Orientation to the Vertical During Water Immersion

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THERE IS MUCH speculation concerning the effects which a gravity-free state may have on the occupants of space vehicles.[11] Relaxation of the muscles which are involved in the maintenance of posture on the earth's surface may result in a loss of tone which will interfere with motor performance capability when gravitational fields are again encountered. Eating, excretion, and a variety of physiologic processes may be disturbed in the prolonged absence of the earth's gravitational field.[12,13] On the optimistic side there has been some speculation to the effect that the complete relaxation possible in a weightless state may completely eliminate the need for sleep.

It will not be possible to study the effects on man of a prolonged condition of zero gravity until one is able, successfully, to place a manned satellite in orbit. It has been suggested, as an alternative, that man can be made effectively weightless with respect to his immediate environment by immersing him in a liquid of a density which is approximately the same as his own. Under these conditions, he will be weightless even though he will remain in the field of the earth's gravitational force. There are several disadvantages inherent in this procedure. One is the problem of respiration. The necessary respiratory device involves undesirable encumbrances. In addition, the density of the liquid will serve to damp movements considerably. The presence of the earth's gravitational force-field is important because the human body is not of uniform density. Even though the body as a whole is supported uniformly by its liquid environment there will be displacement of more dense parts of the body with respect to their less dense surroundings. One of the receptor systems of the vestibular apparatus, the utricular system, is believed to function on the basis of just this principle. The relatively dense otoliths are displaced with respect to the gelatinous macula in which they are imbedded in relatively different ways when the linear acceleration force resultant changes in either magnitude or direction. Adrian[1] demonstrated a prolonged discharge in the afferent neural connections of the utricles following changes in linear acceleration acting on the body. Presumably the utricles signal changes in the orientation and/or magnitude of linear acceleration forces. An individual immersed in liquid may therefore be expected to have some basis for orientation in the absence of any of the usual visual, tactual, and other cues. This is not to say that the utricles should be expected to provide him with a continuously available sense of reference for the gravitational vertical, but following a few simple changes in position of the head the pattern of change of utricular stimulation may afford a cue as to the orientation of the vertical, or "which way is up."

In spite of these disadvantages, immersion as a method of simulating zero gravity is believed to have some utility. At the present time the National Aeronautics and Space Administration laboratory at Langley Field, Virginia, has undertaken a project to study the responses of subjects when they are immersed in a liquid-filled capsule. The capsule may be rotated about a horizontal axis to eliminate any constant vertical reference for a subject who is held in a fixed

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position inside the rotating capsule. Muller[8] suggested such a project several years ago. He proposed that a cylindrical tank be employed which could be rotated about a horizontal axis coinciding with the long axis of the cylinder. In this arrangement, the subject would lie outstretched within the cylinder, supported by the liquid within the cylinder. His head would be supported to prevent movement with respect to the axis of rotation. A visual display within the cylinder would remain fixed in orientation with respect to the subject in order to afford a cue which might help to suppress the perception of motion in this situation. Muller has suggested that some rate of rotation might be found at which there would be a "fusion" of the stimulating effects of rotation on the utricles. At this rate there would be no available vertical reference for the observer. Rotation may not be necessary if the subject is restrained within a tank, particularly when he is prevented from making any head movements. The possibility of utricular cues as to the orientation of the vertical in the absence of any changes in utricular stimulation is highly questionable. Recently the Lockheed Aircraft Corporation at Marietta, Georgia, has constructed a device according to the design proposed by Muller.[7]

Whiteside[15] has tested orientation as measured by pointing during immersion in water up to the neck. Some loss of directional sense was found in this situation even though the utricular sense was not diminished. Loss was attributed to altered muscle balance, absence of visual information and reduced proprioceptive cues.

