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SUMMARY REPORT

SPATIAL ORIENTATION IN A WEIGHTLESS ENVIRONMENT

Part I Summary of Reports

Part II Conceptual Simulation of the System of Spatial Representation and the Disturbance it May Create

Part III The Orientation of Man in Space Explorations

Robert Mayne
Faculty Associate
Arizona State University

This final report is submitted in full compliance with the requirements of Contract NAS9-4460 under the
National Aeronautics and Space Administration
Manned Spacecraft Center
Gemini Flight Support Procurement Section
Houston, Texas

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FOREWORD

The reports listed below have been submitted to the National Aeronautics and Space Administration, Manned Spacecraft Center, under Contract NAS9-4460.

GERA-1049	Functional Aspects of the System of Spatial Representation in the Control of Body Movements
GERA-1056	The Functional Parameters of the Semicircular Canals
GERA-1057	Three-dimensional Aspects of the Operation of the Semicircular Canals
GERA-1080	Nystagmus and Body Control for Inputs of Repeated Patterns
GERA-1083	The Constants of the Semicircular Canals
GERA-1085	The Dynamics of the Semicircular Canals
GERA-1100	Otolith Functions and Operating Principles. Part I. The Functions of the Otoliths
GERA-1112	The Functions and Operating Principles of the Otolith Organs. Part II. The Mechanics of the Otolith Organs
GERA-1113	The Functions and Operating Principles of the Otolith Organs. Part III. The Interpretation of "Single Fiber" or "Few Fiber" Recordings.

This final report includes the following three parts:

Part I	Summary of Reports
Part II	Conceptual Simulation of the System of Spatial Representation and the Disturbance it May Create
Part III	The Orientation of Man in Space Explorations.

Robert Mayne, the author of the report, was Principal Investigator on the contract and is now with Arizona State University following his retirement from Goodyear Aerospace Corporation.

NOTE: References are keyed to the bibliography in the original reports. For instance, 2-1083 refers to reference 2 in report GERA-1083.

CONTENTS

INTRODUCTION AND SUMMARY

The investigation covered by Contract NAS9-4460 had for a main objective a search for a better understanding of the operation of the system of orientation in space and the possible associated disturbances. It was hoped that the investigation would show how man can best be conditioned for space environment; predict what reactions may be expected in situations not yet encountered in space, as in a rotating platform or walking on the moon; and possibly indicate what countermeasures may be effective in minimizing likely disturbances.

It is felt that the program has been successful in achieving its major objectives. A clear theory of what malfunctions of the system of spatial orientation are likely to occur in environments other than 1-g without previous adaptation is now available. The theoretical conclusions appear in general agreement with experimental data reported in the literature. The present report indicates that while flight experience and flight training have seemed effective conditioners for space flight in a capsule or free floating in space, they may not be appropriate for other environments such as a rotating space platform or walking on the moon.

The program under the above contract sought answers to specific practical problems and therefore fell into the class of "Applied Research" as the term is usually defined. Current vestibular theory, as revealed in a literature survey, did not appear to supply the basic background for such an applied investigation. It was necessary, therefore, to begin the program with a broad basic investigation. Distinction between basic and applied research is often arbitrary. Norbert Wiener pointed out that significant truths may lie hidden in a "no man's land" between scientific disciplines. It seems to the author that other "no man's lands" may have been created within the same disciplines by the classifications of scientific work into "Basic Research," "Applied Research," "Advanced Development," "Development," etc. As the case may be, the preliminary background studies did not wander far from the central objectives. While all the material covered in the previously mentioned reports may not be directly applicable to the problems of man in space, it all contributed to provide a rounded-out picture of the system as a whole and in this sense to the central objectives of the program.

The present concluding report shows that among the various features of the vestibular system investigated in the background studies there is one which is most likely to cause disturbances when a man is transferred from an earth to a weightless environment without previous adaptation. This feature is related to the determination of the direction of the vertical, and the attempted cancellation of the effect of gravity during head movements. These functions are said to be performed by the otoliths and semicircular canals operating synergetically. Strong evidence about the validity of the theory is brought out from experimental data taken from the literature.

The report indicates how flight training is effective in conditioning man for the space environment encountered to date, but points out that this conditioning may not be appropriate in the case of rotating space platforms and walking on the moon surface.

It was stated in the proposal for Contract NAS9-4460 that an ideal goal would be one of constructing a computer analog which would predict the probability that disturbances would occur in a specific environment. It was not expected that such an objective would be attained during the contracting period, but that the discipline of holding to such a goal would make for greater clarity and rigor. In a similar vein some fifteen years ago, Mayne, then with Goodyear, undertook the design of an analog computer setup to simulate the performance of a pilot in maintaining an aircraft at the proper attitude when acted upon by random vertical gusts.

The computer setup which was devised under this contract provided an excellent simulation which was practically indistinguishable from that of the actual performance of a pilot. The investigation made a significant contribution to the understanding of the control of body movements and is frequently quoted in the literature. It goes without saying that a computer simulation of the disturbances that may be caused by weightlessness is far more complex than one of a hand movement in tracking a random input. The theoretical concepts are much more elusive and difficult to express in concrete terms. They include:

1. A theory of motion-sickness-type disturbances, since this is the type most likely to occur in a space environment. The theory should state

what physiological events may be taken as causes of these disturbances, or as inputs to assumed physiological-psychological transducers. A computer simulation must be, naturally, limited to such physiological inputs as there is no way to reproduce a conscious reaction in a physical model.

2. A theory of the system of spatial representation and of the part played by various sensors
3. A theory of perception and of the interpretation of sensory data
4. A theory of adaptation
5. A theory of the operation of the system of spatial orientation under both normal and space environments.

These theories should be in mechanizable form. As indicated in theoretical concept 1., conscious reactions such as nausea, sensation of velocity, surprise, etc. cannot be duplicated in a physical device. Simulation must be limited to the physiological causes of these reactions if they can be discovered and if, indeed, they exist. The attempted simulation should establish both the possibilities and the limitations of a model which excludes all conscious reactions.

This concluding report will outline conceptually how such a computer may be designed for a simplified situation. It will recommend that the construction of models of various aspects of the vestibular and spatial representation systems with associated disturbances be undertaken in future programs. Such a discipline calls for greater rigor and clarity and makes possible easier communication with other research workers.

A simulation of the complete system, however, would be quite complex and it is not believed that it would make possible more accurate predictions than possible by logical and intuitive deductions once the principles involved are understood and clearly demonstrated in a model.

In other words, it is believed that the attempt to design a physical model of theoretically developed concepts is as good discipline in the investigation of spatial representation as it has proved to be in the investigations of other fields. However, once the theory has been thoroughly understood and demonstrated by the model, the computer would have served its main purpose. Prediction could then be made by logical and intuitive deductions. The computer is likely to have the same limitations as a logical approach in the estimate of individual variabilities which may well be dominant factors.

Two well-established facts have emerged from actual space flights to date: (1) some personnel have been disturbed, and (2) other personnel have not been disturbed. American astronauts have been particularly free of disturbances while some of the Russian cosmonauts have been less fortunate. From this we may conclude that space environment can be stressful, but that the American method of selecting and/or training astronauts is effective in conditioning them for the environment encountered to date. The report attempts to account for these findings. It shows, however, that it should not be concluded that since no difficulty has been experienced under conditions of space flight in a cabin or free floating in space, disturbances may not occur under other conditions, as in a rotating space platform or walking on the surface of the moon. It appears that vestibular adaptation during flight training is transferred to situations experienced to date. It is unlikely, however, that it will be similarly transferred to a space rotating platform or walking on the moon. The problem of adapting to a rotating room may be much more difficult in space than in an earth environment. Walking on the surface of the moon may be more disturbing than floating in space. The matter of adapting to these various conditions merits further investigations. It may be necessary, also, to utilize personnel without flight experience and to devise faster conditioning procedures than a full flight-training program.

PART I - SUMMARY OF REPORTS

Part I of this concluding report will summarize briefly the reports previously submitted under Contract NAS9-4460.

1. GERA-1049 - Functional aspects of the system of spatial orientation in the control of body movements.

   This report attempts to give an over-all view of the problem as a whole. It includes the following topics:

   a. Spatial Representation

   Man and, presumably, animals keep a record of the position of various objects in their environment. This record is organized with respect to three axes at right angles to each other: a vertical and two horizontal axes. The latter two may be oriented along the main axes in the organization of the environment such as the length and breadth of a room. The representation pertains to both angle and distance with respect to the body. The necessary data are obtained mainly by vision. When the body is moved either angularly or linearly, the representation is moved correspondingly, mainly as the result of sensory data provided by the vestibule, and therefore does not have to be reacquired following every movement of the body.

   Spatial representation is, then, essentially a memory of the position of objects about us, but a memory which is modified as needs be during body movements to maintain its accuracy.

   The system makes it possible to program body movements to a first approximation of accuracy using only internal data. The program may then be corrected as the result of more precise estimates of the environment supplied by vision.

   b. The Control of Body Movements

   The control of body movements is said to be achieved by means of a program which is set up in the central nervous system (CNS) and carried out in closed loop through proprioceptive sensors on the basis of data acquired by external sensors and recorded in the system of spatial representation.

In order to carry out the act of picking up a pencil, for instance, it is necessary that the position of the pencil and of the fingers in space be available to the computing centers. The act can be performed with eyes closed utilizing data supplied by spatial representation memory. If the head and body are moved corrections are made on the basis of data supplied by the vestibule.

An inertial system based on a double integration of acceleration is required to determine motions of the body as a whole, while proprioceptors determine motions of the arms and fingers with respect to the body. It is significant that monkeys having suffered bilateral labyrinthectomies can adapt fairly well to their environment but experience a loss of agility for over-all body movements.[1] It is in these movements that vestibular sensory data are required.

c. Shift of Sensed Body Position

The paper presents evidence from the literature to the effect that during an over-all movement of the body we sense ourselves to be displaced in position in the direction of velocity.

d. Sensations

Experimental evidence is to the effect that physiological reactions are not predictable without control of other reactions which may be called "psychological." The magnitude of nystagmus, for instance, depends upon reactions or conditions such as "interest" or "motivation." It follows that biological systems can only be understood in terms of a psychological-physiological context. Any successful approach to life sciences must take this hard fact into account.

