SUMMARY

The EDGE seems suitable for measuring and recording the various dive parameters, such as depth, times, temperature, etc. It seems suitable for some single fixed depth dives and on some single multi-level dives, if sufficient care is taken to ensure a sensible dive plan, eg. diving from deep to shallow.

Its use in any repetitive dive situation, with either fixed or multi-level dives, should be discouraged.

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Dr C Edmond's address is 25 Battle Boulevard, SEAFORTH NSW 2092, Australia.

Dr T Anderson's address is 6 Abbott Street, BALGOWLAH HEIGHTS NSW 2093, Australia.

DIVER NAVIGATION BY MEANS OF ACOUSTIC BEACONS

Harry Hollien

SUMMARY

Divers traditionally have difficulty navigating underwater. In air, they have vision plus all types of sensory cues to accomplish this task. However, when submerged, the diver's visual modality is sharply impaired and in a sense, he or she is left virtually blind. Ordinarily divers attempt to navigate by compass (dead reckoning) but research has demonstrated that this approach leads to unacceptable errors. Some other approach, then, needs to be developed. In this regard, we have carried out and reported a number of experiments focused on the abilities of divers to navigate by means of programmed acoustic signals. It has been found that sound which "moves" underwater (ie. via the UAPP or Underwater Auditory Phi Phenomena) greatly aids sound localization and, ultimately, navigation. Indeed, for diver retrieval this phenomena is so powerful that no subject in any of our experiments has ever swum to an area except that containing the signal source. Previously published data will be reviewed briefly and new data on the effects of experience and/or training on diver navigation by acoustic signal will be presented.

INTRODUCTION

Diver navigation and retrieval of personnel continues to be a very serious problem. At present, only a very few partially developed systems are available (explosives, dead reckoning, beacons, etc.) that will permit even the most limited (controlled) travel underwater. This situation results from the fact that, when a person is submerged, there are very few (to no) location markers and his or her vision is sharply limited. That is, in the normal situation (ie. in air), humans utilize their vision for observing markers, localizing objects and moving from place-to-place. Underwater, however, human vision is greatly limited, the diver quite often is functionally blind or close to being so. As stated, the consequences of this condition are quite serious; divers often are unable to locate objects or team members, swim to desired locations/targets and/or find their way "home". This latter problem can be a pretty grim one if the diver is saturated. Traditionally, the solution to the problem has been the use of an underwater compass with the diver navigating by "dead reckoning". However, Anderson[1] has reported an experiment wherein he states that "even for well-trained subjects ... the average performance accuracy ... was plus or minus 53 feet from the centerline of the measurement array or 3.98 degrees in compass error ... in an operational situation when a diver might be engaged in an underwater search task or in accurate placement of underwater sensors, this level of performance would be marginal." Indeed so. A navigational error of this magnitude would become crucial, and possibly fatal, for saturated divers or divers attempting to find a moving vehicle. To illustrate, if a saturated diver made an error in navigating back to the underwater habitat as large as that reported by Anderson, he could easily miss it, and being saturated he would be unable to surface and reorientate himself. As a matter of fact, navigational errors of this size would prove undesirable under almost any underwater situation. Further, due to the nature of diving, the use of complex, bulky (and often unreliable) electronic systems for navigation has proved to be but minimally effective. Hence, we suggest that some other type of sensory mechanisms be substituted for vision to compensate for the cited deficit. Specifically, we propose that it is possible to utilize the diver's sound localization abilities as a substitute.

DIVER HEARING

Knowledge about underwater auditory function is both sparse and primitive. It would appear that a great deal of data must be obtained before very many basic hypotheses and postulates can be (inductively) generated. We have found that, when attempting to predict underwater hearing behaviours and mechanisms, immersing humans resulted in effects that biased our predictions. In other cases, existing variables (noise, reflective surfaces, stress, etc.) appeared to change human behaviour in significant ways. Perhaps the most important fact is that it is impossible to directly duplicate normal research techniques underwater. Rather, a great variety of life support systems must necessarily be attached to the diver with their concomitant, and shifting, effects on the responses made to heard stimuli. On the other hand, we believe that current technology permits systematic and appropriate research to be applied to these problems with the result that reasonable solutions can occur. A brief review of some of the more important findings in this area of inquiry would appear appropriate to demonstrate that some useful concepts are already available.