Years ago, Stigler[10] attempted to measure the orientation of swimmers after they had been rotated on a bar while completely submerged. Their eyes and ears were covered to eliminate visual and auditory cues. They were instructed to point in an upward direction upon termination of rotation. Apparently they were seldom able to do this accurately. The experiment was terminated by the unwillingness of the subjects to repeat the procedure after one trial. They found the experience most unpleasant and anxiety provoking and, perhaps partly because of their anxiety, they were unable to hold their breath long enough for adequate observations to be made. Additional observations were later made with subjects stretched out on a board under water. The problem of breath holding was eliminated by the use of underwater breathing apparatus. The board was turned back and forth on fixed bearings and then set in one of several terminal positions. The subjects then attempted to point in the upward direction. They were usually in error by approximately 15 degrees.

Determination of Thresholds of Stimulation for the Utricles.—Many attempts have been made to measure the threshold of the utricles for changes in resultant linear acceleration. Reported threshold values range from 0.000344 G up to 0.010 G or higher. A number of these determinations have been made on tilt tables. The subject is strapped on the table and an effort is made to determine the minimum change in table orientation which can be detected when the angular accelerations of the table are sufficiently low to avoid stimulation of the semicircular canals. Slight changes in position result in tactual stimuli from the restraining straps. It is difficult to eliminate noises and mechanical irregularities which may serve as cues to changes in position of the table. In most experiments, control of table motion has been manual and hence cannot be precisely specified or repeated. Graybiel and Patterson[4] measured the threshold of the utricles in terms of the oculogravic illusion. They have reported a threshold of 0.000344 G for subjects in the sitting position and 0.00203 G for subjects lying on their sides. These values may be much better than those obtained on tilt tables, but it is still generally conceded that we have no really definitive values for utricular thresholds.

The finding by Graybiel and Patterson of a change in threshold with a change in position of the subject is not a surprising one in view of the anatomy of the utricles. It is logical to assume that displacement of the otoliths with respect to the macula and attendant stimulation of hair cells will be maximal when the head is in an upright position. In 1928 Quix[9] reported a "blind spot" in the utricular sense for subjects in a supine position with the head depressed.

In order to avoid many of the problems associated with tilt table experiments, some of which may have influenced the results obtained by Quix, Knight[6] attempted to repeat the experiment of Quix under water. Knight was also interested in the possible application of his results to simulation of the null-gravity state. He employed a tilt table with a protractor and changed position of the table at a very slow rate, measuring the amount of change necessary for detection. He encountered a number of problems and was unable to get clearcut quantitative results. He did find, however, that thresholds were higher with the head oriented downward than they were for other head positions.

The existence of a utricular sense has been questioned.[5] Few present-day investigators doubt it, but it has probably never been measured acting all by itself. Its normal function is in conjunction with semicircular canals[3] and it probably should not be considered an independent sensory component. As a basis for the existence of the sense, Wendt[14] cites the subjective awareness of the direction of gravity when one is under water, but he gives no experimental evidence. Gernandt[2] states that after bilateral loss of vestibular function an individual submerged in water is disoriented and may swim downward in attempting to reach the surface. It is probable that vestibular function is of primary importance, but as indicated below there may be a variety of supplementary cues to the direction of the vertical for a subject immersed in water.

A Preliminary Investigation in the Navy Underwater Escape Training Tank.—A preliminary investigation has been conducted to determine the extent of possible disorientation in a liquid environment when visual cues, tactual cues, kinaesthetic cues, and buoyancy cues are eliminated to a large extent. Orientation to the vertical under such conditions may be indicative of perception via the labyrinthine senses although, as discussed below, other cues may still be present. Human subjects can very easily be disoriented with respect to the direction in which they are facing by rotation about a vertical axis. Such disorientation is attributed to the effect of angular acceleration and deceleration on the semicircular canals. It does not follow that they can as easily be disoriented with respect to the direction of the vertical by rotation about a horizontal axis. Rotation about a horizontal axis in a vertically oriented gravitational field results in a characteristic changing pattern of stimulation of the utricles on each rotation. Thus, in addition to the disorienting effect of semicircular canal stimulation, there is another source of stimulation which could, conceivably, enable the retention of orientation with respect to the vertical. Three specific experimental questions have been posed: (1) When submerged in a tank at a point near neutral buoyancy can a man, placed in some random orientation after several disorientating turns by an experimenter, point correctly in the direction of the vertical without any gross movements of the head? (2) If he is unable to point directly in the direction of the vertical can he, after some exploratory head movements, point in the vertical direction? (3) How accurately can he orient his entire body to the vertical and swim in the direction of the surface?