Sensations, as conscious reactions, fall into the class of "psychological" reactions. It is apparent that all electrical activities in the CNS may not result in sensations. It is useful to postulate the existence of physiological-to-psychological transducers. While it is not possible to describe their

[1] 22 - 1049.

mechanisms, or to build a computer simulation of the operation, it is possible to say something about their input-output relations. Normally, the system tends to eliminate psychological reactions and sensations in the control of body movements and refer them to the physiological system. This is achieved by so-called "training" or "conditioning." Sensations reappear, however, when a conflict or unexpected sensual data is experienced. There is no sensation of velocity, for instance, when playing a game of tennis, but a strong sensation when we are suddenly stopped following a period of constant rotation.

Sensations are in part, therefore, alarm reactions warning higher levels of consciousness that all is not well and their attention is required.

A theory of motion sickness belongs in this psychological-physiological context.

e. Perception

Perception is discussed as a low level intelligence which interprets sensory data before they are acted upon. The interpretation is shown to depend on logical operations and bound by "set conditions" determined by past experiences. The classical illusion of a rotating trapezoidal window which appears to be an oscillating rectangular window may be said to result from a logical interpretation of visual data with the imposed "set condition" that the window is rectangular. This set condition is the result of having observed nothing but rectangular windows in past experience. Conflicting data from various sense organs are first evaluated in perception and the reaction to this evaluation is believed responsible for the reaction of sensations including nausea. A theory of perception is necessary to a theory of motion sickness.[1]

f. Adaptation

Adaptation is described as a process according to which the response to or the interpretation of sensory data is altered, generally to the advantage of the organism. Adaptation is of particular significance to a theory of motion sickness. Psychological reactions are said to result from

[1] 32 - 1049

conflicts between sensory data of different modalities or between prediction and experience. Adaptation then may operate to reduce the confiict by harmonizing sensory data through compensatory reactions, making adjustment to the prediction, or suppressing sensory data. Sensations of nausea, as in motion sickness, are believed to result generally in sensory suppression. Other sensations may result in a tendency to harmonize sensory data.

g. Motion Sickness

As stated above, a theory of motion sickness must be laid in a psychophysiological context. It is hoped that a more complete theory will be developed later. Its implications to a unified theory of physical and life sciences are believed highly significant. For the purpose of the present summary, it is perhaps enough to state three conditions which appear necessary to produce motion-sickness disturbances related to spatial orientation.

1. There must be a conflict between sensory data or between prediction and actual experience
2. The perception of the data must involve a threat
3. The interest must not be high.

More specifically, motion sickness is visualized for the purpose of this report to be caused by a long-time integration of reactions to disunity accompanied by a tendency of this integrated value to decay gradually. When the rate of increase is faster than the decay, a disturbance is the result. This concept is needed to account for the fact that a given situation may become stressful only after it has been experienced for a period of time. The magnitude of the reaction to disunity depends upon the threat implied in the perception. At the same time, they may be caused to dissipate faster if interest is high. The effect of nausea, however, is one of reducing interest and the reaction, therefore, is self-regenerative. As expressed here, the theory is mechanizable. Its simulation would consist of leaky integrator having for inputs differences between sensory data and between anticipatory functions and sensory data. The gain of the system would be controlled as a function of threat and the decay as a function of interest. Interest, in turn, would depend on the integrated value in order to simulate the reduction of interest with the sensation of nausea.

While motion sickness can often be traced to vestibular reactions, it is equally obvious that these cannot be the sole cause of motion sickness. The often cited case of the driver of a car who never gets car sick while his passengers may, when both are subjected to the precisely same vestibular stimulation is a case in point.

It is well known that "interest" has an inhibitory effect on the tendency to be sick. In the coriolis illusion, a turn of the head such as to produce an illusion of pitching forward is much more disturbing than one which causes the illusion of pitching backward. There is a greater threat of a fall in the first than in the second case.

These limited conclusions regarding motion sickness will suffice for the purpose of the present report. As mentioned earlier, it is hoped to develop later a more rounded theory of motion sickness.

h. Conclusion

The above report outlines some of the broader considerations which must be taken into account in a study of possible disturbances in weightlessness. It suggests the manner in which they interact and may be mechanized as discussed in Part II of the report.

2. GERA-1056 - The functional parameters of the semicircular canals.

This report is intended as a contribution to the understanding of the various physical parameters pertaining to the performance of the semicircular canals. The result of this study would be useful in the design of an analog of the semicircular canals.

particularly true when the body is subjected to a continuous rotation about an axis, and the head is inclined in any direction. This results in the so-called coriolis illusion.

The effect of such a movement is computed formally and a simplified method is proposed to determine the effect of sudden head movements while the body is rotated at constant velocity. A check was made to the effect that this computation corresponds to experimental results.

b. Proposed Simulation

The computations for coriolis illusion even by the proposed simplified method are always complicated and confusing. Furthermore, the simplified method applies only to simple head movements. The report suggests that a model simulating the response of the three canals be constructed and attached to the head of a subject. The outputs of the three canals could then be obtained continuously and their resultants determined by a computer operation. The output of the model could then be compared to the sensations of the subject.

c. Psychological Reactions to Coriolis Illusions

The disturbance produced by the coriolis illusion depends on psychological as well as physical factors. As indicated earlier, an illusion of forward rotation of the body is more disturbing than one of backward rotation. The first is associated with a forward fall unhampered by anything, while in the latter case the back of the chair gives a sense of security against a fall.

d. Conclusion

The report is a contribution to any model construction of the vestibular system. It emphasizes the part played by psychological factors in motion sickness and adaptation under conditions similar to those encountered in weightlessness. The paper provides a simple method for experimentors to compute the coriolis sensation for typical experimental conditions.

The paper is based on a paper by Jones and Spells (1963)[1] relating the dimensions of the semicircular canals to the weight of different species. The approach appears particularly appropriate in showing how the parameters of the canals may be adjusted to different dynamic requirements of various species. While Jones and Spells utilized dimensional analysis in their paper, the above report relies on frequency response and elementary information theory.

Jones and Spells considered mainly two adaptable characteristics of the canals; i.e., response to the maximum head angular velocity and sensitivity. Five characteristics were considered in the report:

1. High limit of frequency response
2. Low limit of frequency response
3. Resolution
4. Dynamic range
5. Information rate.

The physical parameters of the canals affecting these characteristics are discussed and formulas derived to relate them. It is believed that the report gives an insight into the mechanism of canals in relation to their functions in the control of body movements.

Excellent agreement was found between canal dimensions as measured by Jones and Spells and canal characteristics computed on the basis of weight of animals.

3. GERA-1057 - Three-dimensional aspects of the operation of the semicircular canals.

a. <u>General</u>

This report reviews the operation of the semicircular canals when subjected to angular movements about more than one axis. It shows that when the movement is within the frequency response of the semicircular canals, the velocity measured by every canal is utilized to compute a resultant velocity in terms of both amplitude and direction. No illusion or difficulty results from this operation. However, when the movement about any axis is outside the frequency response, disturbing illusions may occur. This is

[1] 4 - 1083.

4. GERA-1080 - Nystagmus and body control for inputs of repeated patterns

a. Nystagmus for Anticipated and Non-Anticipated Head Movements

This report discusses nystagmus in the context of body control. Nystagmus has been utilized in vestibular research as an indication of the response of the semicircular canals. The normal function of nystagmus is to provide short fixating periods of a scene during a turn of the head. To fulfill this function, the slow phase of nystagmus should be of the same velocity as that of the head and in the opposite direction so that the eyeballs would remain stationary in space during the fixating period. It appears, however, that for inputs of movements such as step acceleration there is no such correspondence between head velocity and slow phase nystagmus. There is good correlation, however, for steady-state oscillations of the body. Nystagmus in this case fulfills its postulated function of providing fixation periods. It appears, therefore, that there are two modes of response to a turn of the head. The difference is believed to depend upon the degree of anticipation of the movement. In the case of a steady-state oscillatory movement, or a movement of simple repeated pattern, there is complete prediction. Similarly, there is complete prediction in the case of a willed movement. Experimental data show that inthe first, slow phase nystagmus is of the right magnitude to provide fixating periods. It is postulated that this is also true for willed movements. The lack of correspondence between head angular velocity and slow phase nystagmus during non-anticipated movements must be explained on other grounds and is discussed in a subsequent part.

b. The Leading Eye Movement

The report discusses an eye movement which is superimposed on nystagmus and is identified as "leading eye movement" or "lem." It is shown that in the case of steady-state oscillation, lem is superimposed on nystagmus to cause a shift of the gaze in the direction of velocity by an amount proportional to velocity. A theory of involuntary eye movements is discussed in a later report.

c. Prediction of Body Movements

The basic mode of control of body movements is compared with that of typical physical control. The factor of anticipation is discussed for both systems. It is shown that eye movements obey the same laws as other body movements.

d. Programming of Body Movements

A hypothesis is developed regarding the manner in which programs for various movements are evolved. The tendency is to relegate the control to the non-conscious level. When, for instance, a subject is oscillated at a constant frequency, he experiences at first definite sensations of velocity. These sensations result from postulated physiological-psychological transducers. A compensating reaction is then developed to cancel out the sensory output and thereby the sensation.

The compensatory reaction is, so to speak, the negative of the sensory pattern and provides "anticipation" of the movement. Experimental data on adaptation to slow rotating rooms fit this concept.

e. Analysis of Data

The data on nystagmus by Niven and Hixson[1] are analyzed to show that there is a very close correspondence between the velocity of the slow phase nystagmus and body velocity, and that the gaze is shifted in the direction of velocity by an amount proportional to velocity as the result of lem.

f. Conclusions

The paper is believed a contribution to a theory of motion sickness and reactions to weightlessness by classifying the conditions under which there is unity or disunity between anticipatory functions and sensory data and the manner in which the system adapts to produce harmony. The paper lays some of the ground-work for a further development of a theory of eye movements discussed in a later report. This paper shows that nystagmus is properly coordinated with body velocity when a movement is fully

[1] 40 - GERA-1080.

anticipated. A more complete explanation of nystagmus response to non-anticipated movements is needed.