Initially, there was a substantial question about the sensitivity and nature of underwater auditory function in humans. However, it has been shown recently that the auditory capability of the submerged ear is not nearly as impaired as was thought. For example, when divers are submerged, their hearing is conductively reduced but they do not experience neurological impairments. That is, although there is a loss of sensitivity, a diver can detect a sinusoidal signal between 125 and 8000 Hz at 60-70 dB SPL.[2,9] This sensitivity to sound is within the normal range for conversational speech in air at a distance of one foot. Thus, although underwater hearing is accomplished primarily by "bone conduction", hearing function otherwise is normal as speech reception thresholds relate normally (ie. plus 15 dB) to standard thresholds for sinusoids and speech discrimination is normal once the sound can be heard.[6,10,11]

Divers' sound localization ability also has been found to be far superior to that which was originally predicted,[11-13] as has the possibility that divers can navigate by sound.[11,12,14,17] The combined results of these experiments result in the suggestion that pulsed low-frequency sinusoids or glides (up to 1 kHz) and broadband noise are superior to other signals for localization purposes and there is no distance effect.[18] Further, it was found that the sensation of acoustic "movement" can be a powerful localization cue.[11,18-11] It also has been observed that the difference in the minimal audible angle (MAA) in air and water is less than 10 degrees and the difference between absolute localization precision in air and in water is approximately $\pm$5 degrees.[16,22] Finally, Thompson and Herman[23] found that the pitch discrimination of divers does not differ markedly from that of listeners in air. Thus, a diver is potentially capable of identifying subtle pitch, quality and distance differences in acoustic signals and should be able to utilize this information in order to determine the location of various underwater sound sources.

On the basis of the several sets of data discussed above, it appeared that divers might be capable of localizing sound sources underwater and of potentially utilizing this ability to navigate. For example, if they were able to "home" on a beacon, a substantial improvement in underwater safety would result. Accordingly, we consider it profitable to study human behaviours and capabilities related to this issue. Moreover, data from a related set of experiments convinced us that we had inadvertently uncovered a perceptual characteristic related to underwater hearing that could provide a powerful aid to diver navigation and retrieval. As a consequence, we were able to hypothesise that a line array of underwater projectors, energized in sequence to produce an apparent auditory "movement", would provide an effective localization signal. In theory, the array would produce an Underwater Auditory Phi Phenomenon (UAPP) similar to that produced (visually in air) by landing light systems for aircraft runways or on theatre marquees. The resulting pilot investigations suggested that the Phi characteristics were of such good potential, that we developed and have partially carried out (nine major experiments) an extensive research effort designed to study its effectiveness relative to diver retrieval and navigation. This paper reviews the already published information plus reports new data resulting from one of the cited experiments.

METHOD

While much of our earlier work on sound localization and underwater distance estimation abilities, plus the pilot studies assessing acoustic beacons and the UAPP approach, was carried out in the ocean, most of the current studies were conducted in a quiet lake on a military reservation (Camp Blanding). Lake Magnolia is almost 1.5 by 1.0 km in size and slopes gradually to a large central area with a depth of nearly 15 m. It proved to be an ideal site for the highly controlled, basic research that we found necessary to carry out initially. For the cited experiments, three J-11 transducers were positioned 3m apart in a linear array at a depth of 7m perpendicular to a straight line 150m experimental range as seen in Figures 1 and 2 (page 129). The acoustic signals used in the "training" investigation were chosen from among those evaluated in pilot work and earlier experiments.[17] Specifically they were:

1. A 500Hz square wave of 500 ms duration and with 25 ms rise/decay times.

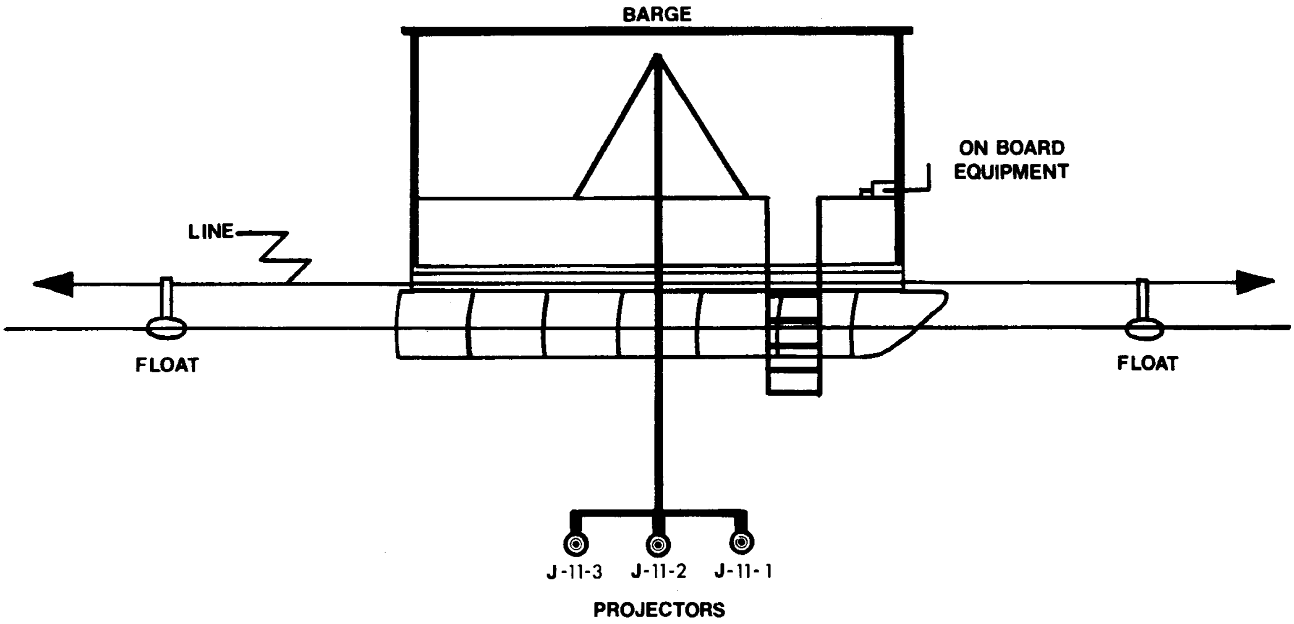

Figure 1. Schematic diagram of the barge, the transducer array and the plane (float to float) also included as part of the target.