The Elimination of Extraneous Cues.—A number of possible cues may be anticipated which are distinct from utricular stimulation and which may serve as indices of the vertical.

1. Temperature gradient. The temperature gradient vertically in the escape training tank is not a serious problem. The water is heated

and the air surrounding the outside of the tank is of relatively uniform temperature.

2. Relative buoyancy of the human body. An appropriate depth can be determined for experimental subjects at which they will be approximately neutrally buoyant. Density differentials from limbs to trunk may still provide cues to orientation but these differentials cannot all be eliminated easily.

to observe the subjects. An opaque face mask worn by the subject may be used to eliminate visual cues.

PROCEDURE

The initial part of the investigation was conducted at a depth of approximately 18 feet. Most adult males achieve neutral buoyancy at a depth of between 15 and 25 feet. A lock

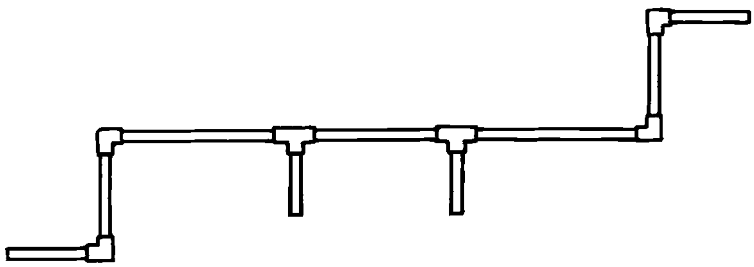

Fig. 1. Illustration of the rod which was employed for rotation of subjects.

at a depth of 18 feet with a diving bell positioned opposite it provided a base of operation. Of the first five subjects employed, four were experienced underwater swimmers and the fifth was an experienced diver. Subjects worked from the surface of the tank in order to eliminate any possibility of ascents with high pressure air in the lungs. Oxygen was available, but four of the five subjects preferred not to use it. After hyperventilating for several seconds, subjects donned an opaque face mask and descended to the appropriate depth on a vertical cable which was moored at the top and bottom of the tank. A safety swimmer guided the subject to a rod which extended between the lock and the diving bell. The rod is illustrated in Figure 1. Grips for the right and left hands of the subject were located near the center of the rod and handles were located on each end. The subject assumed a position on the rod with knees pulled up and head tucked down on the chest. The rod was rotated at a

3. Cues from respiratory equipment. The relative pressures required for inspiration and exhalation with standard Aqualungs change in relation to valve position with respect to the mouth. It is therefore desirable to avoid the use of Aqualungs or similar respiratory equipment. This requires the use, as subjects, of experienced underwater swimmers who are capable of holding their breath for a sufficiently long time to go through an experimental procedure without interruption.

4. Flow of air bubbles over the surface of the body. Expired air bubbles will travel upward and may provide a cue as to direction of the vertical. This cue may be avoided by instructing subjects not to exhale during the course of an experimental procedure.

5. Visual cues. It is necessary to eliminate all visual cues from subjects. At the same time, it is desirable to have a prevailing illumination level which will enable safety officers

rate of approximately one rotation in two seconds by two experimenters, one on each end. On any given trial, the rod was rotated three, four or five times plus some fraction of a full rotation in order to vary the terminal position of the subject from one trial to another. The number of rotations and the terminal positions for each trial for each of the five subjects are indicated in Table I. Upon completion of rotation, the end of the rod was tapped once to provide a signal to the subject. The subject then released his right hand hold and attempted to point toward the surface of the tank with his right arm. After approximately 5 seconds the end of the bar was tapped twice. This served as a signal to the subject to tilt his head back slowly then forward following which he corrected his estimate of "up" if he considered any correction necessary. Following this procedure, three taps on the end of the rod served as a signal to the subject to swim slowly toward the surface.

