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# MASSACHUSETTS INSTITUTE OF TECHNOLOGY

STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Principal Investigators: L.R. Young
Y.T. Li

June 1968

Status Report on
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MAN-VEHICLE LABORATORY
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

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for the period July 1967-June 1968
(combining Eighth and Ninth Reports)

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Principal Investigators: Professor L. R. Young
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Massachusetts Institute of Technology
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# STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY


## ABSTRACT

During the period July 1967-June 1968 the Man-Vehicle Laboratory pursued a multitude of research topics, all associated with the central problem of understanding and assisting man's orientation in space. Three professors, a full-time research staff member, and twelve research assistants were supported in part by NsG-577, and five graduate students supported by fellowships or the military participated in associated projects. Two Sc.D. theses and six masters theses were written during this period based on work supported by this grant. The research topics are all concerned with transmission of orientation information to a man, his manual control process thereafter, and the resulting manual output. Our research areas are thus classified according to presentation of information (display research), physiological sensor modeling (vestibular system and eye movements), manual control modeling, and output mechanisms (postural and neuromuscular control). The following areas have been investigated during this past year:

- A. Manual control modeling
  - A.1. Effects of roll motion cues (Sc.D. Thesis)
  - A.2. Effects of roll and yaw motion cues (S.M. Thesis)
  - A.3. Use of variable feel control stick (A.E. Thesis)

A.4. "Inverse optimal" manual control problems
A.5. Bayesian learning model for skill acquisition (S.M. Thesis)
A.6. Digital adaptive control (S.M. project)

B. Display research
B.1. 3-D display development (S.M. Thesis)
B.2. VTOL integrated display (Sc.D. project)
B.3. "Anti-vertigo" display (S.M. project)
B.4. Development of a "head position sensor" (with Instrumentation Laboratory)

C. Vestibular research
C.1. Unified model for vestibular function
C.2. Nonlinearities in rotation sensing (S.M. Thesis)
C.3. Direction preponderance (bias) in semicircular canals
C.4. Physical modeling of semicircular canals (Sc.D. Thesis)
C.5. Adaptation and habituation (S.M. project)

D. Eye movement modeling
D.1. Vestibular effects
D.2. New hybrid model for eye tracking (S.M. Thesis)
D.3. Eye movement in learning to read (S.M. project)

E. Postural and neuromuscular control
E.1. Research on balance reflex (Sc.D. project)
E.2. Basic neuromuscular modeling (Sc.D. project - new)
E.3. Data presentation of muscular activity in skilled action
E.4. Postural control for EVA propulsion system (new)

# I. INTRODUCTION

With the help of enthusiastic and talented graduate students, the Man-Vehicle Laboratory made significant progress in five general research areas related to man's orientation in space during the academic year 1967-68. This research led to twenty-four theses and publications and contributed to the training of nineteen graduate students in the area of manual control. During this year the entire laboratory moved into the new Center for Space Research at M.I.T. The hybrid computer facility was extended, and a new single-axis vestibular testing chair was constructed and used on the M.I.T. Centrifuge. Brief descriptions of the individual projects are given on the following pages according to the major classifications outlined in the abstract, and including abstracts of published material for completed projects.

## II. MANUAL CONTROL MODELING

Our past research on models for the human operator concentrated on three major areas: effects of motion cues, learning and decision making models, and models for operators' nonlinear behavior. The last of these topics has been temporarily dropped, but the first two directions continued. We have additionally resumed research on the stabilization augmentation possible with a variable feel control stick, begun work on the "inverse optimal" manual control problem, and initiated research on digital adaptive control.

### 2.1 Effects of Roll and Yaw Motion Cues

For some years we have been attempting to develop a quantitative description of the effects of motion cues on the human operator describing function, with the aim of extending fixed-base data to predict man-machine control characteristics in flight. An extensive series of experiments carried out over the past two years using the NE-2 Pitch-Roll Simulator yielded the required data. The bulk of the experiments were performed by Richard S. Shirley (now at NASA-ERC) in his doctoral thesis (abstract below) and reported by Shirley and Young at the 4th Annual NASA-University Conference on Manual Control (abstract below). To isolate the motion cue effects in terms of semicircular canal vs. otolith contributions, another series of experiments was carried out comparing yaw to roll motion and is summarized in the masters thesis of Peter B. Dinsdale (now at General Research Corp.) (abstract below). An earlier summary paper on motion cues by L. R. Young was published in October (abstract below).

<u>Motion Cues in Man-Vehicle Control</u>

by

Richard S. Shirley

Sc.D. Thesis, M.I.T., January 1968

<u>Abstract</u>

An investigation is made to determine how the human operator makes use of roll motion cues in a man-vehicle control system. To this purpose the human operator's describing function is measured over a wide range of vehicle dynamics and under conditions of visual inputs only, motion inputs only, and combined visual and motion inputs. Both the describing function (amplitude and phase of the human operator's output relative to his input) and the remnant (power spectral density of that part of the human operator's output which is uncorrelated with his input) are measured as a function of frequency. The relative integral squared error is also measured. Visual inputs are made by means of a dot moving laterally on an oscilloscope, and roll motion inputs are made by means of a motion simulator.

An analytical method of correcting the experimental measurements for errors introduced by the remnant is developed and applied to the data. The corrections are generally small.

Examination of the describing function data leads to some conclusions about the human operator's use of angular motion cues in a man-vehicle control system. When the roll motion cues are added to the visual cues, the human operator is able to increase his lead in the frequency range above one radian per second. This permits him to increase his gain and cross-over frequency without decreasing his phase margin. The net effect of these changes in the human operator's control behavior is to increase the open loop gain without a loss of stability, and thus to reduce the relative integral squared error for the closed loop system.

The percentage reduction of the relative integral squared error upon the addition of the motion cues to the visual cues varies as a function of the controlled vehicle dynamics. The human operator can make the most use of motion

cues for vehicle dynamics which lead to significant roll motions above one radian per second. Such vehicle dynamics include low order dynamics (1/s as opposed to $1/s^2$) and dynamics with an associated high control stick gain.