5. GERA-1083 - The constants of the semicircular canals

a. General

This paper attempts to resolve differences that have existed in the literature regarding the values of the constants of the semicircular canal differential equation for man. These have varied between 10 and 1 as proposed by Van Egmond, et al,[1] and 200 and 24 as proposed by Mayne.[2]

The methods used by various investigators are reviewed. A formula originally developed by Schmaltz and used by various investigators is shown to be in error. The methods used by Van Egmond, et al, and Niven and Hixson[3] are criticized on the grounds that the ratio between damping and inertia was determined at frequencies where phase shift is insensitive to the values of these constants. It is shown that very small errors of angular measurements would suffice to account for the discrepancy and that the higher valued constants are consistent with experimental data on fish on the basis of canal dimensions. The effect of cupula leakage is investigated. It is shown that it could not account for the discrepancies of the values of the constants.

b. Conclusions

The weight of evidence is well in favor of the higher valued constants. It is obvious that if any computation or analog simulation of semicircular canal performance is to be carried out, the values of the constants in the differential equation must be known to be an approximation better than a factor of 20 to 1.

6. GERA-1085 - The dynamics of the semicircular canals

a. General

This report is intended mainly as reference in the way of a formal analysis of semicircular canal responses based on the physical structure of canals.

[1] 2 - 1083. [2] 5 - 1083. [3] 40 - 1083.

The report analyzes the response of the canals for sinusoidal inputs as well as for various transient functions. Curves were run on a computer and plotted in nondimensional form to make possible the determination of the responses for similar inputs of different magnitudes.

The report brought out an interesting theoretical point. When the head is moved from one position to another, the signal from the canal should be such as to indicate a movement in the direction of the actual head movement of somewhat lesser magnitude than the actual one, then a slow return to the initial position. The fact that the return is not sensed to take place indicates that a compensatory reaction must have been developed to cancel out this potential illusion.

b. Conclusion

The report contributes to the quantitative prediction of canal response based on the classical overdamped pendulum theory. The report reveals an unexpected result regarding the response of the canals for a head movement from one position to another.

7. GERA-1100 - Otolith functions and operating principles. Part I. The functions of the otoliths.

a. General

The series of three reports covering otolith functions and operating principles constitute probably the most direct contribution of the program to the problem of man in space. However, this contribution would not have been possible without the previous investigation of the semicircular canals, since synergetic interactions between the two systems are key reactions in possible disturbances in weightlessness. The reports are believed to constitute, also, a contribution to vestibular theory. Some parts of the theory are undoubtedly speculative and call for experimental verifications. These parts, however, are of more academic or scientific interest than they are of practical value to the problems of man in space. The more practical aspects of the theory in its application to this problem appear rather well established and could be further confirmed by simple experiments as discussed later.

b. The Separation of Gravity from Acceleration

This portion of the theory appears directly applicable to the problem of man in space.

The otoliths are said to function to supply the following data to the system of spatial orientation:

1. The direction of the vertical
2. The linear velocity and displacement of the body as a whole
3. A function related to the rate of change of acceleration.

The operation of the otoliths is greatly complicated by gravity. The above functions can only be performed if the system can separate gravity from acceleration. The value of gravity independently of the transient accelerations during body movements must be available in order to determine the direction of the vertical. This direction must be known in order to program body movements properly. Vision, kinesthetics, and otolith sensors contribute to this information.

The value of acceleration due to body movements must also be known independently of gravity if linear velocity and displacement are to be computed. Otherwise we would sense ourselves being continually accelerated away from the center of the earth at a rate of 32 $feet/second.^2$

The theory developed in the report states that the direction of gravity is obtained by long-time integration of the acceleration detected by the otoliths to cancel out transient values due to body movements. It must be clear, also, that kinesthetic reactions insofar as they are utilized to determine the direction of the vertical must be similarly averaged as they are also affected by both acceleration and gravity. A sudden change of the direction of the body with respect to the vertical is normally detected by the semicircular canals or by the eyes. The otoliths and kinesthetic reactions provide, therefore, data about a slowly adjusted direction of the vertical while the semicircular canals provide data for sudden changes. The long term integration appears to be exponential with a time constant of about 35 seconds. The averaging process must take place in higher neural centers as the signal from the otolith organs is not delayed with respect to the stimulus as indicated by single fiber recordings at the periphery.[1]

The cancellation of gravity in the computation of body movements is said to be accomplished by a computation based on the angular change of orientation of the head axis with respect to the vertical. This amount is determined from semicircular canal data.

The process is similar to that utilized in an inertial navigation system. As in this system, there is no delay in the utilization of otolith signals in the determination of acceleration.

8. GERA-1112 - The functions and operating principles of the otolith organs. Part II. The mechanics of the otolith organs.

   a. The Otolith Transducer

   This report proposes an hypothesis regarding the mechanics of the otolith organs. According to this hypothesis, the otoliths would incorporate two transducers into a single organ. The two transducers would correspond to two modes of motion of the otolith mass, a shear with respect to the epithelium and a deflection of the whole mass into the perilymph. The first mode would be less than critically damped while the second would be overdamped. Consequently, the under-damped movement would correspond to an accelerometer while the overdamped mode would correspond to a velocity transducer within a given band of frequencies. Both motions would react on the same hair cells so that the same fiber would carry both acceleration and velocity signals. Organization of fibers and modes of attachment of the membraneous sacs would account for the different responses from different cells.

[1] 32-1113.

It is realized that similar responses may be accounted for in terms of cells having different rates of adaptation. Experimental explorations are required to distinguish between the two possibilities. However, the previous discussion regarding the separation of gravity from acceleration will not be affected by the outcome of these experiments.

b. The Interaction between Vestibular Signals and Eye Movements

A distinction is made between two types of involuntary eye movements controlled by vestibular signals. One type is taken into account in the determination of the spatial representation by optokinesthesis and the other type is not. Slow phase nystagmus is of the first type, while the leading eye movement discussed earlier is of the latter type. When the eye movement is not taken into account in the determination of the position of an object in the environment, a mistaken estimate of its position occurs and an illusion is produced.

The hypothesis is advanced that vestibular signals corresponding to acceleration are added to visual signals by means of such illusion-producing eye movements. If this is the case, vestibular signals are of value in the control of body movements only when vision is possible. Considerable weight is given to this conclusion by tests conducted at Pensacola. In these tests the best and the worst performers on the trampoline among student pilots were tested over a period of years on a battery of ataxia tests. Highly significant differences of performance were found on walking and standing on a narrow rail with eyes open. There were no differences with eyes closed. At the same time labyrinthine defective subjects performed very poorly in these tests, again, with eyes open. It appears from these results that better trampoline performers have more effective vestibular signals but these better signals require vision to improve performance. It follows that vestibular signals must be added to visual signals by means of involuntary eye movements of the illusion-producing type. This is a highly significant theory, if it can be confirmed in further tests, toward the better understanding of the control of body movements in normal and space situations.

9. GERA-1113 - The functions and operating principles of the otolith organs. Part III. Interpretation of "single fiber" or "few fiber" recordings.

a. General

An analysis was performed of data in a report by Lowenstein and Roberts.[1] The data pertained to the firing rate of fibers associated with the otoliths during a rotation of a fish preparation. The data indicated that the rate of firing varied sinusoidally with a full period corresponding to a 360-degree rotation. This showed, as would be expected, that otolith signals were affected by the component of gravity acting upon the organ.

The data gave the rate of firing for both dynamic and steady-state condition and the phase shift between the two. The model previously proposed was applied to these data to compute the characteristics of the response to velocity. The result of the computation appeared to be reasonable, lending weight to the validity of the previously suggested model.

b. Conclusion

The theory of otolith functions, particularly of the separation between gravity and acceleration, is believed to be a key to the understanding of the operation of the system of spatial orientation in environments other than 1-g.

The hypothesis that vestibular signals are added to vision by means of illusion-producing eye movements is highly significant to vestibular theory and should be checked by further experiments as discussed later in the report. The hypothesis about the mechanics of otolith organs should also be checked by appropriate experiments. The analysis of Lowenstein and Roberts' data is a partial check on the validity of the theory.

[1] 32 - 1113.

PART II - CONCEPTUAL SIMULATION OF THE SYSTEM OF SPATIAL REPRESENTATION AND THE DISTURBANCES IT MAY CREATE

1. INTRODUCTION

The discipline of requiring that theoretical concepts about biological systems be simulated by a mechanical model has many advantages. It calls for greater clarity and rigor by invalidating statements that may have the ring of truth but have no operational correspondence. It makes possible a convincing demonstration of its validity by a comparison between the response of the model to a stimulus with the response of the model to the same stimulus. It makes possible unambiguous communication between research workers.

This discipline has been used to advantage in many fields. The model of the basal membrane built by Bekesy served to settle a long-standing controversy about the mechanical characteristics of this organ. Models of learning devices have helped to clarify features of learning theory. An example was given earlier of a simulation of the control of body movements.

There is little doubt that model simulations could serve a significant function in the development of a theory of vestibular and associated reactions. Some relatively simple mechanical concepts are not generally understood and could be made clearer by a model. For instance, the statement that the semicircular canals are velocity transducers when operating within a certain range of frequencies is confusing to many workers. It is difficult for them to reconcile this statement with the fact that canals can only be stimulated by acceleration, not velocity, and that they cannot detect constant velocity. The idea that acceleration inputs are processed to give velocity, but only for certain frequencies of motion is difficult to communicate even in the experience of the author, to graduate students in electrical engineering. Everything would become clear if a dynamically similar model of a canal were constructed. The model could then be subjected to different inputs and the response of the model could be plotted versus acceleration, velocity, and displacement inputs. It would then become clear that for movements within the range of normal body activity there would be close correspondence between input velocity and canal response. The limitations of the transducer for movements outside of this range would also become immediately apparent.

A somewhat more complex and elusive simulation would be that of adaptation, perception, and disturbances of the motion-sickness type. As indicated earlier, such simulation would have to be limited to physiological reactions. The attempt, however, would force a more rigorous explanation of a theory and would serve to illustrate both the possibility and the limitations of a simulation where conscious reactions are excluded.

The present section of the concluding report describes a simulation of a portion of the vestibule and associated reactions for a simple situation in order to illustrate what principles may be involved in such an attempt.

The exercise will be limited to a simulation of the reactions of a subject in a rotating chair.

2. GENERAL DESCRIPTION OF THE MODEL

The model would consist of a simulated body trunk and head mounted on a rotating platform. The head would be articulated with respect to the trunk of the body and could be inclined in any direction under command of a programmer which could be set by the experimenter. Three sets of sensors would be simulated: three semicircular canals, neck proprioceptive sensors, and kinesthetic sensors. The three semicircular canals would be mounted on the head, the neck proprioceptive sensors would provide data about head position with respect to the trunk. The kinesthetic sensors would measure angular moments with respect to the platform about three axes. They would measure, therefore, body angular acceleration in space. The platform could be controlled to move in any desired manner by two types of controls: a direct control at the command of the experimenter, and a programmer which could also be set by the experimenter. These two modes of control would be intended to simulate forced and willed movements. Sensory data would be analyzed and processed as discussed later to produce simulated reactions of motion sickness.