TABLE I. OBSERVATIONS AT A DEPTH OF EIGHTEEN FEET
Direction numbers for each of 5 subjects at each of 3 steps in the procedure

Subject 1					Subject 2					Subject 3					Subject 4					Subject 5				
* Rot. No.	* Term. Pos.	Step** 1	Step** 2	Step** 3	Rot. No.	Term. Pos.	Step 1	Step 2	Step 3	Rot. No.	Term. Pos.	Step 1	Step 2	Step 3	Rot. No.	Term. Pos.	Step 1	Step 2	Step 3	Rot. No.	Term. Pos.	Step 1	Step 2	Step 3
5	B	6	4	0	4	B	6	4	0	3	U	4	4	0	3	B	3	3	0	5	B	5	2	0
4	U	1	1	0	4	U	1	0	0	4	U	7	1	0	5	D	8	3	0	4	D	6	3	0
4	F	0	0	0	4	F	1	0	0	3	D	5	1	0	3	F	5	4	X	4	F	4	1	0
5	D	4	1	0	5	D	8	5	0	5	U	0	0	0	3	D	7	†	X	3	D	8	4	4

*No. of complete Rotations and Terminal Position: U–Head Up; F–Head Forward, Face Down; D–Head Down; B–Head Back, Face Up.
**1–Pointing with right arm; 2–Pointing after nodding head; 3–Swimming to surface.
X Subject did not swim; slight neg. buoyancy caused him to sink slowly, feet down.
†Touched vertical cable, obtained cue to vertical.

The direction in which the subject pointed was estimated by an observer to the nearest 22.5 degrees from vertical in the upward direction. A direction number was assigned for each of the three steps on any given trial in accordance with the scheme which is illustrated in Figure 2.

A supplementary investigation was conducted in the same manner with four subjects at an approximate depth of 25 feet. The subjects included two submarine medical officers, the diver of the initial investigation and the author. The number of rotations and the terminal positions for each trial in this part of the experiment are presented in Table II.

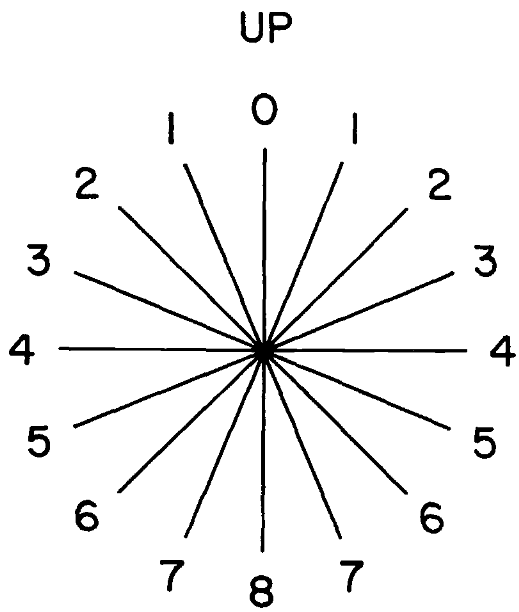

Fig. 2. A graphic illustration of the direction numbers which were assigned to directions in which subjects pointed. Assignments were based on an observer's estimate.

RESULTS

Four trials were conducted for each of the subjects in each part of the investigation. Twelve trials were planned for each subject in the initial part of the investigation but it was not possible to complete this entire experimental program. The results of the initial part, in terms of direction numbers, are presented in Table I. The same results are presented in Table III where they have been rearranged to illustrate the relation of direction number to terminal position on a given trial. It is evident that the direction numbers are somewhat higher, *i.e.*, indicate greater error, when the terminal position was such that the subject's head was in the back or down position. In all cases there is a reduction in the direction number, *i.e.*, improvement in orientation, after the subject was given an opportunity to nod his head. Four of the subjects were of slightly positive buoyancy at the 18 foot depth; the fifth was negatively buoyant.

Only two of the five subjects appeared to have any difficulty whatsoever in swimming toward the surface. One of these subjects appeared to be somewhat disturbed by a need for air, and swam in a horizontal direction instead of swimming upward on one of his four trials. The negatively buoyant subject made no effort to swim on two trials but relaxed and as result of his negative buoyancy began to sink. His body oriented quickly to the vertical with head up and feet down. He later reported that he was unable to determine whether he was floating upward or downward while in the relaxed position.