It is possible, in some cases, to use the body of data obtained for this thesis to predict actual in-flight or moving-base measurements of the human operator's describing function from fixed-base measurements of the human operator's describing function.

## Motion Cues in Man-Vehicle Control

by

R. S. Shirley and L. R. Young

Presented at Fourth NASA-University Conference on Manual Control, March 1968

### Abstract

The human operator's use of roll angular motion cues in man-vehicle control is investigated. Extensive data for the human operator's describing function and remnant are taken for a wide range of vehicle dynamics under conditions of visual cues only, roll motion cues only, and simultaneous visual and roll motion cues. Addition of roll motion cues to visual cues permits the human operator to increase his phase lead at frequencies above 2 rad/sec, thereby allowing higher gain and cross-over frequency and reduced tracking error.

## Relative Effects of Roll and Yaw Motion Cues in Manual Control

by

Peter B. Dinsdale

S.M. Thesis, M.I.T., September 1968

### Abstract

Experiments were performed to determine the relative contributions of otoliths and semicircular canals to manual control of difficult ($K/s^2$) vehicle dynamics. Motion cues (yaw and roll) were provided to subjects with head orientations

carefully specified such that in one case semicircular canals only were stimulated, whereas in the second case the otoliths as well as the same semicircular canals were stimulated. Human operator describing functions were measured and compared for the two cases. High frequency human operator amplitude ratio was greater when both otoliths and semicircular canals were stimulated than when only semicircular canals were stimulated.

### Some Effects of Motion Cues on Manual Tracking

by
Laurence R. Young

J. Spacecraft and Rockets, Vol. 4, No. 10
October 1967, pp. 1300-1303

Abstract

Although sustained high acceleration or vibration can have a deleterious effect on a pilot's tracking ability, there are some situations in which motion cues, as felt in flight or moving-base simulation, yield a significant improvement in pilot performance. The first of these situations is in a control task requiring more lead compensation than is easily developed from visual displays. The vestibular and tactile sensations contribute velocity and acceleration information which is used in stabilization. Experiments on control of inverted pendulums and VTOL's with and without motion cues are discussed. Tests of labyrinthine defective patients on similar tasks demonstrated the critical importance of vestibular inputs. The second situation required rapid adaptation to controlled element failures in a simulated blind landing experiment. Other tests showed motion effects to be important in a class of flexible booster control problems. These results were combined with many comparisons of fixed-base-moving-base flight experiments in the literature to arrive at some general conclusions regarding the effects of motion cues on tracking.

## 2.2 Stochastic Models of Human Learning Behavior

Several extensions have built on the earlier work of Preyss and Meiry on using a stochastic model for human switching behavior with Bayesian updating. Tze-Thong Chien, in his masters thesis, demonstrated the validity of the learning model when applied to control of harmonic oscillators and unstable processes (abstract below). The original model had been tested only on a double integration. Meiry presented his current notions for modeling decision making and learning behavior in papers presented at the 1968 Manual Control Conference and at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics (abstracts below).

Human Learning Behavior in Manual Control Tasks

by

Tze-Thong Chien

S.M. Thesis, M.I.T., September 1967

Abstract

In this thesis applications of a stochastic model of human learning behavior to harmonic oscillators and unstable dynamic processes are verified. Experiments are performed to compare model learning behavior with subject learning behavior in manual control tasks. A modified model in the form of a computer program is presented in the light of the experimental and analytical results.

The main conclusions of this thesis are the following:

1. Verification of the theory of the basic model for explanation of human learning behavior in application to the dynamic processes of harmonic oscillators and unstable plants.

2. A single revision rule based on the double integration dynamic process for estimating posterior probabilities can be applied to all dynamic processes experimented.

3. The reaction time delay between the reception of a visual stimulus and the execution of a motor response has a significant effect upon the state history of the high speed dynamic processes being controlled. This effect should be taken into account in evaluation of weighting of evidence in resolving control policy uncertainty.

4. Both subjects and model can learn to control the multi-switching optimal dynamic system in a sub-optimal way.

## Stochastic Modeling of Human Learning Behavior, II

by

Jacob L. Meiry

Fourth NASA-University Conference on Manual Control
University of Michigan, Ann Arbor, Michigan, March 1968

Abstract

The application of a stochastic model of human learning behavior in manual control tasks is extended to the performance of the human operator in regulating all second order dynamic processes. In particular, human control decisions for optimal multi-switch and unstable dynamic systems are found to correlate well with responses recorded by the model in the study of simulated subjects. The universality of the model is discussed in the light of a series of compensatory task experiments.

## Skill Organization and Human Learning Behavior

by

Jacob L. Meiry

IFAC Symposium on Technical and Biological
Problems in Cybernetics, Yerivan, Armenia, September 1968

Abstract

A theory and model of motor skills learning postulate a statistical decision process for the human operator controlling a dynamic system.

The selection of response alternatives and the revision of preferences for them are functions of a decision center in the human mind. This decision center is one component of a hypothetic single-channel information system. Also included in this information processing system are a sensor, which perceives the information upon which the decision center acts, and an effector, which executes the response decisions made by the center.

The model of human learning behavior is a digital computer program which is obtained from a translation of the theory into machine language. Behavior of this model is compared with subject behavior in a controlled series of motor skill experiments. The extent of the model's characterization of the time-varying random nature of human learning is brought out by this comparison.

## 2.3 Use of Variable Feel Control Stick

One of the central themes of our manual control research during the past six years has been the utility of nonvisual feedback in stabilizing higher order control system, including the use of vestibular cues, tactile cues, and force feedback. Our earliest attempts to determine the utility of variable mechanical impedance control sticks were hindered by inadequcies of the available hydraulic control systems. More recently we have been concentrating on the use of a control stick with adjustable mechanical impedance, to match the undesirable poles of the vehicle dynamics, in order to take advantage of the high gain human operator postural control loop, and the principle of cascade-reciprocal feedback. The control signals to be sent to the vehicle will be a weighted sum of the force applied to the control stick (high frequencies only) and the average position of the control stick. It is anticipated that high frequency vehicle instabilities, leading to pilot-induced oscillations because of visual delay times, may be eliminated through the fast postural control loop, while the visual system and control stick displacement continue to act in a conventional manner in low frequency tracking. This investigation is in part the subject for an engineers thesis by Capt. Philip Noggle. The M.I.T. Instrumentation Laboratory and Dr. Richard Pew of the

University of Michigan have been hlepful in design of the variable mechanical impedance single axis stick. Mr. C. M. Fan and Mrs. H. L. Galiana of our laboratory also contributed to this project.

