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VOICE COMMUNICATION PROBLEMS IN SPACECRAFT AND UNDERWATER OPERATIONS

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INTRODUCTION

Space exploration has compelled man to function in new, different, and indeed, exotic environments. The astronaut wears a space suit and is placed inside an artificial atmosphere that is cramped for space. He is required to manipulate controls, read dials, mentally analyze the situations, and make operational decisions. In addition, he must communicate with controllers on the earth. The task is difficult and complex.

Not only is man venturing beyond the atmosphere, but he also is exploring the frontiers of vast inner spaces contained within the oceans of the world. Many of the problems encountered are the same for both situations. For example, underwater habitats, like space capsules, contain artificial atmospheres, and divers must wear special suits outside the habitat. The lack of immediate contact with the rest of the world imposes both physical and psychological restraints. Communication links between the astronauts or aquanauts and surface control stations are vital to the integration of specific tasks and other activity that leads to successful operational functioning.

Communication involves the generation of ideas, an attempt to implant these ideas elsewhere, and a subsequent response resulting from the communication itself by some individual or thing. The use of some form of language wherein signs function to make common an idea and hence convey meaning is fundamental to communicating.

In this paper, the enormous scope of communication is restricted to human speech. Various problems in voice communication found in operations underwater and in outer space are considered. Since the production of speech is basic, the major part of the presentation is devoted to factors affecting local production. Additionally, problems associated with electronic components, difficulties encountered by the listener, and the importance of language considerations are discussed.

FACTORS AFFECTING THE TALKER

Masks and Helmets

In attempting to speak intelligibly, deep-sea divers have long experienced difficulties associated with the masks or helmets they wear. Surprisingly few improvements in deep-sea diving gear, to increase reliability of communications, have been made over the years. The intake of breathing mixtures still produces noise that masks feedback of the diver's voice, affecting self-monitoring mechanisms. Reverberation within helmets continues to interfere with production of clear speech. The existing distorted communication may be adequate for some routine diving operations. However, highly intelligible speech, needed to facilitate certain tasks or to permit appropriate action in emergency situations, does not exist.

* Opinions or conclusions contained in this article are those of the author and do not necessarily reflect the views or endorsement of the Navy Department.

Underwater masks worn by swimmers have as a major function the introduction of life-supporting breathing mixtures. Problems are introduced by adding communication systems to these masks. If the respiratory system is not a closed one, bubbles escape into the sea, making noise. Swimmers often hold their breath and wait until the noise from the respired gas bubbles subsides before they talk. When they do this, intelligibility is improved. Different placements of the escape valve have only a minor effect on bubble noise.

Noise within the underwater mask arises when breathing mixtures pass through restrictive valves located close to the microphone. In order to prevent carbon dioxide buildup, these valves must be close to the mouth. For microphone placement in space suits and diving masks, certain designers choose locations near the mouth for increased intensity of the voice, while others prefer locations such as the forehead for picking up speech because of the lower level of noise at that point. In both instances, a more favorable signal-to-noise ratio is sought.

The noise referred to above comes from equipment close to the individual's head. In spacecraft, the astronaut is surrounded by high levels of external noise. Orrick¹ has noted a decided advantage in the pilot's helmet regarding speech intelligibility. When communication is accomplished by electronic means, the ambient noise level is attenuated by the helmet. In addition, signal gain can be increased to advantage in high ambient noise levels. Von Gierke² points out that the major interference by noise on spacecraft occurs from the propulsion power, which is most severe during launch and reentry phases. He predicts that "with proper cabin and personal equipment design, adequate speech communication should be possible during both phases." He assumes that, even though intense noise levels might occur within the helmet, such levels would be of short duration and have an estimated capability of a 10-db speech-to-noise ratio. On the other hand, von Gierke cautions that noise levels of future manned space operations could be 20 db higher than today's predictions, and reliable communication would be a real problem, perhaps impossible.

Face masks and helmets restrict free movement of the articulatory mechanism. Hansen³ found that physical restriction of jaw movement alone has an insignificant effect on speech intelligibility. However, further studies could investigate compression of the facial muscles and resonance characteristics of the cavities in the mask. Interference with the normal loading of respiratory gases within head cavities of the submerged diver as well as effects of water compression on his cheeks pose additional problems for investigation.