The results of the supplementary investigation at 25 feet are presented in Table II. They have been rearranged in Table IV to illustrate the relation of direction number to terminal position. These results are in very close agreement with those of the first part of the investigation. None of the subjects had any difficulty in swimming toward the surface. One of the four subjects was negatively buoyant at 25 feet; the other three were of approximately neutral buoyancy.

TABLE II. OBSERVATIONS AT A DEPTH OF TWENTY-FIVE FEET
Direction numbers for each of 4 subjects at each of 3 steps in the procedure

Subject																			
3					6					7					8				
		Step					Step					Step					Step		
Rot. No.	Term. Pos.	1	2	3	Rot. No.	Term. Pos.	1	2	3	Rot. No.	Term. Pos.	1	2	3	Rot. No.	Term. Pos.	1	2	3
4	B	4	2	0	3	U	0	0	0	5	F	3	2	0	4	D	5	2	0
5	U	0	2	0	4	D	4	4	0	3	B	3	2	0	3	F	4	2	0
3	F	0	0	0	5	B	3	0	0	5	D	3	3	0	4	U	4	2	0
3	D	6	3	0	4	F	4	3	0	4	U	1	1	0	5	B	8	3	0

TABLE III. DIRECTION NUMBERS FOR OBSERVATIONS AT EIGHTEEN FEET COMPARED IN RELATION TO TERMINAL POSITION

	Terminal Position											
	Up			Forward			Down			Back		
Step:	1	2	3	1	2	3	1	2	3	1	2	3
	4	4	0	5	4	0	5	1	0	3	3	0
	1	1	0	0	0	0	7	4	4	6	4	0
	1	0	0	1	0	0	8	5	0	6	4	0
	7	1	0	4	1	0	4	3	0	5	2	0
	0	0	0				6	1	0			
							4	3	0			
							8					
Average:	2-3/5	1-1/5	0	2-1/2	1-1/4	0	6	2-5/6	2/3	5	3-1/4	0

DISCUSSION

It is evident that with a moderate amount of disorienting motion subjects tend to lose their orientation to the vertical when immersed at a depth of 18 to 25 feet. In addition, there appears to be a relation between the position of the body at the termination of rotation and the extent of error in orientation as indicated by pointing. This is illustrated by the averages of the direction numbers presented in Tables III and IV. The fact that trials which were terminated in the head-backward, face-upward position or the head-downward position resulted in greater deviation from correct orientation than trials terminated with the head up or forward, may be compared with results of earlier experiments on utricular function. As mentioned above, other investigators using various methods have found that thresholds for detection of changes in the orientation of resultant gravitational force are lowest with the head erect and highest with the head back and down. The relation of accuracy of orientation to terminal position and the fact that subjects were able to improve their orientation to the vertical following slight head movement suggest that orientation was based on utricular cues. The magnitude of errors made would appear to suggest that the utricles do not provide good static indication of orientation. That is, when the body is in a fixed position the utricles do not appear to afford an accurate sense of that position with respect to gravity in the absence of any head motions. However, when slight head motions are made with the body in any position there is a marked improvement in the ability of subjects to point in the upward direction.

It might be argued that the apparently superior orientation to the vertical when the head is in an upright position is simply the result of a habit to consider the direction above the head as "upward," when no other cues are present. This would not explain the superior performance with the head forward as compared to performance with the head back.

Additional cues were probably provided by the mode of rotation of the rod. Neither end of the rod was rigidly fixed. Although an effort was made to hold the rod horizontal, rotation by hand with no fixed bearing resulted in slight wobbling motion on each rotation. In addition, there were variations of the rotational force which may have enabled subjects to discriminate position during a rotational cycle. None of the subjects reported any awareness of these factors as orientation cues.