## 2.4 Optimization in Manual Control

Two projects in the area of optimization have begun in our laboratory this year. The first of these, carried out by Major Albert E. Preyss in the summer of 1967, was an outgrowth of a specific application of his doctoral thesis on human operator learning behavior. He treated the practical problems associated with aerial combat with an important example, in which pilots learn sub-optimal programs. The early explorations in this field are summarized in the abstract from Major Preyss' research summary given below. Following his return to the U.S. Air Force Academy, Major Preyss and Major Richard Willes further developed the concept of optimization applied to aerial combat, with specific results which have been demonstrated.

### Summary of Research Efforts, June-July 1967

by

Albert E. Preyss

Memorandum to Professors Li, Young, and Meiry


#### Abstract

Research has been directed toward the development of tactics and strategies for use by pilots of fighting elements in attaining victory over their opponents. Specifically, this research has investigated the potential of jointly applying

optimal control theory and heuristic programming to the problem of achieving one-on-one superiority in fighter battles. This problem clearly falls into the domain of manned-vehicle control problems, and its solution will greatly facilitate the training of fighter pilots and the specification of fighter aircraft designs.

The problem of achieving one-on-one superiority divides into two parts. First, there is the question of finding the optimal control policy to attain some intermediate objective at minimum cost. For example, during an aerial engagement a pilot typically encounters such tasks as changing heading in minimum time, minimizing forward progress and changing state with minimum loss of energy. To accomplish these and other tasks, the pilot must maneuver his aircraft using the controls available to him, namely pitch, bank, and power. Thus it is necessary to find, by applying optimal control theory, the elevator, aileron and throttle programs which will minimize some cost functional. A composite control program to attain an intermediate objective may be called a tactic.

Once these tactics have been determined, and this requires the ability to define meaningful cost functionals, the second part of the problem may be engaged. This part is the question of which tactic to select in response to an adversary's offensive or defensive move. For example, if a pilot is being tracked and fired upon by an attacking aircraft, his immediate intermediate goal is to disrupt the attack and get out of the line of fire. Several tactics may be suitable for this purpose, but not all of them may be acceptable in terms of his posture at the completion of the maneuver. In other words, the tactic selected must form part of an overall strategy aimed at ultimately reversing his role of defender. Such strategies may be identified by simulating air battles and constructing a heuristic program which learns, after a number of trials, the best tactical response to an enemy overture.

Work has begun to define some of the fundamental objectives in air combat maneuvering and to initiate computer programs for determining the associated optimal control policies.

## 2.5 Inverse Optimal Control Problem

The other optimization problem involved a view of the pilot as a quasi-optimum controller. A recurring and basic question in manual control is not merely "what is the human operator's control law?" but "why is a particular human operator control law chosen?" A wide variety of empirical rules have been used; for example: minimization of mean square error, maintaining a given phase margin, placement of the cross-over frequency or open loop dynamics in the cross-over region, adjustment of low frequency gain, etc. It would be useful to know the criterion or set of criteria used in determining human operator control laws, both for understanding of the basic manual control process, and for possible application to adaptive and learning control system. This leads to the following question: given that a control law is optimal for a given plant, and subject to controller constraint, what is the performance criterion? This is called the inverse optimal control problem, and is of interest in the general field of automatic control as well as manual control. One of our doctoral candidates, Mr. Pitu Mirchandani, has begun study of the inverse optimal control problem in manual systems. He has assumed the following restrictions to bound the class of problems: the system is completely controllable, completely observable, and assymptotically stable. All state variables are directly measurable, and the human operator is fully learned (i.e., no adaptation during a run). In theory, the Hamilton-Jacobi equations applied to a given controller and plant permit solutions for performance functions of the state and of the control variables. A limitation in the analysis attempted by Obermayer and Muckler has been noted, and five special cases investigated thus far.

## 2.6 Adaptive Control

Our continuing interest in automatic and manual systems led to two developments in this period which are relevant to the design of practical automatic adaptive systems. The first of these, published as the masters thesis of Syozo Yasui (abstract below), followed our earlier research on the utility of a moving switching locus in the phase plane to guide the human operator into "chatter mode" sub-optimal control. Mr. Yasui's current employer (Tokyo Shibaura Electric Co.) and M.I.T. are expecting to apply for Japanese patent rights to the concept developed in this thesis.

The Use of the Chatter Mode in Self-Adaptive Systems

by

Syozo Yasui

S.M. Thesis, M.I.T., September 1967

Abstract

In an on-off relay control system under the chatter mode, the average motion of the plant is completely determined by the equation of the switching function. This fact has been applied in self-adaptive control systems in which the switching function describes the model dynamics, and the chatter mode is reached. The proposed policy of forward gain (switching level) adjustment takes into account the reduction of chatter frequency and of the control force magnitude, in addition to the sustenance of the chatter mode. A simple two dimensional display is used for manual operation and/or monitoring.

Several examples are presented to demonstrate the analog computer simulation. The results show satisfactory performance of the gain adjustment mechanism.

Known self-adaptive control systems are outlined with emphasis on those using a relay as a key element, and extended application to a class of distributed parameter control systems is considered. As a byproduct of this study, a numerical method without numerical integrations is proposed for the solution of ordinary differential equations.

The other major effort in adaptive control systems in our laboratory involved making practical use of the digital computer in a digital adaptive system. Mr. Charles Oman and Lt. Llewelyn Dougherty, working under the direction of Prof. Li, have been using the hybrid computer to explore the advantages of digital compensation, working in the time domain for adaptive control systems. Some of the results to data are summarized in the paper by Prof. Li (abstract below).