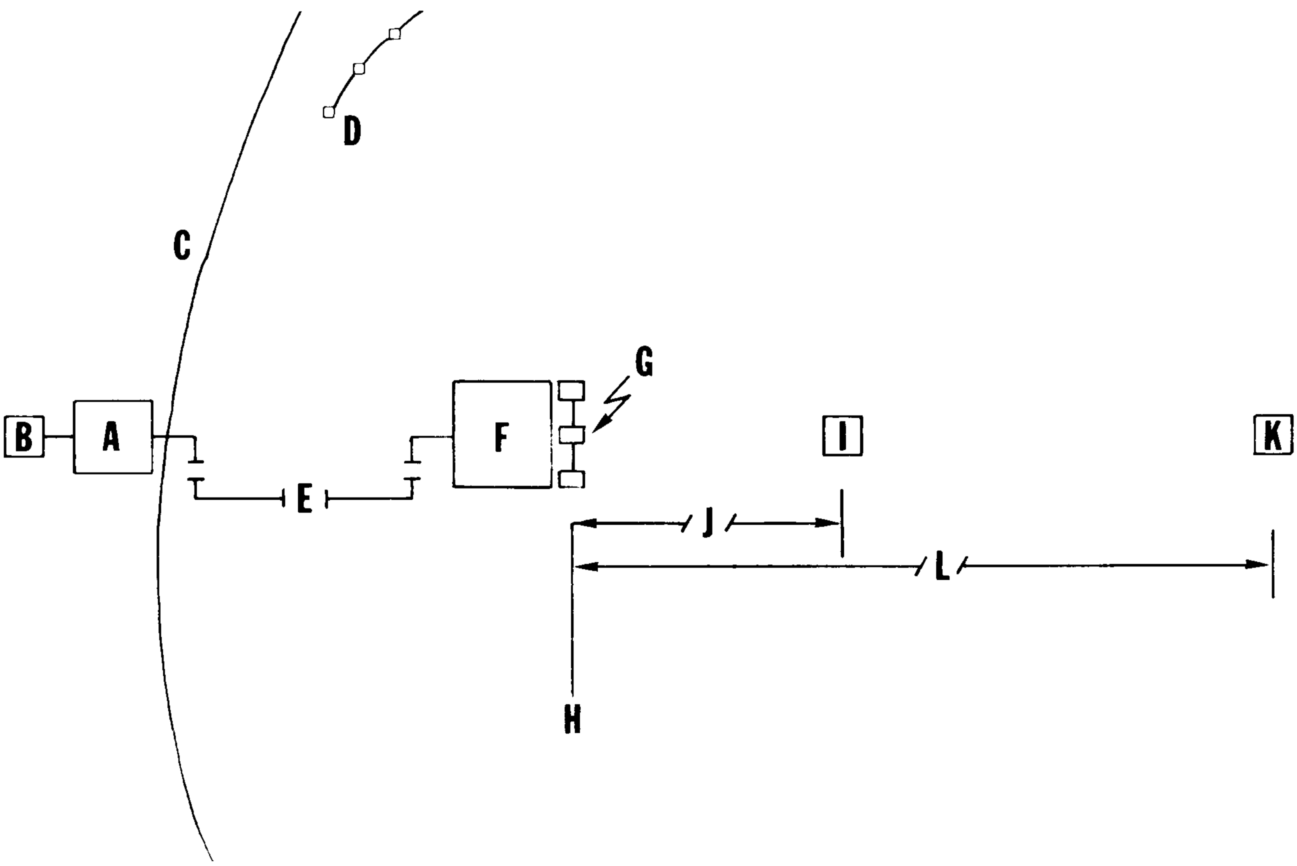

Figure 2. A schematic drawing of the range used in many of the UAPP experiments. A is the equipment van, B a generator and C is the shore. Line E carries the signal to the staging equipment on barge E. The J-11 s are placed 7m under the barge (see also Figure 1) and "hits" are counted when the diver passes line H (between the floats anyway). The range is depicted by L and the starting point by K (I and J refer to other experiments).

2. A 1.0 kHz square wave of 500 ms duration and with a 100 ms rise/decay.

3. A 0.2-2.0 kHz noise of 1 sec duration and with 50 ms rise/decay times.

Depending upon the particular study, the divers generally swam one or more trials involving:

1. a single beacon (SB) source,

2. a compass (C) dead-reckoning procedure (no acoustic signal),

3. a multiple beacon (UAPP) source, and/or

4. a procedure utilizing a compass in conjunction with one or more of the multiple beacon signals (MBC).

In all cases, the diver/subjects participated in two or more "visual" (V) swims in which they followed a line positioned along the bottom in a different part of the range. The visual trials ordinarily bracketed the other trials and the mean of the two swims was used to obtain base-line data relative to the time each diver would need to swim 150 m (see range D; Figure 2). As would be expected, the various multiple beacon (MB) conditions were counter-balanced across divers in order to minimize inadvertent learning effects.

Each diver (K) was transported by boat to the starting point located 150 m (or more) from the acoustic target (see again Figure 2). He descended to a depth of 7 m and was spun approximately three times by a buddy diver. He then indicated his preparedness to begin the trial by pulling several times on his safety line which was attached to a small buoy (he would tow the buoy during the entire trial). The safety line and buoy also served to maintain appropriate diver depth as the connecting line was 7m long and the diver was requested to keep a tight line between himself and the buoy. The diver was timed from his "ready"; signal to when he or she reached the acoustic target (G) or he swam past the vertical plane (H) of the transducers. The processes involved in these experiments can be understood also by consideration of Figure 3, at least from the diver's point of view. Subjects for these experiments were both male and female, trained and untrained divers drawn from the IASCP team and the University of Florida.