Vibration

High levels of vibration can have a deleterious effect on human behavior. Such levels must be considered in the design of future equipment used in manned space flights. The influence of selected mechanical vibrations upon speech has been studied by Nixon⁴. He reports that talkers experiencing low-frequency vibrations have a tremolo-like voice quality corresponding in some degree to the frequency of the vibrational stimulus. Although monosyllabic word intelligibility did not deteriorate when speech under conditions of vibration was heard in quiet, there was significantly less intelligibility when noise was added, for vibrations of 10, 20, and 30 per second, than is found for normal speech when similar noise is added. Intense vibrations interfere with the proper fitting of communication equipment to the body. However, if these vibrations are not severe enough to cause masks and associated communication components to resonate to a degree of physical dis-

comfort or damage to the wearer, then communication is usually adequate except for certain low frequencies

Weightlessness

The question of whether weightless conditions interfere with the intelligible aspects of communication has been studied by Nixon and Waggoner⁵ Neither speech production nor the reception of speech was significantly altered by brief periods of zero gravity They conclude that both talkers and listeners can achieve good speech intelligibility under conditions of weightlessness Since then, there have been a number of space flights that have demonstrated the correctness of Nixon's and Waggoner's conclusions

Training

Tolhurst⁶ investigated the effects on intelligibility scores of specific instructions regarding talking He found that simple instructions to talk loudly, precisely, and fast improved intelligibility The important point here is that simple instructions to talkers typically leads to improvement in their speech

EFFECTS OF VARIED PRESSURE AND BREATHING MIXTURE

Two major factors influence speech in deep-submergence operations One is the effect of increased pressures on vocal production The other concerns exotic gases, such as helium, which are introduced into breathing mixtures to reduce nitrogen narcosis at high ambient pressures These two factors are difficult to consider independently because the higher the pressure, the more pronounced the narcotic effect At depths greater than 100 ft, there is typically an interaction of pressure and helium that produces an alteration in the spoken voice⁷

Pressure

First let us consider speech at shallow depths while a normal air mixture is breathed Several underwater communication systems were evaluated by White⁸ at several shallow depths He found no significant change in intelligibility at depths down to 100 feet Considering other aspects of the diver's speech, he noted a marked handicap to intelligibility caused by the noise of pressurized airflow

Fant (Speech Transmission Laboratory⁹) describes a "nasal quality" for voices under pressures equivalent to about a 100-ft submergence He notes that there is also a differential alteration to the sound pressure of such speech "At high ambient air-pressures there remains a decrease of the sound pressure level of fricatives and stops relative to the average level of voiced sounds" Since Clarke and associates (see Fant in STL⁹) had noted an opposite shift in speech levels at a 35,000-ft altitude, Fant theorizes that a consistent set of variations due to pressure changes exists for densities from high ambient pressures found underwater to low pressures existing at high altitudes His analyses of frequency shifts, formant bandwidths, sound pressure levels, and unvoiced sounds of speech under high ambient pressures support this theory

Breathing Mixture

A number of reports¹⁰⁻¹⁵ describe alterations to speech caused by breathing helium The most striking characteristic is the upward shift in formant frequencies

This shift has been related directly to the velocity of sound for a gas contained within a resonating chamber¹⁵ Although measures of the amount of shift are less than calculated, they approach, to a first approximation, predictions based on changes in the velocity of sound

In an analysis of speech tape recorded during SeaLab II,† MacLean¹⁶ noted certain differences among shifts of frequency that occur for the first three formants These could not be explained simply according to changes in the velocity of sound within the resonators of speech Similar shifts were found by Fant (Speech Transmission Laboratory⁹) with speech produced at a 100-ft depth on an air supply He explains pressure effects on speech in terms of changes to the walls of the vocal cavity and systematic factors of impedance loading of the vocal tract These variations appear to be caused mainly by the increased density accompanying higher ambient pressures

The intelligibility of helium speech has been evaluated under a number of conditions Speech produced in an 80–20% mixture of helium-oxygen at normal atmospheric pressure is highly intelligible¹⁷ In investigations of speech at altitudes to 35,000 feet, Cooke¹⁸ and Cooke and Beard¹⁹ found that helium in the talker's breathing mixture had no significant effect on intelligibility While verbal communication reported for speech in helium or air at normal atmospheric or reduced pressures is good, Wathen-Dunn and Copel²⁰ and Holywell and Harvey¹³ note that at pressures equivalent to or greater than 100-ft depths, a diver's speech is less intelligible when breathing a helium mixture than it is when breathing air In an exceptionally clear recording of helium speech at a 400-ft simulated depth, Sergeant²¹ also found a mean intelligibility of only 78%, while similar data collected at a one-atmosphere pressure resulted in scores over 95% The effects of pressure appear more important than those of gas, in spite of the strikingly noticeable change in voice quality due to helium

When noise is added to either helium speech or normal speech to compare intelligibility, the helium condition suffers most Therefore, the use of helium mixtures rather than air or nitrogen-oxygen mixtures in spacecraft during launch and reentry phases, when noise levels are highest, may not be desirable when verbal communication is the criterion