## Digital Controller for Feedback and Adaptive Control Systems

by

Yao Tzu Li

unpublished

Abstract

Design procedure of digitalized controller for feedback system via Z-transform method is summarized. A new sectionalized digital controller is introduced for the purpose of simplifying the logic elements needed. This type of controller also appears to be more compatible for use in self-adaptive control than conventional types.

The basic scheme for identifying the parameter deviation for adaptive control using information processing concepts is introduced. The crosstalk between the various parameter deviation identifying channels is studied. Several simplified configurations of adaptive control systems with open-loop model, closed-loop model and multi-model scheme are introduced. Filters for adaptive control to minimize noise disturbing to the plant are considered.

# III. DISPLAY RESEARCH

## 3.1 3-D Display Development

We have continued at a reduced level of effort the research and development begun last year on realistic display of depth cues on a single cathode ray tube. Advances in the program for displaying the image of a cube on a CRT as though it were being seen through a window include the following:

1. hidden line blanking
2. brightness vs. line length control
3. brightness vs. depth variation
4. dotting of the "runway lines" on the top of the cube.

In addition, the ability to track lateral head position in a single axis was put into the system with the assistance of a device designed and constructed by the M.I.T. Instrumentation Laboratory (P. Bowditch, H. Seward, and G. Davidson). The 3-D display continues to give encouraging preliminary results and we are proceeding to simulation of a more complex field using the ADAGE Graphics Terminal, being acquired by M.I.T.'s Electronic Systems Laboratory. Charles Oman, Noel Van Houtte, and Robert Vircks have been chiefly responsible for the advances in the 3-D display system during this year. The current 3-D program is summarized in the masters thesis of Robert M. Vircks (abstract below) which evaluates the effectiveness of head movement and intensity modulation on depth perception.

Investigation of Head Movement and Intensity as Depth Cues in a Perspective Contact Analog Display

by

Robert Marvin Vircertificates

S.M. Thesis, M.I.T., September 1968

Abstract

To determine the depth cue value of head movement perspective, and image intensity as a function of depth, an experimental investigation was conducted.

A contact analog 3-D display system was programmed on a hybrid computer. A line drawing of a single cube fixed in space was displayed on a CRT screen as if the screen were a window. This was accomplished by using the equations of linear perspective for a monocular observer whose head position is variable with respect to the screen. Motions of the vehicle, containing the observer and screen, were simulated using the six velocities in body fixed axes.

An experiment was conducted to determine the amplitude of a sinusoidal voltage applied to the CRT intensity grid as a function of line length, so that lines drawn in constant time intervals would have an apparent brightness independent of line length.

Depth discrimination experiments were conducted using the perspective display with combinations of head movement and cube intensity as a function of depth. The cube was displayed as if it were at one of a set of discrete depths and the subject asked to identify that depth. The resulting stimulus-response matrices were analyzed to determine the information transmission. It was found that head movement gives a 40 percent improvement in depth discrimination when the cube is between 50 and 100 cm from the subject. Head movement is four times more helpful when the cube is between 50 and 100 cm from the subject than when the cube is between 150 and 300 cm. Intensity variation resulted in half as much improvement as head movement.

Several alternative techniques for 3-D display generation, including holography, have been explored. A number of experiments were performed to test the effectiveness of the "kinetic depth effect" as described in the following research summary by C. Oman:

Summary of Research Activity, September 1967 to June 1968

by

Charles M. Oman

An investigation begun in July 1967, looking into the possibility of using the depth effect created by the motion of a two dimensional figure on a screen was continued. The illusion, first documented by Wallach and O'Connell, was created by modifying the Man-Vehicle Laboratory 3-D display 290 T hybrid computer program to show alternately views of a cube in two different positions. The "apparent motion" thus produced created the movement necessary for observation of the "kinetic depth effect" in the cube. Repetition rate, image brightness, apparent movement, and on and off times were varied for preliminary experiments. As expected, it was found that at a repetition rate of approximately 3 cps, most observers "impleted" the two different views seen in the presentation and "saw" a moving cube as a three dimensional object rather than a two dimensional figure whose form was changing.

Creating continuous small apparent movements of the cube did not, however, resolve the basic perceptual ambiguity associated with the spatial relationships of the "front" and the "rear" lines of the cube, and subjects continued to report Necker Cube reversals which plagued earlier versions of the 3-D display.

The small oscillatory motions of the cube were judged to be of only marginal value, as reversal of the perceived figure was not prevented. Also, as the display was conceived primarily for vehicle applications, cube motions are the rule rather than the exception, and so the kinetic depth effect is usually present to some degree in the ordinary 3-D display system format. Small additional artificial oscillations of the figure induced to aid the creation of the kinetic depth effect are also distracting, particularly since the display is intended to portray the outside world with some degree of verisimilitude.

At the suggestion of Dr. Paul A Kolers, the 3-D display program was further modified to investigate the possibility of creating a monocular stereoscopic image by using the Schoen effect. It has been suggested that there is a definite relationship between depth values, retinal input, image arrival time at the visual cortex, and the creation of stereopsis. It was suggested that if left and right eye views of a carefully constructed scene are shown alternately, in proper stereoscopic cross registration on a screen, an observer should perceive a motionless object in three dimensional space. By carefully controlling the repetition rate (about 3 cps) and varying the off times, the display allegedly can be made to operate at one of the basic psychological refractory periods associated with the visual system.

Initial attempts to observe the effect with the 3-D CRT display were not encouraging. It was felt that the CRT phosphor persistence might be at fault, so lantern slide projectors were used to flash, alternately, left and right eye photographs of various simple geometric objects (cone or cube) seen against a dark background. The repetition rate and the on and off times were controlled precisely. The observer's position was varied systematically so that the objects projected on the screen subtended various angles on the retina. Ten subjects reported essentially the same results, with one or both eyes: If the repetition rate was slow, the left and right eye views were seen alternately. Above four cps, all subjects saw the object in apparent oscillatory motion, and the kinetic depth effect was observed. In intermediate frequency ranges, with off times which seemed to vary from observer to observer, the object could no longer actually be seen moving. Generally observers were aware that two views were being shown, but if asked where the object was located on the screen would report that its position was somewhat vague, but located somewhere between the screen positions of the left and right eye views. Apparently the observers received information from both the left and right eye views, for they generally perceived some three dimensionality in the geometric objects on the screen. However, no two people reported exactly the same perception. If the observer attempts to do more than just fixate blankly in the area of the object on the screen by looking at one particular part of the object, for example, the illusion is destroyed and a new illusion of objectless pure movement replaces it.