The dynamic characteristics of the semicircular canals have been discussed in detail in the above listed reports and they could be simulated easily by mechanical models. More data should be obtained about kinesthetic sensors in order to devise a satisfactory simulation. Neck sensors could be assumed to have sufficiently good response over wideband width so as not to interfere with the response of other sensors. For simplicity, no attempt would be made to simulate vision.

3. THE SIMULATION OF MOTION SICKNESS AND SENSATIONS

As indicated earlier, a mechanistic model cannot have conscious reactions such as nausea. Simulation must be limited to the mechanistic or physiological "causes" of various sensations, if such causes can be discovered and, indeed, if they exist. A basic difficulty may be encountered if the "cause" of a sensation is another sensation. We can make up for the limitations of the simulation by the use of an experimenter which performs adjustments or setting of the model. The experimenter then must be considered as part of the simulation. We may say that a living system has more "dimensions" than a physical system, and that the limitations of any analog of a living system are similar to those of a representation of a three-dimensional situation in two dimensions. The heart of this problem lies deep in a theory of knowledge outside the scope of this report.

For the purpose of the present simulation, we will assume as discussed earlier, that a physiological "cause" for motion sickness is a discrepancy between modalities of sensory data, or between anticipation and experience, as compared to norms previously established through experience. Such discrepancies in terms of magnitude could be simulated in the model. It would be enough to process properly and compare the data provided by the three sets of sensors and by the predictor to obtain an output which would be a factor in a simulation of motion sickness.

This output, however, must be modified by two psychological factors as discussed earlier: threat and interest. These cannot be well duplicated but their effect may be simulated by an adjustment of gain as a function of expected threat in a given situation. For closer simulation, the gain may be increased as a function of the output to simulate the fact that motion sickness causes a drop in interest and a magnification of the disturbances by what may be called a regenerative process.

The factor of sensory discrepancy as modified by threat and interest is then fed into an integrator. This simulates the fact that the effect of a conflict is cumulative and that motion sickness generally overcomes a person after he has been subjected to a stressful situation for a certain amount of time, the time depending on the degree of the stress. At the same time, there is a tendency for the disturbance to disappear gradually when the stress is relieved and this can be simulated by providing a leak across the integrator. Interest may cause the stress to disappear more rapidly so the leak may be adjusted as a function of assumed interest which, in turn, as indicated above decreases with an increase of motion sickness.

Under a given situation the indicated disturbance may tend to both increase and decrease at the same time. If the rate of increase is greater than the rate of decrease, a disturbance would result following a certain integration period.

4. SIMULATION OF ADAPTATION

It appears that while sense organs are genetically acquired, their organization is developed through experience by so-called adaptation. It was postulated in Report GERA-1080 that adaptation results from a tendency to eliminate sensations which are caused in turn by discrepancies between sensory signals of different modalities or between anticipation and experience. The effect is, therefore, to cancel out what differences may exist between sensory data under given situations. It can be visualized that if the adjustment is carried out over a long averaging period, harmony of sensory data will be achieved for typical frequently repeated responses to life situations as the random variations from such responses will be averaged out.

Adaptation may occur as the result of a compensatory reaction or by suppression of sensory data. It may be surmised that the choice between the two techniques depends on the situation as will be discussed later.

Such a scheme of adaptation can be simulated. In our simple model, for instance, the signal from the simulated kinesthetic sensors following an integration to give angular velocity may be compared with the velocity measured by the semicircular canals. A correction would then be applied to one of the signals to bring it to the same level as the other. If the two signals should vary linearly with the input and would differ only in their magnitude, an adjustment in gain would be enough to bring them in harmony over a given range of frequencies and amplitudes. If the two signals would vary in some arbitrary manner, a complex function would have to be generated whereby a different gain would have to be provided for different values of the signals and for different frequencies. There is some evidence that such complex functions can be generated although experimental data are lacking in this regard. The generation of such an arbitrary function is also mechanizable. The more complex the adaptation, the longer the conflict would last and the greater the likelihood of a disturbance.

It is believed that there are definite pain-pleasure sensations tending to promote a search for sensory harmony and that motion sickness is one such sensation. As the case may be, once sensory data have been harmonized for normal body movements, any such movement will produce no sensory conflict, no sensation, and no disturbance. If, however, a new situation should create a discrepancy of sensory data, sensations will result, with a tendency to produce stress followed by a slow adaptation to the new situation assuming that it persists over a sufficiently long period of time. The system is mechanizable when restricted to physiological modalities.

Another source of conflict, sensation, and disturbance is a discrepancy between prediction and experience. Prediction in this case performs as sensory data and is compared with actual data.

5. OPERATION OF THE MODEL

The chair is first rotated in random fashion with and without head motions, generally within the frequency response of the various sensors. With head stationary, signals from the kinesthetic sensors have been made comparable to those from the semicircular canals by cancelling out any differences that may exist between the two by means of compensatory reactions as described earlier.

For head movements alone, without movements of the chair, there would be a signal from the semicircular canals but none from the kinesthetic sensors. A compensatory signal would then be required to cancel out the vestibular signal. These would be computed on the basis of neck proprioceptive signals. When the two movements would occur at once, compensatory reactions would also have to be developed as a function of head movements. These operations appear to be fully mechanizable.

Once the system has been so adapted to normal body movement, any further programmed movements simulating willed movements would produce no difference between the signals and no simulated sensation.

We next try an imposed sinusoidal movement of constant frequency by oscillating the chair. The movement at first is unexpected and there is a difference between experienced and anticipated movements, and a simulated sensation is recorded. A compensatory reaction is produced to bring anticipation and sensory data in harmony. If the oscillation is within the normal bandwidth of canal response, there would then be no further difference and no simulated sensation. The situation would imply little threat and the disunity would be of short duration so that there would be no significant disturbance.

Next we bring the chair up to a constant velocity for a period of time. We then cause the head to be inclined toward a shoulder. The reaction would be one simulating the so-called coriolis illusion as discussed in report GERA-1057. The semicircular canals give, then, a signal which is associated with a pitch of the body forward or backward, depending upon the direction of rotation of the body and the inclination of the head.

At the same time the kinesthetic senses give a signal corresponding to the body being erect. There is then a severe discrepancy between the two signals as well as between anticipatory functions and semicircular canals. Furthermore, the semicircular canal signals would correspond in real life to a fall. They have been given a strong weight in the model. A few movements of the head are enough to produce integration into a severe simulated disturbance.

Adaptation to the new condition takes place slowly through the development of compensatory reactions calculated to bring semicircular canal signals in harmony with kinesthetic senses. These compensatory reactions, however, are complex. For a constant speed of rotation, they depend on head movements but must be different for inclinations of the head in different directions. Further, they are not directly proportional to the amount of head movement as detected by neck sensors or semicircular canals. It can be visualized that the development of these reactions is complicated and, therefore, takes a long time. A mechanization of the process, although rather complex, is possible. If the speed of rotation of the body is altered after development of the compensatory reactions, a transient disturbance would result while the reactions are modified by adaptation to fit the new speed.

A more realistic simulation should include other senses such as vision, otolith organs, eye movements, etc. The model would then simulate reactions such as nystagmus and its adaptation, the reactions to weightlessness, etc. It can be visualized, however, that such a model would be quite complex. Figure 1 illustrates diagrammatically some of the principles involved in the construction of the model.

The over-simplified simulation of an over-simplified theory of vestibular and associated reactions as described above illustrates some of the principles applicable to the design of a more complex model.

A limited mechanical model simulating sensory discrepancies which may occur in complex situations such as a rotating space platform where both semicircular canals and otoliths are involved would be useful in demonstrating and illustrating the complex mechanics involved in this situation. Such a model, however, would leave considerable doubt regarding the precise reactions of man in such an environment. It would be difficult, for instance, to simulate accurately factors such as adaptation, threat, interest, as well as individual