When the speech signal is accompanied by high levels of broad-band noise, proper filtering seems a logical means of removing much of the noise and thereby increasing intelligibility Sergeant²² evaluated speech produced after the breathing of an 80–20% mixture of helium-oxygen that was combined with white noise and then passed through a selection of band-pass filters The intelligibility of this helium speech was, as has been found with speech in air, quite distortion-resistant to filtering Even with the severe filtering restrictions of a 600-to-1,200-cps passband, and a 1db speech-to-noise ratio, 38% intelligibility was achieved Most important was that no condition of filtering increased intelligibility over the no-filter condition

METHODS TO ALTER HELIUM SPEECH

The following methods have been suggested for increasing the intelligibility of helium speech by reducing the formant frequencies of the speech spectrum (a) slowing down original speed of transmission, (b) incorporating side-band

† SeaLab II was an undersea experiment conducted by the U S Navy off the coast of California during the summer of 1965 Men survived for several weeks on the ocean's floor at a depth of approximately 200 feet They were able to swim in and out of a habitat that contained a mixture of helium and oxygen

techniques, (c) utilizing computers, (d) splicing a magnetically taped speech sample, either physically or electronically, and (e) using a speech-pattern playback machine

Holywell and Harvel¹³ report a decided increase in intelligibility of helium speech simply by slowing down the recorded message to 6/10 of its originally recorded speed. This lowered all frequencies by a constant factor. In another investigation of speech obtained in a chamber containing 94% helium at a simulated depth of 400 ft, this technique produced an increase in intelligibility of the talker from 78 % to 97% when a speed of one-half was used²¹—a remarkable improvement indeed. The major difficulty in simply slowing down speech is that you lose real time and the fundamental frequency of the voice is also lowered. Nevertheless, for routine messages wherein time is not a deciding consideration, this technique is quite appealing.

Frequencies can be lowered in a selective manner with single-side-band and demodulation equipment. Holywell and Harvey¹³ were able to show appreciable improvement by using this technique. Copel (Wathen-Dunn & Copel²⁰) designed an "unscrambler" for helium speech, which has been used by the U S Navy for speech in helium-rich atmospheres. However, serious distortions typically are introduced by single-side-band equipment, and the linear frequency shift suggests that completely normal speech might never be attained by this technique.

A means of making helium speech, recorded during SeaLab II, sound fairly natural as well as more intelligible has been reported by Golden²³. Using a formant-restoring vocoder, the spectral energy of helium speech is separated into a number of narrow bands that amplitude-modulate lower-frequency pitch harmonics derived directly from helium speech. At the present time, there is a need for an inexpensive machine that is portable and has as its primary function improvement of verbal communication in helium atmospheres at depth.

A splicing technique for improving communication in helium is simple in theory. Small sections of a magnetic tape can be parcelled out and the remaining pieces spliced together into a shorter length than the original. If the tape is then played back at a slower rate, the original rate can be recaptured while the frequencies are shifted downward toward more normal positions. Following this procedure, Jefferies²⁴ has demonstrated a decided improvement in helium speech. However, the time required to accomplish this type of splicing makes it very impractical.

Fairbanks and colleagues²⁵ devised a rotating pickup head for use on a tape recorder that enables a tape to be electronically spliced nearly in real time. The Varivox from Kay Electronic Company and the Eltro from Gotham Electronic Company are two commercially produced machines that operate on this principle. When either of these machines is used to lower speech frequencies while retaining the original rate of talking, and the stimulus material is helium speech under pressure, there is a significant increase in intelligibility and naturalness. Although preliminary data indicate that the improvement is not as great as that obtained by the simpler slowing-down technique, there is a decided advantage to this method. The process is in real time except for an insignificant delay caused by separation of the record and pickup heads.

Apparently no one has as yet tried to use a speech-pattern playback machine such as the one at Haskins' Laboratory²⁶ to lower the frequencies in helium speech. The theory of operation of this machine should enable an excellent normalization of helium speech. During the playback mode, a brilliant light

passes through a rotating disc that produces a series of bands of pulsating light, each representing a specific frequency. Selective reflections from spectrographic tracings determine the spectral content of the light that is picked up by a photoelectric cell, amplified, and fed into a loudspeaker. By altering the rotating speed of the wheel, frequencies could easily be shifted by any constant ratio desired.

COMMUNICATION COMPONENTS

Success in verbal communication depends on the effectiveness of the electronic link between the talker and the listener. New designs from the electronic engineers' workbench have eliminated many problems, both underwater and in space operations. In designing systems that will operate under intense vibrations and rapidly changing pressures, many of the rules and techniques familiar to the average communication engineer do not apply. Calibration equipment must be able to withstand pressure changes that will implode some vacuum tubes. Care in selecting the proper microphone is required. For instance, susceptibility of carbon microphones to pressure changes precludes their use in many cases. Other transducers required special corrections owing to variations in level of output with pressure change.

A special problem for the communication engineer is introduced during the reentry phase of a space capsule. At that time, an ionization barrier to radio waves produces a communication blackout for ship-to-ground messages. The development of an alternate system, possibly incorporating laser beams, is needed to solve the problem.