G. H. Engel, in a recent paper, also supports the conclusion that stereopsis cannot be induced using this procedure. In a considerably more sophisticated experiment, Engel presented subjects with pairs of alternately flashed random patterns, generated by a computer in a manner similar to that used by Julesz in his experiments for binocular stereopsis. Extensive testing by Engel failed to show any evidence of a monocular stereoscopic effect. This approach to 3-D display generation is no longer being pursued.

Finally, as applications of our 3-D display research, the entire area of integrated displays for VTOL flight is being investigated and forms the heart of the doctoral thesis research program of Noel Van Houtte. In preparation for the VTOL research, the analysis of the equations of motion of the V/STOL aircraft in altitude and range has been completed on our hybrid computer. It is being used for studies of optimum flight paths using minimum fuel by Prof. Walter Hollister and one of his students, as well as by Mr. Van Houtte.

## 3.2 Antivertigo Display

The goal of our research on orientation and disorientation is not merely to understand the mechanism, but hopefully to arrive at ways of combatting the deleterious effects of disorientation. The 3-D display described above is one approach. Another uses our models of the vestibular system to derive a "pseudo-stable" peripheral display which might reduce the onset of vertigo. Some of our work in this regard is cited in the research summary of Charles Oman (see below), and will form part of the work for his masters thesis.

## Summary of Research Activity, September 1967 to June 1968

by

Charles M. Oman

### Anti-Vertigo Display System

Man-Vehicle Laboratory efforts to develop valid mathematical models for the semicircular canals and otoliths using the techniques of control theory were reviewed with a view toward defining and attempting to determine the etiology of vertigo and a possible explanation for the apparently related motion sickness syndrome.

It became apparent that vertigo was a loosely defined term applied (often indiscriminately) to many types of perceptual illusions. Most studies have been aimed at determining the exact statistical relationship between perceptual disorientation and other forms of motion induced malaise and aircraft accidents. Etiological theory is in a relatively embryonic stage, due to the complicated psychological factors involved. Many conflicting theories have been advanced.

One is led to the conclusion, however, that the one basic circumstance associated with most cases of vertigo occurs when, because of the interaction of vehicle motions with a man's motion sensors and the nature of his visual field, a conflict arises when a man attempts subconsciously to continue the process, normally unimpeded, of establishing a conception of his dynamic orientation in space.

It has been suggested by Fogel and others that the occurrence of disorientation resulting from conflicting sensory modalities might be alleviated by a system which showed a vertiginous subject a display of the outside world oriented with respect to him so that it would agree with his subjective prediciton of the orientation of the outside world based only on his nonvisual modalities. In essence, the conflict between the visual and the vestibular input, presumably the major source of modality conflict in most situations, would thereby by resolved.

Man-Vehicle Laboratory research in recent years towards the development of viable control theory models for the human vestibular sensors and a control theory approach towards the problem of modeling the method which the human CNS uses to organize the motion sensing inputs suggests that initial steps could be taken to construct a prototype anti-vertigo display. Construction of such a display offers an unusual opportunity to test the relevance of the conflicting sensory modality approach to the etiology of vertigo and is a practical application for the mathematical vestibular models themselves, which heretofore have been primarily the objects of research.

The basic concept of an anti-vertigo display system is quite simple. Based on the motions of the vehicle, sensed in the frame of reference of the observer's head, the models of the various sensory modalities (including a model of human visceral sensation, perhaps) predict the inputs to a man's central nervous system. These are modeled in the display system by a heuristic program which determines a man's concept of his spatial orientation based on non-visual modalities, and displays either peripherally or foveally his subjective orientation in a visually compelling fashion.

Work has begun on the preparation of a prototype display in which only the horizontal axis is stimulated in a very simple fashion. These initial tests should yield meaningful results concerning the validity of the whole concept, despite the simplicity of the model.

Initially we hope to deal with "dizziness," the simplest form of vertigo, which results from lingering sensation of rotation after a cessation of angular velocity. We will use the Man-Vehicle Laboratory rotating chair constructed last year by Katz and Steer and require the subject to perform compensatory tracking on an unrelated visual task. Display effectiveness could be related directly to mean squared error of the primary task, rather than to some other measurements of the onset of vertigo, e.g. galvanic skin potential or onset of sweating.

Initial tests will evaluate the display concept for single axis dizziness, and if these prove encouraging, a case of "Coriolis" stimulus will be considered by allowing a head rotation and combining the outputs of canal models operating on orthogonal axes. It is expected, however, that the choice of the most effective display format may require considerable experimental work.

## 3.3 Development of a "Head-Position Sensor"

Both of the display programs described above require a means of monitoring the observer's head position without encumbering his movement. Ultrasonic and optical sensors were both considered.

The single axis prototype head position monitoring system used is a photo-optical device built by the M.I.T. Instrumentation Laboratory to our specifications. The system consists of a light source mounted on a head band worn by the subject. A lens and two silicon photocells were mounted 84 inches above the light and masked so that the light source threw a rectangular patch of light onto the two photocells. Translation of the head changed the relative illumination on the two photocells, yielding an output voltage proportional to light position, which was suitable for processing by the analog computer and A-D conversion in our 3-D display system. The monitor was tested over a range of ±10 cm head position with accuracy of 4.5% of full scale. Details of the operation are contained in an appendix of Robert Vircks' masters thesis.