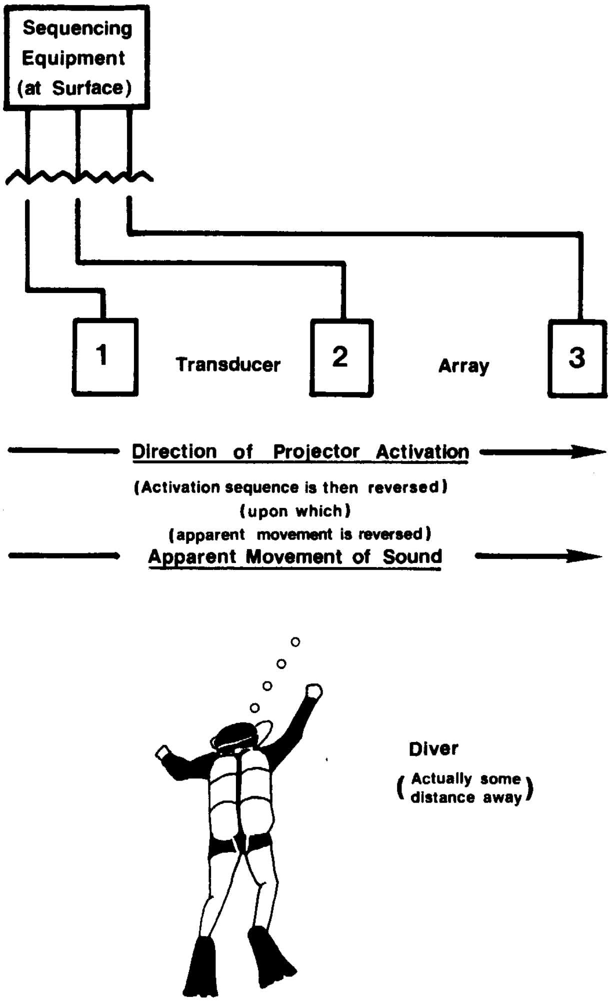

Figure 3. This drawing portrays the procedure by which the diver navigates. The sound attracts him to the target by first moving from left to right (from J-11-1 to J-11-3) and then from right to left (J-11-3 to J-11-1) and so on.

RESULTS

Basic Data

Table 1 provides basic data previously reported;[17] that is, it will serve as a summary for several of the earlier experiments. All values are proportions of the mean visual swim trials. It should be noted that values of less than 1.0 indicate a trial time which is faster than the visual swim and, conversely, trials with values greater than 1.0 required more time to complete than did the visual swim. As can be seen, the fastest trial (0.8) was shared by divers M-1 for the noise signal (MB3) alone (a hit) and M-7 for the compass swim (a miss), while the slowest time (5.7) was turned in by diver M5 in response to the single beacon (SB); this trial ended in a miss also. A hit was scored when the divers either reached the transducers (G in Figure 2) or bisected the transducer line between the buoys (H); a miss was scored when the diver stopped before reaching the buoy (even if only by a few feet) or missed the area between the buoys.

The primary conclusion that may be drawn from these and related data is that the divers were, in fact, able to effectively utilize the multiple beacon signals to navigate to the target. Indeed, while the times for some divers were occasionally high, no subject swam into any area other than that at, or adjacent to, the target. Furthermore, in many instances performance times are very close to those for the visual swims, ie. where the divers simply swam the 150 m distance following a line along the bottom. In short, it is clear that divers are able to "home" on the basis of heart stimuli.

It was expected after the pilot study, the multiple beacon

TABLE 1

Navigation scores for each diver and condition; values are proportions of visual swimtimes. Data for subject M-7 are incomplete as he did not return for the final set of trials.

CONDITION	M-1	M-2	M-3	M-4	M-5	M-6	M-7	MEAN	% HITS
C	1.7	1.5	1.2*	1.2*	1.7	1.5	0.8	1.37	29
SB	2.6*	2.4	2.7	2.7	5.7	1.9*	2.6	2.94	29
MB1	2.4	4.1	3.6	3.6	2.3	3.9	2.0*	3.13	14
MBC1	1.1'	2.2	3.1	1.1*	1.4*	1.6*	1.0*	1.64	71
MB2	2.6*	1.8*	5.2*	3.2	2.9	2.7*	—	3.07	67
MBC2	1.0'	2.9	3.5	1.3*	1.9	1.2*	—	1.97	50
MB3	0.8*	2.3*	3.9	1.1 *	2.4	1.9'	—	2.07	67
MBC3	0.9*	1.7	2.4*	1.1*	2.2*	1.4	0.9	1.15	57