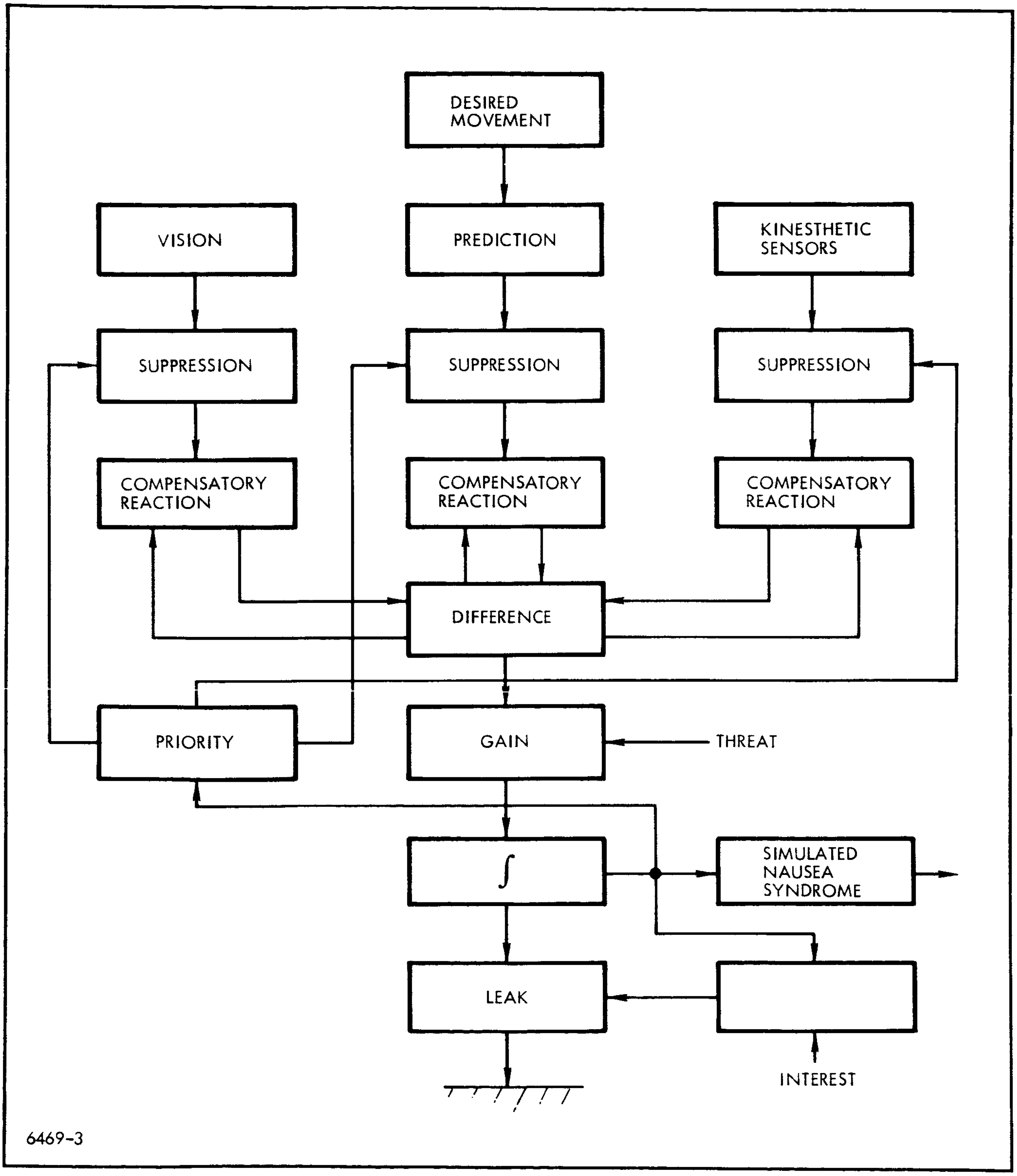


Figure 1 - Tentative information flow diagram in the simplified simulation of the nausea syndrome and adaptation through suppression or compensatory reactions.

differences and ultimately a man would have to be tested under actual conditions.

The main value of such a model would be in the clearer demonstration it would provide of the simulated functions and the immediate answer it would give of conflicts produced by such complex situations without lengthy computations. Such a model would be useful, also, in demonstrating the sensory conflicts arising in earth-bound situations, as on board a ship in a rough sea with and without head movements, floating in a space capsule while awaiting rescue, airplane aerobatics, etc.

It is certain, however, that again no computer simulation would dispense with the need of testing subjects in the actual environment. It is probable, also, that if the principles involved in motion sickness disturbances had been thoroughly demonstrated by such a model, fairly good predictions could then be made by logical and intuitive processes without the use of a computer.

Continued investigation of model simulation of motion sickness production is recommended for the limited purpose indicated above.

PART III - THE ORIENTATION OF MAN IN SPACE EXPLORATIONS

1. INTRODUCTION

This portion of the final report draws upon the material published in previous reports as summarized in Part I to develop a comprehensive theory regarding what orientation disturbances are likely to occur in the exploration of space. It discusses various situations such as living in a space capsule, floating in space, living in a rotating platform and walking on the moon. Some of the most relevant aspects of vestibular theory as developed in the previous reports will be first reviewed briefly.

2. THE SEPARATION OF GRAVITY FROM ACCELERATION

Previous investigations revealed that the vestibular functions most directly affected by transfer from an earth to an environment other than 1-g appeared to be those related to the separation of gravity from acceleration. This theory was covered in Report GERA-1112 and was discussed briefly in Part I of this report. Essentially, the theory states that gravity must be determined independently of acceleration so that the direction of the vertical may be ascertained, and at the same time, that acceleration must be measured independently of gravity so that linear velocity and displacement of the body may be computed.

Gravity is said to be separated from acceleration by a process of integration, or averaging over a period of time, so that successive transient accelerations in opposite directions may be cancelled out and the constant value of gravity be retained. At the same time, it is indicated that the direction of a sudden change of the orientation of the body does not depend on such slow processes, but on signals from the fast responding semicircular canals or vision.

The techniques are similar to those used in a simple navigational system. Such a system generally includes a gyroscope and a pendulum. Any difference between the erection of the gyroscope and the direction of the pendulum produces a light precessing torque tending to bring the gyroscope in line with the pendulum. The latter is, of course, affected by both acceleration and gravity. If, however, the torque is light enough, random accelerations will average to zero during the relatively long erection time so that the gyroscope will be maintained in a nearly vertical position. If, now, a sudden gust should disturb the attitude of the airplane, the disturbance will be detected immediately as an angle between the stable gyroscope and the air frame. Here, as in the biological system, the over-all task is performed by a combination of fast and slowly responding components.

Experimental evidence about the biological system is in accord with this theory. If the orientation of a man sitting in a chair is changed rapidly by inclining the chair, he will detect the change immediately by means of vision or through the semicircular canals, if vision is excluded. If, now, the change of orientation is performed without stimulation of the semicircular canals and without visual reference, there should be a delay in the detection of the change because of the long averaging process. Such a change of orientation may be achieved in a centrifuge where centripetal acceleration combines with gravity to change the direction of the resultant force acting upon the body without stimulation of the semicircular canals in the direction of the change. Under these conditions there is, indeed, a delay in the detection of the change of direction of resultant inertial force with respect to the body[1] as shown in Figure 2. To the knowledge of the author, no functional reason has been proposed for this phenomenon. Similarly, if the gyroscope of a typical airplane autopilot were placed on a centrifuge it would show precisely the same sort of delay in the detection of the change in the direction of resultant inertial force.

It must be emphasized that the direction of gravity may be detected by both the otolith and kinesthetic sensors. Experimental evidence with normal and labyrinthine defective subjects shows that the delay in the detection of a change of direction of the resultant force on the body applies to both sets of sensors, although to different degrees.

While gravity must be measured independently of acceleration in order to determine the direction of the vertical, acceleration should be differentiated

[1] 17, 18 - 1112.

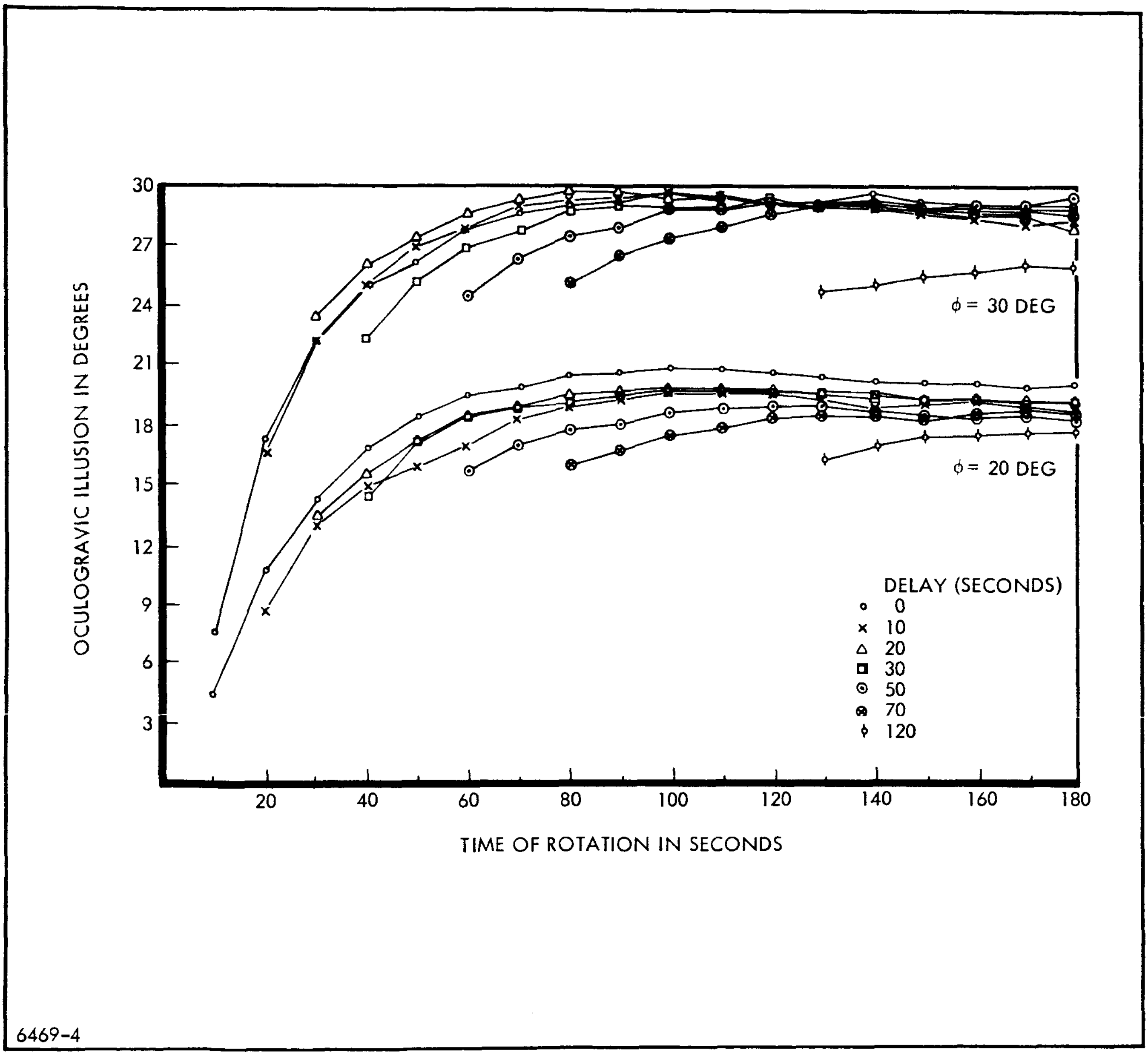


Figure 2 - Lag experienced by normal subjects in the detection of a change of the direction of inertial forces caused by rapid acceleration from zero to a constant angular velocity. ϕ = amount of angular change.

Reproduced from "Some Factors Contributing to the Delay in the Perception of the Oculogravic Illusion," by Brant Clark and Ashton Graybiel, Proc Symposium on the Role of the Vestibular Organs in the Exploration of Space, School of Aviation Medicine, Pensacola, Florida. NASA SP-77, p 156, January 20-22, 1965.

from gravity; otherwise we would feel ourselves accelerated continuously away from the center of the earth at a rate of 32 feet/second^2. No physical transducer can possibly react to acceleration without reacting to gravity. If, however, the head could remain erect with respect to gravity, the reading of the vertical accelerometer in the otolith under the influence of gravity could be called zero and only accelerations differing from this value would then be taken into account for integration into velocity. Horizontal transducers would then be unaffected by gravity and would measure true acceleration with respect to the earth. The difficulty would come when the head would be inclined with respect to gravity. The vertical transducer would then sense a reduced effect of gravity which would be interpreted as an acceleration toward the center of the earth, while a horizontal transducer would pick up a component of gravitation which would be interpreted as a horizontal acceleration of the body. The two accelerations would combine into a resultant inclined with respect to the vertical. Report GERA-1113 showed evidence taken from the literature[1] on single fiber recordings to the effect that the otoliths respond to a change of orientation of the head with respect to gravity.