# IV. VESTIBULAR RESEARCH

## 4.1 Unified Model for Vestibular Function

A primary goal in our research has been the development of practical mathematical models for the functioning of the vestibular system, relating linear and angular acceleration of the head to perception of orientation in space. For several years, these efforts have been directed towards analysis of the otoliths, to develop models comparable to those extant for the semicircular canals. This phase having been virtually completed, we are now concentrating on unified models of the entire vestibular system and some important nonlinear effects in both the semicircular canals and otoliths. We have been particularly concerned recently with modeling the adaptation and habituation phenomena, whereby subjects show reduced sensitivity to long duration stimuli or repeated familiar patterns of motion. The practical applications of this latter approach are obvious, particularly with respect to "vestibular training," for flying or for living in unusual environments, such as in a rotating spacecraft or under reduced gravity.

An invited paper synthesizing our current models of the entire vestibular system was presented at the Edsel B. Ford Institute for Medical Research International Symposium on Biocybernetics of the Central Nervous System, Washington, D.C., February 1968 (Little Brown Co., in press, abstract below).

An engineering oriented paper stressing the bionics applications is being given at the AGARD Bionics Symposium, Brussels, September 1968, and excerpts of the paper representing the biological control analysis problems are being presented at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, U.S.S.R., September 1968.

## On Biocybernetics of the Vestibular System

by

Laurence R. Young

Edsel B. Ford Institute for Medical Research
International Symposium on Biocybernetics of the Central Nervous System, Washington, D.C., February 1968

### Abstract

The human vestibular system for dynamic space orientation is described mathematically, using the identification methods of control theory. A biocybernetic model is useful in predicting man's perceived orientation in space, postural reactions, nystagmus eye movements, and piloting actions based on motion cues. The semicircular canals, which act as angular velocity sensors, have been subjected to a fluid dynamics analysis. The limitations of the torsion pendulum model are examined, and a quantitative description of adaptation is proposed. An otolith model, responding to linear acceleration forces, is presented and shown to agree with perception of tilt and translation, eye counterrolling, and electrophysiological data. Cross-coupling effects are discussed, including the influence of linear acceleration on the semicircular canals.

## 4.2 Revised Dynamic Otolith Model

Our linear model of the otolith system was revised last year to account for a steady-state perceived tilt in response to steady offset from the vertical, and to agree with electrophysiological data. The paper, first presented at the Third Symposium on the Role of the Vestibular Organs in Space Exploration, Pensacola, Florida, 1967, was revised and published in Aerospace Medicine, June 1968 (abstract below).

The revised otolith model remains untested at frequencies below 0.1 rad/sec, and experiments are currently being planned to explore this region, using otolith stimulation via sub-threshold rotations about a horizontal axis.

A Revised Dynamic Otolith Model

by

L. R. Young and J. L. Meiry

Aerospace Medicine, Vol. 39, No. 6, June 1968

Abstract

The application of control theory to analysis of vestibular function has yielded mathematical models of the semicircular canals and, more recently, the otoliths. A proposed dynamic otolith model is based on "input-output" experiments including dynamic counterrolling, subjective perception of velocity during sinusoidal linear oscillation, and threshold to constant acceleration. This model is consistent with electrophysiological data and includes a low frequency lag term to permit a steady output to sustained tilt or acceleration.

## 4.3 Nonlinearities in Rotation Sensing

One of the techniques available for exploring habituation and adaptation involves the separation of two paths in higher mental processing of vestibular data: the subjective sensation of rotation reported by the subject, and nystagmoid eye movements objectively recorded. Some preliminary data on the difference between subjective and objective phase lag for sinusoidal rotations suggested a possible hysteresis component in semicircular canal function. Considerable effort is being directed toward determination of the form of the threshold and saturation nonlinearities. Our first investigations in this area required the construction of a new single-axis yaw rotation chair and the sinusoidal rotation of subjects on it. This work is reported in the masters thesis of Gerald B. Katz (abstract below).

## Perception of Rotation - Nystagmus and Subjective Response at Low Frequency Stimulation

by

Gerald B. Katz

S.M. Thesis, M.I.T., September 1967

Abstract

A rotating chair was built to submit subjects to sinusoidal angular accelerations at various combinations of frequencies (.01 cps to .1 cps) and peak angular acceleration levels ($10°/sec^2$ to $45°/sec^2$), for the purpose of studying the human subjective and objective response to rotation at low frequencies. Each of four subjects was seated in the completely dark chair with the axis of rotation passing through his head.

His subjective response was measured by means of a directional switch; his objective nystagmus eye movement response was simultaneously measured and recorded. A study of the resultant phase differences between both subjective and objective perceptions of angular velocity and actual angular velocity leads to the following conclusions:

1. The phase lead of both objective and subjective response exhibited no simple functional dependence upon amplitude of acceleration.

2. The amount of phase lead in both cases is inversely proportional to stimulus frequency.

3. The objective phase lead is larger at any stimulus condition than the corresponding subjective phase lead.

4. Intersubject response differences were very evident, irregular, and relatively great.

5. The data presented agrees in a gross manner with the data of Hixon and Niven.

## 4.4 Directional Preponderance (Bias) in Semicircular Canals

In some preliminary experiments we have observed a tendency for any one subject to have a preferred direction of rotation, or bias, which dominates the low frequency drift characteristics of his nonvisual rotation perception. Experiments are being carried out to quantify this phenomenon, to differentiate between bias and other types of disturbances, and to explore possibilities for using this information to combat disorientation.

## 4.5 Physical Modeling of Semicircular Canals

A very important adjunct to our "black box" modeling of the semicircular canals has been an intensive study of their biophysical characteristics. It has entailed measurement of the physical properties of both endolymph and perilymph, caloric testing, and analysis of the fluid dynamics of liquid-filled flexible tubes. This work was primarily supported by Grant NGR 22-009-156 and reported in the doctoral thesis of Robert W. Steer, Jr. (abstract below).

The Influence of Angular and Linear Acceleration and Thermal Stimulation on the Human Semicircular Canals

by

Robert W. Steer, Jr.

Sc.D. Thesis, M.I.T., August 1967

Abstract

The hydrodynamic properties of the human semicircular canal system were studied to determine its dynamic characteristics and their relationship to observed subjective and objective vestibular responses to various motion inputs. Four topics of particular importance in current vestibular research were examined in detail.