MB1 = 500 Hz; 500 ms; 25 ms, MB2 = 1 = kHz; 500 ms; 100 ms, MB3 = N2k; 1 sec; 50 ms, * = hit

TABLE 1. Navigation scores for each diver and condition; values are proportions of visual swimtimes. Data for subject M7 are incomplete as he did not return for the final set of trials.

proved to be a more powerful cue than did the single beacon with the noise signal associated slightly better times and scores. Moreover, even though the times for the beacon swims often were slower than for dead-reckoning, accuracy was substantially greater and perhaps, most important, the beacons provided self-correcting information not available from a compass. Finally, since greater than expected variation was observed among diver performances, a learning function was suggested. That is, all divers showed improvement as the experiment progressed (no matter what the sequence of trials) with some showing greater improvement than others. Unfortunately, due to the structure of the early experiments, the nature of this training function could not be isolated. It was tested later and is reported below.

Training Effects

As stated, the results of the several previous experiments suggested that a much stronger learning function existed in the development of diver navigation by UAPP than was previously thought possible. Therefore, the effects of learning (or training) on the diver's ability to perform the cited tasks was studied. Only one MB signal was used in this experiment; it was the 0.2-2.0 kHz white noise of 1 second duration with a 100 ms rise/decay time and a 100 ms overlap. Nine certified divers served as subjects; four were experienced with underwater research on hearing and auditory localization whereas five were not. Training consisted of a lecture, a training trial with feedback and the multiple trials of the experiment itself. The diver's task was to navigate a 150 m course (using the cited beacon) either 10 times or until his performance plateaued. In addition to the acoustical trials, the diver also swam three 150 m visual trials (as swim speed controls). The diver's learning curve was assumed to have plateaued if he achieved consecutive trials in which:

1. Two were "hits" and arrival times were less than 1.5 of the mean visual swim time (VST);
2. three were hits and arrival was less-than or equal-to 1.5 of VST; or
3. three trials were within 3 m of the target and the times were less than 1.2 VST.

As with the earlier studies, a "hit" was defined as the diver navigating to the acoustical target, ie. arriving at one of the transducers, passing between them (the water was turbid and sometimes the subjects passed the target without seeing it) or passing between a J-11 and an outlying buoy.

The data from this experiment can be utilized to establish several relationships. First divers improved their performance as a function of continued trials and a diver's previous experience, or lack of it, with the underwater hearing research turning out not to be a factor in the determination of his or her performance. Thus, since the functions of all diver/subjects were similar, we would suggest that it should be just as easy to train naive divers to navigate acoustically, as it would be to train divers with previous exposure. Second, three measures of performance were utilized (time, angle and a time/angle composite). Of these, only the angle metric was found to dramatically measure change in performance. Specifically, swim times stabilized very quickly, ie. from 1.1 to 1.5 of visual swim by the second trial. A similar observation could be made for accuracy; indeed, there were only 4 per cent misses, and very close ones at that, in all the trials after the fourth and all divers arrived at one of the transducers 87 per cent of the time from the fifth trial on. In other words, divers improved in their navigational accuracy while maintaining fairly constant swimming rates and, as may be seen from observation of Figure 4 (page 132), most of the improvement in accuracy occurred within the first few trials. By that time, subjects had reduced the angle metric to about 1.5 degrees, which corresponds to an error of less than 4 m at