The effect of a turn of the head could be cancelled out by compensating reactions based on a measurement of the head rotation in both magnitude and direction. This measurement could be made by the semicircular canals. Again, this is precisely the technique utilized in some inertial navigational systems to cancel out the effect of gravitation. A computation is performed as the result of a measurement of the amount of turn of the system to give "compensatory reactions" which, when added to the signals of the accelerometers, cancel out the effect of gravity. It would be expected, if this is the mechanism, that difficulties would occur when the head is turned without semicircular canal signals. Report GERA-1100 brought out an observation by Lowenstein and Roberts[2] to the effect that a fish reacts violently to being rotated following destruction of the semicircular canals. Significantly, the fish's reflexes did not oppose the turn and were of inappropriate direction to return the fish to an upright position.

[1] 32-1113. [2] 23-1100.

3. DISCUSSION OF NASA REPORT TND-2195 BY STONE AND LETKO (1964)

Report TND-2195 describes the sensations experienced by a subject being rotated at a continuous velocity while totally immersed in water. These sensations can be fully accounted for in terms of the theory of the separation of gravity from acceleration and are believed to have direct application to the problem of man in space.

During the test the subjects were fully immersed in water in a rotatable tank, strapped in a chair, and provided with suitable breathing equipment. In one of the tests the subjects were positioned so the rotation took place about an axis passing through their two ears. In another test the rotation was about an axis passing through the long axis of the body. The second test leads to conclusions similar to the first and will not be discussed in this summary.

With immersion in water kinesthetic reactions are minimized because of water buoyancy. They are certainly very greatly reduced over those which the organism has adapted to associate with a change of orientation of the body. At the same time vision gives no clues that the body is rotated since it is limited to the inside of the tank. Also, because of the continuous rotation of the tank there are no signals from the semicircular canals. The otolith signals, however, are undiminished over those experienced under a normal life situation. It would be expected, therefore, that perceptual interpretation of the situation would depend entirely upon otolith signals.

It must be clear that under test conditions the body is merely rotated about an axis passing through the two ears without any linear translation and will assume successive positions as indicated in Figure 3. The perception, however, is as indicated in Figure 4, reproduced from the original report. The perception, therefore, differs in two respects from the actual movement: (1) the rotation of the body about an axis passing through the ears is not perceived so that the body is sensed to remain erect at all times, and (2) there is a perception of linear translation in a continually changing direction. The over-all perceptual interpretation of the sensory data is similar to that of

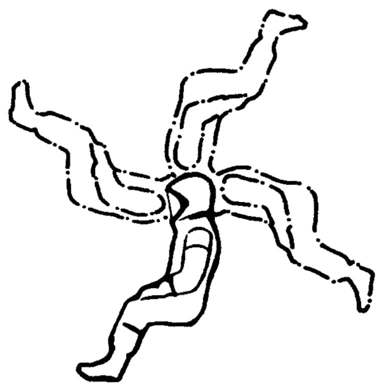
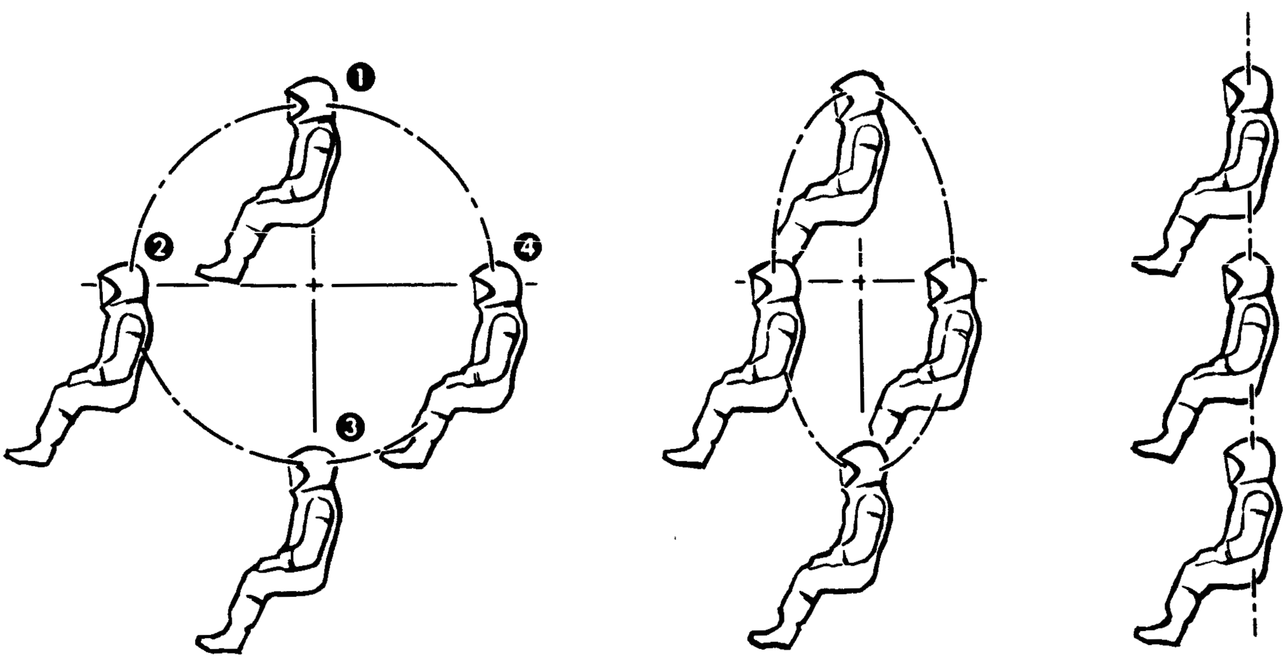


Figure 3 - Actual successive positions assumed by subject during rotation.



(a) 0 to 20 rpm. (b) 20 to 55 rpm. (c) 55 to 60 rpm.

Figure 4 - Sensed position of subject during rotation.

Reproduced from "Some Observations during Weightlessness Simulation with Subject Immersed in a Rotating Water Tank," NASA TN D-2195, by Ralph W Stone, Jr., and William Letko, p 16, September 1964.

being rotated in a ferris wheel. There are clear explanations for these illusions on the basis of the theory of separation of gravity from acceleration.

a. Failure to Sense the Rotation of the Body

As stated in paragraph 3 of this discussion, the only sensory data related to body movement and available to the subject under conditions of the test are those from the otoliths. Perceptual interpretation must then be based on these signals. Since they change direction with the rotation of the body, it might be thought that they would indicate that the body is rotated with respect to the vertical. However, because of the averaging period and consequent delays in the determination of the vertical, the continuous varying signals during the rotation of the body average to zero, signifying no rotation. The delay in this case performs its intended function of cancelling out transient accelerations of successively opposite directions.

b. Sensed Linear Displacement

The gravity acting on the otoliths during a rotation is continuously changing direction with respect to the body, and produces a corresponding signal at the periphery. This is indicated in various references on the firing rate of otolith fibers in vestibular preparations. With normal head movements, as indicated earlier, these signals are cancelled out by compensatory reactions based on semicircular canal sensory data. Under the conditions of the test, however, there are no semicircular canal signals because of the continuous rotation of the body and, therefore, no compensatory reactions. The gravity acting on the otoliths is then interpreted as linear acceleration and integrated into an illusory perception of linear displacement. The perception as the result of otolith signals during rotation when gravity is interpreted as acceleration because of lack of semicircular canal signals and associated compensatory reactions consists of two sinusoidal displacements 90 degrees out of phase. The two illusory oscillations add up to the perception of rotation of the body as a whole as described in the report.

c. Lack of Symmetry between Displacements along Two Body Axes

According to the paper, the perception of movement remains circular up to a velocity of 20 rpm. At higher velocities, the magnitudes of the perceived movement along two main body axes of the body are different. The perception is then one of elliptical movement. This phenomenon can be best accounted for in terms of different transfer functions for the corresponding otolith transducers.

d. Disturbances under Conditions of the Test

The report makes no mention of any disturbances experienced by the subjects. Since they were subjected to the test for periods of as long as one hour, it is probable that none was experienced. This is as should be expected although the situation is quite strange. The only sensations available are those of the otoliths and there is, therefore, no possibility of conflict with other sensory modalities. Furthermore, the sensory patterns which are experienced can be organized into a perfectly harmonious and coherent perception, that of being moved as on a ferris wheel and there is no threat associated with such a perception.

Without threat or discrepancy of sensory data there should be no disturbance. Conceivably, however, some subjects may be disturbed by claustrophobia and boredom as the result of partial sensory deprivation. Boredom and motion sickness disturbances are believed to be related in a manner which cannot be discussed here.

e. Suggested Additional Tests

The above discussion shows that the results of the tests covered by the report of Stone and Letko are in complete qualitative accord with the theory of separation of gravity from acceleration. Further tests on a similar setup could provide quantitative predictions as a further check of the theory.

4. MAN IN SPACE

It is now possible on the basis of the previous discussion to visualize what disturbances may occur when man is transferred from an earth to an environment other than 1-g without previous adaptation.

a. The Perception of Up and Down

We have seen that it is natural for man to organize his environment with respect to three perpendicular axes. One such axis is the vertical. There is an enormous advantage in knowing the direction of the vertical and having the knowledge stored in the system of spatial orientation. The equilibrium of the body and the programming of body movements depend on such knowledge. At the same time much of what we perceive is organized with respect to this direction or its perpendicular in the way of the horizontal. The main lines of buildings, furniture, telegraph poles, the horizon, the surface of the lakes, the main axis of trees are either horizontal or vertical. The knowledge of the vertical provides, therefore, for an easier or more harmonious organization of our spatial representation.