The density, coefficient of expansion, and viscosity of the labyrinthine fluids, endolymph and perilymph, have been measured to provide precise values for the coefficients of the dynamic models. A microviscometer was designed, built, calibrated, and used to measure the viscosity of 1-2 microlitre samples of endolymph and perilymph. Density measurements were made via precision balance scales and accurate volume measurements and coefficients of expansion were made by microscopic measurements of the volume of the fluids at several temperatures.

The semicircular canal is modeled as a rigid torus of fluid, with the cupula acting as an elastic and viscous restraint. A system transfer function is evaluated for cupula displacement as a function of angular acceleration. It is shown that the cupula's effective inertia and viscous drag on the wall of the membranous labyrinth influence the dynamic performance of the system but do not resolve the disparity between previous calculations of damping, which only considered hydrodynamic drag of endolymph in the canalicular duct, and experimentally measured damping coefficients.

Caloric stimulation of the vestibular apparatus is examined, and a model is proposed, based on the published measured time history of the temperature gradient across the lateral canal when the external auditory meatus is irrigated with water above or below body temperature. The presence of a thermal gradient across the lateral canal is shown to produce the physiological equivalent of an angular acceleration because of the torque which acts on the endolymph as a result of its thermal coefficient of expansion. Caloric experiments were performed which attest to the validity of the model.

The influence of linear acceleration on the semicircular canals was investigated. Human objective and subjective responses to rotation about a horizontal axis, to couter-rotation, and to stimulation by a rotating acceleration vector were

examined. The observed responses of long duration nystagmus and continuous sensation of rotation are not in conformity with classical models of the vestibular system and there has developed a sizable body of experimental evidence which attributes a significant portion of these unusual responses to the semicircular canals. It is shown, through the distensibility of the canalicular duct under the influence of linear acceleration, that the observed bias component of nystagmus can be attributed to a first order nonlinearity of the semicircular canal dynamics. Experiments were performed on a centrifuge equipped with a rotating chair to show the relationship between the magnitude of the acceleration field, the rotation rate of the subject, and the slow phase velocity of vestibular nystagmus.

# V. EYE MOVEMENT RESEARCH

## 5.1 Advances in Modeling the Eye Movement System

A number of improvements and modifications in the sampled data model for eye tracking movements have been included in a revised hybrid model based on experimental results in our laboratory and elsewhere. This hybrid model considers the stochastic nature of this system (and characteristic of any biological system) and shows how the observed classes of eye movement responses to a given input stimulus can be predicted on the basis of random distributions of synchronization between the timing of a sampler and the occurrence of a target transient input. Work is continuing on the fine structure of this model and on the determination of the numerical values of specific delays. The model was first presented in a paper by Young, Forster and Van Houtte at the 1968 NASA-University Conference on Manual Control (abstract below).

### A Revised Stochastic Sampled Data Model for Eye Tracking Movements

by

L. R. Young, J. D. Forster, and N. Van Houtte

Presented at Fourth NASA-University Conference on Manual Control, March 1968

Abstract

Our sampled data model is revised by changing the pursuit system to be continuous and proportional to target rate.

Transient responses of the model are shown to agree in detail with observed classes of eye movements. Target-synchronized and non-synchronized sampler control logic are compared. Predicted latency distributions of a non-synchronized sampler with unknown intersample time distribution are analyzed, and saccade synchronized input experiments are compared with predicted mean model responses. The results show properties of both types of sampler control logic. The assets, limitations, and extensions of the model are discussed. The sampled data model proves to be a useful tool for predicting eye response based on target movement only.

In addition to the model determining eye movements on the basis of tracking a single unpredictable target, we have also been concerned with the variety of other stimuli which go into determining direction of gaze and dynamic visual acuity. Some of these other factors are: vestibular inputs (both semicircular canal and otolith), caloric stimulation, counterrolling, and voluntary direction of gaze.

## 5.2 Eye Movement Recording

L. R. Young was invited to contribute a chapter on this topic to the forthcoming McGraw-Hill book entitled Medical Electronics and Engineering. The abstract of this chapter is given below.

"Recording Eye Position"

by

Laurence R. Young

For Medical Electronics and Engineering, McGraw-Hill
(in press)

Abstract

Long standing interest in measurement of the direction of gaze as an indication of visual information processing, as

well as the clinical importance associated with eye movements, has resulted in the development of a wide variety of measurement techniques. In recent years perfection of several electronic measurement methods has eliminated the tedious and often inaccurate estimations of the older methods and has made these visual performance measures available to a great number of investigators. This chapter reviews the instrumentation problems and solutions for measuring eye movements.

## 5.3 Eye Movements in Learning to Read

As an outgrowth of a course project, Anthony Van Hover has begun an experimental and analytical approach to modeling the learning of reading. By treating the reading problem as a class of the general problem involving interpretation of symbolic information, we hope to be able to generalize on the manner in which men proceed from taking in a few bits of information at a gaze to taking in "words" or "phrases." This is being accomplished by using Dr. Kolers' techniques of learning to read English text with inverted letters. Mr. Van Hover is recording eye position in reading tasks over a period of months, showing how the number of fixations per line, number of regressions, and duration of fixations changes as subjects are able to take in larger quantities of information per fixation.

## VI. POSTURAL AND NEUROMUSCULAR CONTROL

With increasing amounts of quantitative physiological data on neuromuscular control becoming available, a "rational parameter" approach to understanding the "neuromuscular lag" component of the human operator describing function appears reasonable. Some interesting new neuromuscular models have been reported, and two projects are being carried out in our laboratory. One of these is a new attempt to create a neuromuscular model based on "component models" for triple muscle innervation (two gammas and one alpha), dual afferents (stretch and stretch rate), Golgi tendon organs, joint receptors, and Renshaw cells. John Allum plans to apply control theory to the problem of analyzing the alpha and gamma stimulation loops. The other project is an input-output approach to the problem of man's neuromuscular output, using postural control as an example. The following summary is from the Ph.D. thesis proposal of Lewis Nashner.