Very often, the interaction of two effects will produce a significant distortion greater than either effect alone. For example, a rubber boot will render a toggle switch waterproof, and the same switch will function at very high pressures. But if that switch is submersed 200 ft into the water, it floods and becomes inoperable. Such problems are not, of course, restricted to the design and implementation of communication equipment.

Before using equipment on a deep-submergence dive, there should be tests of the effects of intense pressures in special chambers. This is true for vacuum tubes, microphones, tape recorders, and other units making up the voice communication system. Equipment reliability in space or under the sea is paramount, because spare parts are not available. Destructive tests using high levels of vibration can lead to effective alterations to equipment that may prolong the system's operating life and reliability.

Size and weight restrictions for undersea and space programs are well known. Microminiaturization and solid-state electronics are solving many of the problems encountered. Radios the size of a cigarette pack are already a reality because of advances in these fields, and more complex electronic systems are being developed that are even smaller and lighter.

Frequently, the appropriate personnel to evolve an operational system for communication are not available. Talents from fields of electronic engineering, speech sciences, psychology, and medical science, as well as the people who will use the equipment, should be utilized during developmental stages. However, it is not uncommon to find some poor soul asked to improvise a voice set for a diver to use at 400 ft underwater the next morning. Considering the complexity of specific operational problems encountered in space and undersea programs, there is a need for an organized team approach that would combine several disciplines, including the spectrum of speech sciences, to design optimal communication by voice. There must be good coordination among the members of this team.

FACTORS AFFECTING THE LISTENER

Problems in voice communication associated with the listener are usually less severe than those associated with the speaker. In many cases, they are the same and have already been mentioned. For example, the noises that mask intelligible speech must be eliminated or reduced not only at the speaker, to improve his speech signal, but also at the listener, so he can better hear an intelligible signal. Embedding earphones in circumaural cushions is one method of decreasing external noise reaching the ear. Helmets also have desirable attenuation. Many of the calibration problems for the microphone at increased pressures are unimportant for earphones unless one needs a single transceiver instead of two units. Difficulties arising from restricted movement of the articulators for speech do not interfere with the listening task. Major communication disturbances observed in helium-rich atmospheres are associated with production of the voice, not with auditory functioning.

Waterproofing an earphone, especially at higher pressures, becomes a significant problem. Even so, small underwater transducers that are capable of emitting waterborne signals have been developed. Although such units cannot be heard at distances, such as five feet, they serve well as earphones. Unfortunately the reliability of these small transducers is low because of leakage problems. Better enclosures, which would not distort the acoustic output detrimentally, are needed.

More precise information is needed concerning the functioning of the submerged ear. What is the frequency response curve under the mask for waterborne energy? How does an air bubble in the auditory meatus alter an acoustic input? Do we really hear by mass bone conduction when swimming bare-headed, or does the signal also pass through the normal channels of tympanic membrane and ossicles? Precise answers to these questions should be determined and incorporated into communication systems.

THE PROPER USE OF LANGUAGE

Fundamental to the process of communication is the use of language. Special vocabularies, circuit discipline, and communicative behavior are areas needing expansion within research related specifically to operations underwater, in space, and in other highly specialized environments. Previous work has shown the value of specialized "patter" of selected common operational phrases for use by air pilots. Similar selections of words and phrases are not used by divers. Monitoring verbal transmissions during different underwater operations and manned space flights should precede construction of vocabularies specific to different operations. Coded phrases for routine expressions could be incorporated into such vocabularies.

Circuit discipline is vital to successful communications during intense moments. Several talkers on the line in an emergency tend to use unexpected phrases or to become overly excited, to the point of destroying intelligible transmission. The behavior of man in space or the diver during an experimental operation cannot be easily predicted. Emphasized circuit discipline, including the proper use of special vocabularies, must be incorporated within training programs.

SUMMARY

A general description of speech has been presented for environments in outer space and within the oceans. Special problems arise when communication

systems for operations within these environments are considered. Noise, vibrations, unusual breathing mixtures, and restrictions due to fitting of masks and helmets can interfere with the talker's ability to produce intelligible speech. Many of these conditions also interfere with listening. More intelligible and more natural-sounding helium speech can be achieved in several different ways, each having its advantages and disadvantages. The electronic link between the talker and the listener introduces many situations that may be unfamiliar to the communications engineer. In addition to revised calibration techniques, problems of waterproofing, size and weight restrictions, and pressure-proofing of components must be solved. The effectiveness of any communication system can be increased by adherence to circuit discipline, simple training to speak clearly, and utilization of vocabularies specific to the immediate operation. Coordination among different disciplines, including the voice sciences, is vital to the development of optimal verbal communication for operations under the sea or in manned spaceships.

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