linear trend presented allows for simple initial predictions that may be used for comparison with more detailed experimental work. Second, a relationship as presented in Fig. 1 does not elaborate on the relative contributions of individual and environmental factors such as water temperature, depth of operation, and individual skill level or anxiety. Such an understanding is clearly necessary if safety standards, predicated upon performance, are to be set in working underwater.

We have suggested that, following an initial decrement due to submersion alone, there is progressive decrement associated with depth of operation. Superimposed upon this basic function are changes related to intrinsic capabilities of the individual diver. With Baddeley and his colleagues (e g, Baddeley & Idzikowski, 1985) we fully expect that situational anxiety can and will impact performance* and that this effect will be most easily observed in novice or beginning divers. However, with increased diving experience and greater familiarity with the specific performance task, as manifested through performance skill, such deleterious impact may be offset (Hancock, 1986) and efficiency may be improved well beyond the limitations as expressed in Fig. 1. Indeeed, prolonged and consistent task practice may have considerable effect upon subsequent performance under a variety of stressors. It has been suggested that such repetition might act to offset the distraction effect as represented by a novel or noxious environment (Teichner, 1957, 1958).

In summary, we have advocated a lesser role for the single factor of anxiety in reducing performance efficiency on tasks requiring manual dexterity in the open ocean. We have proposed an increased role for environmentally based factors and for the individual level of operator skill in accounting for the tendencies as reported in the present meagre data base. More thorough experimental evaluation of this important applied issue is a critical necessity in order that the relative impact of differing actual and potential factors may be distinguished (see Poulton *et al*, 1964). This understanding is a necessary precursor to the overall evaluation of the limitations of the submerged operator in the practical work arena – the open ocean underwater environment.

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*Although we have argued against the emphasis given to anxiety as the major explanatory construct, both authors are diving instructors and appreciate the subjective impact that anxiety can exert, especially in the novice or first-time diver. Our position is that decrement cannot be mediated by anxiety alone but needs to be considered in light of the multiple environmental and individual sources that can act to affect the diver.

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Acknowledgement

The authors would like to acknowledge the helpful comments made by the reviewer of this paper.