We have shown that the vertical is established by sensory data, primarily from kinesthetic, otolith, and visual organs. These sensors are adapted by suitable compensatory reactions to give predictable and harmonious perceptions in an earth environment. When a man is transferred to weightlessness from an earth environment without previous adaptation, significant differences in sensory organization must take place. First, all kinesthetic reactions due to gravity disappear. Similarly, the otolith transducers along an axis normal to the long axis of the body give no signal. The otolith transducer on the long axis of the body experiences an acceleration which differs by 1-g from that experienced on earth. The signal corresponds, therefore, to an acceleration of 1-g toward the feet. It may be thought that this should result in a sensation of continuously increasing velocity toward the feet. We have seen, however, in report GERA-1112 on the mechanics of the otoliths that a constant acceleration, after a certain delay beyond its initiation, produces no velocity signal. There should be, therefore, no sensation of velocity toward the feet in weightlessness.

The otolith signal, however, on the basis of earth adaptation and following a short delay, would be interpreted to mean that "up" would be toward the feet and "down" toward the head. While the magnitude of the measured acceleration would only be one-half that which would be experienced in an inverted position on earth, experimental data show that the system determines the direction of resultant forces acting on the body as in the case of of a subject in a centrifuge without regard for the magnitude of this resultant. To a man who is adapted to organize his spatial orientation with respect to the vertical and the horizontal, a constant acceleration signal toward the feet, or a resultant force directed toward the head, can only signify that gravity is acting in the opposite direction or toward the head and this, in turn, would be interpreted in perception as being upside down. The perception of free fall, feet first, in the first second or so of the fall when air drag is negligible would produce a similar force reaction, but would produce, also, a sensation of velocity which is not present in weightlessness.

The perceptual interpretation of the upside-down signal produced by the otoliths may differ greatly with different persons, depending on their past experience and conditioning. In some cases it may cause a clear sensation of being upside down with significant disturbances. In other cases visual data may dominate and up or down may be associated with the orientation of the cabin. In still other cases, there may be a "sometimes you see it and sometimes you don't" vague sensation of being upside down with a clear intellectual sense of orientation with the cabin. The feeling may or may not hold unconscious threats, depending on previous conditioning. Some American astronauts have experienced lightly disturbing sensations of being upside down while some of the Russian cosmonauts have been severely disturbed.[1]

b. <u>False Sense of Linear Movement</u>

As indicated earlier, every movement of the head in an earth environment must be accompanied by a compensatory reaction to cancel out the effect of gravity acting on the otoliths and producing signals which would be normally interpreted as signifying linear movements. We have seen that when the head is rotated without semicircular canal signals, visual or kinesthetic data, as in the case of constant rotation of a subject immersed in water,

[1] Paragraph 1, Appendix.

there are, indeed, sensations of linear movement. In weightlessness there is no change of otolith signals upon inclination of the head, but there are semicircular canal signals, and for a man adapted to an earth environment, a compensatory reaction should occur. This reaction by itself without the normally-occurring otolith signals would produce an illusion of linear displacement, or a conflict of sensory data with a nausea syndrome.

The reaction of moving the head in weightlessness bears some similarity to that of being rotated continuously while immersed in water. In both cases the synergetic interactions between semicircular canals and otoliths developed as the result of normal body activity on the surface of the earth are lacking. There should be illusory linear displacemnnt in both cases as demonstrated by Stone and Letko for the immersion case. The difference between the two cases is that in weightlessness there are semicircular without corresponding otolith signals, while in the immersion tests there are otolith without semicircular signals. We have seen, also, that the sensory data in the immersion test can be organized into coherent perception without conflict or threat. This is not necessarily the case in weightlessness and a disturbance may occur as the result of head movements.

It must be clear that the effect would occur not only in weightlessness but also in reduced gravity. The compensatory reactions adapted to an earth environment are computed on the basis of 1-g. Reactions of different magnitudes are required for an environment other than 1-g and it would be expected, therefore, that a man adapted to an earth environment would experience difficulties on the moon without further adaptation.

The situation is quite analogous to that of the so-called coriolis illusion. A man adapted to live in a slow rotating room experiences difficulties when the speed of rotation is changed or the rotation is stopped entirely. It could be, however, that the pitching illusion experienced in the coriolis illusion is more disturbing than an illusion of linear displacement in weightlessness. At least this may be true while sitting in a chair in a cabin or floating in space where there should be no threat of a fall. It is possible, however, that such a reaction would be highly disturbing while walking on the surface of the moon.

An illusion of linear displacement could then create a disturbing threat of a fall over jagged lava flow with the possible puncturing of the pressure suit and may, indeed, result in an actual fall.

While it appears that American astronauts have not experienced disturbances as the result of head movements, it could be that in the space missions to date the head movements of astronauts have been minimized and that, as in slow rotating rooms, the degree of disturbance depends on the frequency of head motions rather than on the time spent in the environment. With greater activity, more head movements would have been necessary and more disturbances might have been experienced. Some disturbances accompanying head movements have been recorded, however, but mainly with Russian cosmonauts.[1] In any case, it appears certain that the manner in which American astronauts are selected and/or trained is effective in minimizing stresses under the space situations encountered to date.

c. Flight Training as Conditioning for Space Environment

American astronauts have been selected from among well-qualified jet pilots. They have therefore undergone a rigorous training in aerobatics, instrument flying, various air maneuvers, and have had many flight hours following completion of their training. All of this represents considerable conditioning to an environment vastly different from that normally found on the surface of the earth. Although theories of adaptation and perception are by no means rigorously established, it is possible to visualize intuitively how such conditioning may apply to living in a space capsule or floating in space.

A pilot's mode of orientation in flight is quite different from that on the earth. In the first place, the vertical loses much of its significance. The angle of attack of the plane, for instance, with respect to the air mass may be of greater significance than its attitude. A minor deviation of the

[1] Paragraph 2, Appendix.

orientation of the body with respect to the vertical involves no threat of a fall as it does on earth. The pilot is strapped to a seat in the cabin and identifies his attitude with that of the airplane. The main threats to the pilot are related to occurrences such as stalls, uncontrolled side slip, excessive gravity, which have no correspondence on earth. Further, the sense organs of the pilot are ill-adapted to determine the attitude of the plane. The integration time constant of the otoliths is far too short to keep track of the vertical in a turn, and similarly the semicircular time constant is thoroughly inadequate to measure the amount of the turn. Had man been adapted to flying during his evolutionary development, he may have acquired long-time constant organs like birds or fish, but even these would be inadequate for high-speed flight. As it is, a pilot must learn to disregard his internally built-in navigational system and depend entirely on cockpit instrumentation when flying blind. It may be guessed that during flight vestibular signals are suppressed at the peripheral level. Their data are useless and, indeed, dangerous if relied upon.

A pilot must, therefore, develop through adaptation an entirely different mode of spatial orientation and representation with a different schedule of threatening situations. The vertical loses much of its significance and cannot be established in any case by vestibular or kinesthetic senses. The student pilot who is originally disturbed by simple aerobatics on the basis of his earth experience loses all fear as he becomes adapted to the new environment. Even the passenger of a commercial airliner may experience a disturbance when he first looks out the window of a plane while in a bank, but he, too, learns to adapt to this situation.

At the same time, the pilot of a jet airplane during various maneuvers experiences widely varying g's, from very high-g in a pullout to less than 1-g in a pushover. These periods of other than 1-g are relatively lengthy with respect to vestibular time constants. A turn of the head caused by a voluntary movement or a roll of the plane should then cause sensations of linear displacement. These sensations are probably suppressed if they contradict other sensory data as in formation flying or may simply be accepted as true, modifying slightly the actual flight pattern without conflicting sensory data.

Flight as a passenger would appear to be a poor substitute for flight training as it is one of the basic rules of adaptation or learning that it takes place more effectively as the result of willed rather than passive actions. Pilot training, therefore, must be more effective in conditioning an astronaut than flight as a passenger. In any case, there appears to be a clear explanation of why American astronauts selected from proficient jet pilots experienced little disturbance in space, while some of the Russian cosmonauts, not selected on the same basis, were disturbed. More specifically, why American astronauts were less disturbed by upside-down feelings, or were not significantly disturbed by head movements.

d. Possible Limitations of Flight Training as a Universal Conditioner for Space Explorations

While flight training and flight experience have proved effective in the conditioning of an astronaut for life in a space capsule[1] or for floating in space, it cannot be assumed that they will be equally effective for every space environment. It is certainly totally ineffective in conditioning an astronaut for floating on the sea in a capsule while awaiting rescue. Sea duty may have been a better conditioning program for this situation and possibly would be better, also, for some space environments. It is true that floating on the sea is not a space situation. Still, there are similarities between the stressing factors under both conditions. Sitting in a floating capsule involves, as in the case of space, some turns of the head during conditions other than 1-g because of the rise, fall, and roll of the capsule.[2] Flight adaptation applied only to conditions similar to flight. There is, of course, no over-all suppression of vestibular data.

A person may be adapted to more than one situation and pass rapidly from one to the other. A skater must suppress his emicircular canal signals during and following a spin, but only during this period. After his spin, he recovers the normal use of his vestibule.[3] A sailor may experience a

[1]Paragraph 3, Appendix. [2]Paragraph 4, Appendix. [3]Paragraph 5, Appendix.

slight vertigo when he steps on a pier after a long sea voyage, but the re-adaptation to an earth environment is rapid. When a pilot returns to earth he recovers the full and normal operation of his vestibule, the vertical reassumes its significance, and he is no longer dependent on external instrumentation to maintain his equilibrium.

All of this only emphasizes the fact that adaptation must be for specific situations. It does not appear possible to make a man completely visually dominant so that he will ignore vestibular signals for all situations.[1] It appears that space situations in a capsule or floating in space are similar enough to flight conditions that conditioning for the latter is effective in the former case. It would be dangerous, however, to assume that flight conditioning would be equally effective in all space situations.

5. ROTATING SPACE PLATFORMS

It has been proposed to rotate space platforms at slow velocity in order to provide some artificial gravity. The likely reactions to a rotating environment have been investigated on the earth. It was found that highly disturbing coriolis illusions accompany head movements, but that subjects can ultimately adapt to the conditions and after several days in this environment be relatively free of disturbances. It is well to examine the likely reactions to be expected in a rotating space platform. These platforms will provide for an artificial gravity substantially less than 1-g as the adaptation to the high rotational velocities necessary to provide acceleration approximating 1-g is difficult with platforms of a practical size. Reasonably good adaptation has been shown possible, for instance, with speeds of about 5 rpm. With a platform 15 ft in diameter, a g-force of about 1/15 g would be experienced at the periphery and, of course, would be less at a shorter radius. The condition would be nearly that of weightlessness. The signal given by the otoliths would be interpreted by one adapted to an earth environment as a constant acceleration somewhat less than 1-g and directed toward the feet, causing the perception of being upside down. It could be that flight training may eliminate this sensation as it

[1] Paragraph 6, Appendix.

does in a flight capsule. On the other hand, the conditions in a space platform are now quite different from those of an airplane cockpit or a space capsule. The astronaut is now walking about in a situation resembling that of the surface of the earth. It may be assumed that he would return to his earth adaptation and, if so, perceive himself as walking on the ceiling.