Actual buoyancy of a given subject varied from trial to trial with variations in the amount of air inspired prior to descent. Whether the over-all buoyancy of the body was positive, negative or neutral, it was evident that the greater density of the legs as compared with the density of the trunk resulted in fairly rapid orientation of the body with feet downward and head up upon release of the rod. The present experiment does not provide an answer to the question of whether there is any relation between the extent to which a subject may become

TABLE IV. DIRECTION NUMBERS FOR OBSERVATIONS AT TWENTY-FIVE FEET COMPARED IN RELATION TO TERMINAL POSITION

	Terminal Position											
	Up			Forward			Down			Back		
Step:	1	2	3	1	2	3	1	2	3	1	2	3
	0	2	0	0	0	0	6	3	0	4	2	0
	0	0	0	4	3	0	4	4	0	3	0	0
	1	1	0	3	2	0	3	3	0	3	2	0
	4	2	0	4	2	0	5	2	0	8	3	0
Average:	1-1/4	1-1/4	0	2-3/4	1-3/4	0	4-1/2	3	0	4-1/2	1-3/4	0

disoriented and his relative buoyancy. An answer to this question would require investigations at a relatively shallow depth with all subjects positively buoyant, at a depth which would render most subjects of near neutral buoyancy, and at a greater depth with all subjects negatively buoyant. The greater the latter depth, the smaller would be the density differential between trunk and limbs.

It would be desirable to obtain sufficient additional data for the determination of the statistical significance of differences in orientation to the vertical which are associated with the different experimental conditions, and for the determination of whether learning is involved. Such additional data should be obtained with a rotating rod having fixed bearings if possible. In addition it would be desirable to obtain data at several different depths in order to obtain a clearer understanding of the influence of relative buoyancy upon disorientation.

The Simulation of Zero Gravity.—On the basis of this preliminary experiment and previous work, it would seem that one method of simulating zero gravity may be superior to others for the study of relatively long-term psychologic and physiologic effects on the occupant of a space vehicle. This consists of submerging subjects in water in a position such that the head is rotated back and down from the upright position through an angle of approximately 135 degrees. Small head movements may be made around this position with a minimum of utricular stimulation. This procedure would probably be superior to any in which the body is subjected to continuous rotation. At a constant rate of rotation movements of the head will result in stimulation of the semicircular canals and the otolith organs with consequences which may be disturbing at 6 to 10 r.p.m. or higher.

The respiratory requirements of subjects in a small enclosed container can easily be met with apparatus which will provide no cues to the vertical. Additional enhancement of the illusion of zero gravity may be accomplished by the use of anti-motion sickness drugs to further suppress vestibular effects, and the appropriate placement of buoyant materials and weights at various points on the body to equalize buoyancy.

SUMMARY

Subjects were immersed in water at a depth of either 18 or 25 feet and then rotated in a tucked position on a rod through 3, 4, or 5 revolutions. Rotation was terminated with the head in one of 4 positions: upright, inclined forward, down, or back. Upon termination of rotation subjects were directed to point in the up direction, then to nod the head and correct the direction of pointing if necessary, and finally to swim toward the surface. There were errors in direction of initial pointing of as much as 180 degrees. Errors were greatest with the head down or back and least with the head up or forward. Nodding of the head was followed by consistent improvement in the direction of pointing. There was little indication of any difficulty in swimming in the upward direction. Greater density of the legs as compared to the trunk resulted in fairly rapid vertical orientation of the body upon release of the rod. The results are interpreted to reflect the relative inefficiency of the utricles as gravity sensors when the head is in certain positions. The simulation of zero gravity may be enhanced by utilizing these positions with water immersion.

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The Ideal Physician

It is the possession of the scientific outlook that distinguishes the ideal physician from any well-veneered practitioner of the healing art. However, to study patients instead of diseases objectively requires of the observer a cultivated man capable of compassionate and perceptive responses. He must look at Nature for its own sake, as well as for the immediate value of the knowledge obtained. Fortunately, it is the actual training in observation that matures the observer emotionally at the same time as it develops intellect in the ways discussed above. Such a "trained observer" is more impartial in his judgments and more adequate to the task in general. Whether he becomes a research worker or a practitioner, he is rewarded by the thrill of discovery—similar to that described by the surgeon John Keats "on first looking into Chapman's Homer."—Raymond L. G. Newcombe: The Value of Observation in the Training of Medical Students. *The Medical Journal of Australia*, December 12, 1959.