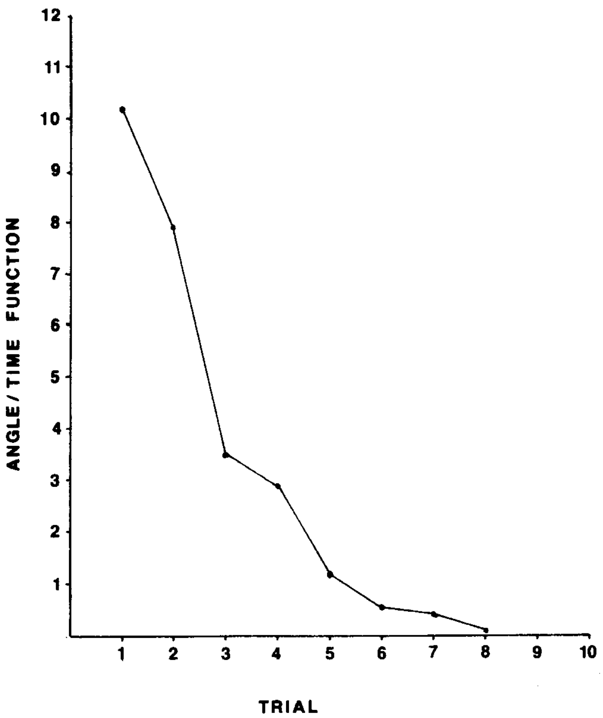

Figure 4. Graphed data depicting the function by which divers learn to navigate by UAPP. As may be seen, most learning takes place within the first few trials.

the transducers. Moreover, a particular feature of the multiple beacon approach is that it appears to be self correcting.

CONCLUSIONS

An integrated and systematic programme of research has been undertaken at the University of Florida in order to develop an operational system for acoustic diver navigation. As can be seen from the cited data, the research that has been completed to date has demonstrated that divers not only can localize sound underwater reasonably well but also can use this ability to navigate. To be specific, it was found that (1) when a multiple sound source was used to produce the Underwater Auditory Phi Phenomenon (UAPP), the divers are able to navigate to the target almost as well as if they had a visual line to follow and (2) even untrained divers could learn to "home" acoustically and do so very quickly. Finally, substantial progress has been made toward optimizing the parameters of the acoustic signals for the purpose of diver navigation and research in this regard is to be published soon.

Finally, two features of this approach should be stressed. First, when a UAPP signal constituted the underwater beacon, not a single diver ever swam to a sector other than that which contained the sound source. This relationship has been found to hold for all trials with in all experiments. Second, the procedure clearly is self-correcting, at least when the task is to bring the diver to a fixed source. We are now developing experiments which are designed to study the possibility that UAPP information may be employed to permit a diver to navigate freely underwater.

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Professor Harry Hollien, PhD is the Founding Director of the Institute for Advanced Study of the Communication Processes, University of Florida, Gainesville, Florida 32611, USA. His address is ASB-50, IASCP, University of Florida, Gainesville, Florida 32611, USA.

A SPUMS MEMBER IS HONOURED

We reproduce below the citation of the Craig Hoffman Memorial Award presented at The Undersea and Hyperbaric Medical Society (UHMS) meeting in Baltimore, Maryland, USA, in May 1987.

The Undersea and Hyperbaric Medical Society takes great pleasure in presenting

THE CRAIG HOFFMAN MEMORIAL AWARD

to

CARL EDMONDS

This award is conferred upon the recipient for significant contribution to diving safety. Dr Carl Edmonds has for over 20 years been a leader in the Australian diving safety community. His contributions to worldwide diving safety have benefited those involved in military, commercial, scientific and sport diving.

Dr Carl Edmonds accepting the Craig Hoffman Memorial Award.

Dr Edmonds' accomplishments cover the gamut of diving. His contributions to the field - marine animal injuries, his work developing the civilian diving medical courses in Australia and the development of in-water decompression techniques have all played major roles in diving safety.

Additionally, his worldwide involvement with the undersea medical community has provided a means of disseminating this works in diving safety for the benefit of all.

SPUMS congratulates Dr Edmonds, known to the diving world in Australia simply as "Carl", on being the first Australian to be given an UHMS International Award.

DIVING AND SAFETY

POLICY OF THE VICTORIAN ASTHMA FOUNDATION

Persons with asthma are at increased risk of potentially fatal lung complications from undersea diving. Diving itself may induce asthma attacks and asthma related diving deaths have been clearly documented. The exercise associated with diving, the changes in body temperature, the inhalation of dry gas mixtures and the potential for inhalation of saline may all play a role in triggering an attack of asthma in the hyperreactive airways of asthmatic subjects. Additionally, the occurrence of an asthma attack may lead to panic reactions with mishandling of equipment and errors of judgement.