During a turn of the head two reactions would take place simultaneously: (1) a pitching sensation caused by coriolis illusion, and (2) a linear displacement sensation because of the less than 1-g environment. Adaptation to this complex environment would probably take place ultimately, but it is reasonable to expect that it would be much more difficult than in a slow rotating room on the surface of the earth. Such adaptation would have to resolve three conflicts: the feeling of being upside down, the sensed linear displacement when the head is moved, and coriolis illusion. Further investigations of the problem appear indicated.

6. WALKING ON THE MOON

An astronaut without previous adaptation may experience a number of disturbing reactions while walking on the moon.

1. Reduced Muscular Effect
   Because of the reduction of gravitational forces to one-sixth that experienced on the earth, natural reflexes adapted to earth movements may be sufficient to cause over-correction for an unbalance of the body. It would seem, however, that there should be relatively fast adaptation to this situation. The experience of less gravity on kinesthetic sensors would not be too different from that of being immersed in water. All reports from astronauts in weightlessness are to the effect that the reduction of gravity results in a rather pleasant sensation. While there might be a difference between walking and being seated in a cabin or floating in space, it would appear that some of the "Peter Pan" tests would have provided a degree of adaptation to this condition. It would seem that difficulties, if present, should result from vestibular sensors.

2. The Upside-down Sensation

In an earth environment any acceleration of less than 1-g acting on otolith organs is interpreted at first as a fall, feet first, with an acceleration equal to the reduction of gravity. A steady acceleration, however, ceases rapidly to be interpreted as movement and is normally interpreted on earth as defining the vertical. As discussed earlier, for the case of weightlessness and slow rotating platforms, a constant acceleration of less than 1-g can be interpreted as signifying that the body is upside down. There could be, therefore, a feeling of being upside down on the moon. Unlike the case of weightlessness, however, where up is always oriented toward the feet regardless of the orientation of the body, up would be toward the center of the moon. It is difficult to predict how rapidly adaptation to this condition would take place. A somewhat similar adaptation takes place on earth when a person is fitted with glasses which invert his vision. After a while the system adapts so that "up" for vision coincides with "up" for otoliths and kinesthetic sensors. The point, however, is that astronauts will remain on the moon for only short periods and there will not be much time for adaptation.

It is difficult to predict what effect flight conditioning may have on this illusion or what may be the result of having spent considerable time in weightlessness before an astronaut lands on the moon. It would seem likely, however, that once an astronaut begins to walk on the moon, he will revert to his earth adaptation. There may be, then, an upside-down feeling, or perhaps only a nausea syndrome as the result of conflicting sensory data.

3. Effect of Head Movements

As indicated earlier, compensatory reactions must occur in an earth environment when the head is inclined with respect to gravity either through a voluntary movement of the head with respect to the body, or as a result of a movement of the body and head as a whole.[1] The magnitude of these compensatory reactions must be different for different values of gravity. Reactions adapted to an earth environment are inappropriate for

[1] Paragraph 4, Appendix.

weightlessness or a subgravity condition as on the moon. We have seen that flight conditioning appears to have minimized these disturbances in weightlessness but has been ineffective in the case of floating on the sea in a capsule while awaiting rescue. Still, the disturbance in the sea is probably caused in part by a combination of slow up-and-down movements combined with roll and, therefore, by the same mechanism of inappropriate compensatory reactions to the inclination of the head for different g-conditions. It may be pointed out in passing that adaptation to this condition is rather complex and depends on the development of anticipatory reactions computed on the basis of both the g-value and the amount of turn of the head. It appears, however, that the biological system can perform this complex task to make it possible for sailors to acquire their sea legs.

Again, the astronauts when walking on the moon will probably revert to their earth adaptation and flight training may be of little value in reducing the disturbances caused by head movements. It is true, however, that head movements will be minimized during a walk on the moon in a stiff space suit. Still, if an astronaut should temporarily lose his balance with a turn of the head, he may then react, like Lowenstein's fish, with a violent reaction of inappropriate direction with a fall the result. It must be clear, of course, that when we speak of a turn of the head it is with respect to space, not with respect to the body. It appears that the problem merits serious considerations.

7. CONCLUSIONS

1. The theory of the separation of gravity from acceleration as developed in report GERA-1112 and amplified in this concluding report seems to provide a clear explanation for the observations made to date of the reactions of man in space situations. The theory is consistent with various experimental data as reported in the literature.

2. The theory predicts that two types of orientation disturbances may be expected when man is transferred from an earth to a subgravity environment without previous adaptation:

(1) A feeling of being upside down

(2) An illusory sense of linear motion when the head is inclined with respect to space.

3. Flight training appears to be ideal conditioning for man in space when confined to a capsule or free floating in space. It does not appear adequate, however, for other space environments.

4. Adaptation to a rotating space platform appears to be more difficult than adaptation to a slow rotating room in an earth environment.

5. Astronauts walking on the moon may experience significant difficulties. Flight training does not appear to be of value in conditioning an astronaut to this situation.

6. A program for continued investigation of the problems is recommended.

4. Dr. Walter H Johnson of the Banting Institute, Toronto, Canada kindly answered questions regarding his observations on the effect of head motion on the incidence of motion sickness. He mentioned that the effect is present during linear up-and-down acceleration as in an elevator. To the knowledge of the author, there is no explanation of this observation which can be easily accounted for on the basis of the theory presented here. The observation lends weight to the prediction that disorientation would occur on the moon as the result of head movements.

   Doctor Johnson's findings emphasize another significant point: motion sickness is worse when the interpretation of the sensory data becomes more complex. This would lend weight to the prediction that adaptation to a rotating space platform would be much more difficult than adaptation to a slow rotating room on the surface of the earth. As indicated earlier, the interpretation of sensory data would be much more complex in the latter case.

5. Dr. William E Collins of the Civil Aeromedical Institute, Federal Aviation Agency, Oklahoma City, Oklahoma presented a paper entitled "Some Special Effects of Visual Vestibular Interaction of Nystagmus and Subjective Responses to Angular Acceleration." The paper covered an investigation of vestibular reactions of skaters during and following a very fast spin. It illustrated the manner in which adaptation to a condition may or may not be transferred to another condition. This paper is particularly relevant to the adaptation of astronauts to space conditions. He showed that skaters following a fast spin and a sudden stop can maintain their balance perfectly well with eyes open, but have considerable difficulty with eyes closed. It can be speculated that post-rotational vestibular signals are suppressed when vision is present but are re-established without vision. Conceivably, compensatory reactions could have developed to harmonize vestibular signals with vision. In any case, the skaters, following a fast spin and a sudden stop, must have a clear representation of space with eyes open. A subject without previous conditioning would certainly have difficulty in maintaining his balance under the same conditions even with eyes open.

APPENDIX

The author attended the meeting of the Aerospace Medical Association in Las Vegas, April 18 through April 21, following final typing of report GERA-1158. Several points of interest to the thesis developed here were picked up during meetings and informal discussions with participants. They are mentioned briefly in this appendix with the thought that they could be incorporated later in a more comprehensive report or paper.

1. Col. F Borman, in his luncheon talk on April 20, mentioned having experienced a vague sensation of being upside down. He insisted that the sensation was not disturbing and that he maintained at all times a clear knowledge of the orientation of his body with respect to the cabin. It can be speculated that his otolith signals in the weightless condition were such as to "mean" an upside-down position on the basis of an earth conditioning. Because of Colonel Borman's extensive flying experience this interpretation was almost completely suppressed; sufficiently so to avoid any disturbance, not enough to eliminate it entirely. Common life experience is replete with similar cases of vaguely sensed impressions in conflict with known reality, but causing no disturbance.

   Some of the Russian cosmonauts chosen from among scientists without flight experience were not so fortunate and found the illusion very real and very disturbing. There are obviously degrees in the sensed realism of an illusion and in the disturbance it may create, depending upon previous conditioning.

2. Mr. Richard E Waite of the Manned Spacecraft Center in Houston, Texas mentioned a Russian report he had recently received describing disturbances as the result of head movements in weightlessness.

3. Colonel Borman mentioned in his talk that the over-all feeling of being in orbit in a space capsule is quite similar to that of flying an airplane. This comment lends additional weight to the argument presented earlier that adaptation to airplane flight is transferable to the space situation.

If a skater is rotated in a chair, he exhibits less nystagmus and has a shorter sensation of rotation than a normal subject. The conditioning to the spin on the ice carries over, at least in part, to a rotating chair. Presumably, however, it does not carry over to normal body activity and the skater resumes the full use of his vestibular apparatus in acts such as walking or jumping.

In a later informal conversation Doctor Johnson pointed out that some of his previous work proved that adaptation to caloric stimulation is not transferable to rotation or vice versa. In other words, it is clear that any given conditioning resulting in suppression of vestibular signals applies only to situations similar to those under which the conditioning had taken place. No over-all suppression of vestibular signals appears possible for all conditions by any conceivable conditioning. It cannot be assumed that conditioning for flight training will transfer to walking on the moon although it appears to transfer to living in an orbiting space capsule.

6. The talk of a Russian scientist during an evening meeting emphasized goals similar to those expressed here - an interest in the broader adaptive processes of living systems, of the origin of life, etc. As one reads Russian literature, one cannot fail to note a more profound interest in basic living processes than is usually exhibited in American literature. It could be that Russia's original difficulties with orientation in space may spark a more basic approach to biological problems which may ultimately work in their favor. In a similar way the Russian failure to develop light warheads for their missiles led to their advantage in the development of higher thrust rockets.

   A more basic approach does not mean a less practical one. The test of any theory is, of course, in the long run its capability to predict occurrences and make it possible to attain desired goals.

7. Dr. G Melvill Jones presented a paper on the recording of single otolith fibers when a vestibular preparation is acted upon by a constant acceleration of continuously changing direction. It is believed that the response he reported can be fully predicted on the basis of the model presented in earlier reports.