### Ph.D. Thesis Proposal

by

Lewis Nashner

The goal of this thesis is to model the flow and interaction of sensory information necessary for the maintenance of posture in man. The formulation of a model of posture control directly from physiology would be difficult for several reasons:

1. A complete description of the neural circuitry involved in posture control is not known.

2. Experimental observation of the many information channels in man is not practical.

Instead of being a necessarily weak model based on neurophysiological data, the model will be developed by defining two major posture control modes. After a thorough experimental description of these two control modes, the resulting model will be re-examined in the light of current physiological evidence.

The reflex response is defined as a continuous linear control of limb position and force output, responding to muscle length and tension only. The response will have terms proportional to displacement and to the rate of displacement. The gains of the length and velocity terms are independently variable over a limited range.

The orienting response is defined as the control of posture with respect to the external environment. The orienting control responds to proprioceptor, visual, and motion cues. The response reflects both subconscious learned patterns and the conscious desires of the man. Because the orienting response incorporates complex processing patterns and memory, its output can be expected to be of form significantly different than that from the reflex response.

Since the passive dynamic characteristics of the body and its reflex responses have state variables in common, the total dynamic characteristics of the body will be viewed as the combination of these properties. The control of the reflex response "gains" is therefore a parametric control of the body's dynamic characteristics. The other inputs are the external disturbances and the orienting responses. From this viewpoint posture control is effected in two ways:

1. with orienting responses, reacting to body motions with respect to its external environment.

2. with the parametric control of the body's dynamic characteristics, both to orienting response commands and to external disturbances.

A major emphasis of the model will be a description of the relative roles of the two posture control modes. The total range of the reflex response control of the body's dynamic characteristics will be determined experimentally. The criteria by which control is delegated between the two modes for a variety of external conditions will be described.

Past research in human posture control has concentrated in two distinct areas. Engineering studies have described the capabilities of human subjects in a variety of manual control tasks and have developed input-output models for the major sense organs. These studies, however, have not attempted to ascribe in any detail specific physiological mechanisms to the integrative functions of posture control.

Considerable effort has been made in the description of the basic physiological properties of the many components in posture control. Data on component function and interaction sufficient to construct a complete posture control model is not yet available. Experimenters have observed component function only in special restrained conditions where general function during posture control cannot be accurately determined.

The differentiation of two defined modes of posture control, consequently grounded in the current physiological evidence, will allow the observation of two distinct information channels during natural control conditions. While separation into two channels is far from a complete mode differentiation, this separation of posture control into an intracomponent mode (reflex response) and a body-external environment mode (orienting response) will represent a significant advance.

The research will concentrate on obtaining an accurate description of the flow of information in the reflex and orienting response loops. The work will be conducted in four major phases:

1. The basic posture control model will be proposed with the definition of two basic control loops. Definition of the dynamic characteristics of the body and of muscle will allow the calculation of the muscle activation history from the measured torque and motion history of the body.

2. Experiments will be conducted to describe the range of the reflex mode control characteristics.

3. The interaction of the reflex and orienting modes of control will be experimentally investigated under varying disturbance conditions.

4. The experimental results will be correlated with a detailed investigation of human neurophysiology related to posture control. Physiological interpretations of the model will be made wherever they can be justified.

Since a general attack on the posture control problem is a broad and multidimensioned one, the experiments will concentrate on the specific case of a man standing erect in a fixed position with his feet together. The choice of a simple posture control task is necessary to maintain the description of information paths and the definition of the component transfer functions on a workable level.

The proposed posture experiments will require the design and construction of an instrumented actively controlled platform. Instrumentation will be necessary to give continuous measures of the ankle and hip angles. Active control of the platform deflection angle will permit the initiation of small torque disturbances to the ankle to measure ankle stiffness and will also permit alteration of the apparent reflex response "gain" about the ankle joints.

# VII. PUBLICATIONS AND THESES OF THE MAN-VEHICLE LABORATORY, 1967-68


1. Chien, T. T., "Human Learning Behavior in Manual Control Tasks," S.M. Thesis, M.I.T., September 1967

2. Dinsdale, P. B., "Relative Effects of Roll and Yaw Motion Cues in Manual Control," S.M. Thesis, M.I.T., September 1968

3. Forster, J. D., "A Stochastic Revised Sampled Data Model for Eye Tracking Movements," S.M. Thesis, M.I.T., June 1968

4. Katz, G. B., "Perception of Rotation - Nystagmus and Subjective Response at Low Frequency Stimulation," S.M. Thesis, M.I.T., September 1967

5. Li, Y. T., "Digital Controller for Feedback and Adaptive Control Systems," in press

6. Meiry, J. L., "The Control System of the Deep Submergence Rescue Vehicle," Fourth Symposium on Marine Instrumentation, January 1968

7. Meiry, J. L., "Skill Organization and Human Learning Behavior," to be presented at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, USSR, September 1968

8. Meiry, J. L., "Space and Deep Submergence Vehicles, Mission and Guidance, Navigation and Control Synthesis," AIAA Third Marine Systems and ASW Meeting, paper no. 68-473, San Diego, California, April 1968

9. Meiry, J. L., and A. E. Preyss, "Stochastic Modeling of Human Learning Behavior," IEEE Trans. on Man-Machine Systems, June 1968

10. Meiry, J. L., "Stochastic Modeling of Human Learning Behavior, II," Fourth Annual NASA-University Conference on Manual Control, Ann Arbor, Michigan, March 1968

11. Shirley, R. S., and L. R. Young, "Motion Cues in Man-Vehicle Control," Fourth Annual NASA-University Conference on Manual Control, University of Michigan, Ann Arbor, Michigan, March 1968, and IEEE Symposium on Man-Machine Systems, Washington, May 1968

12. Shirley, R. S., "Motion Cues in Man-Vehicle Control," Sc.D. Thesis, M.I.T., January 1968

13. Steer, R. W., "The Influence of Angular and Linear Acceleration and Thermal Stimulation on the Human Semi-circular Canals," Sc.D. Thesis, M.I.T., September 1967

14. Vircks, R. M., "Investigation of Head Movement and Intensity as Depth Cues in a Perspective Contact Analog Display," S.M. Thesis, September 1968

15. Yasui, S., "The Use of the Chatter Mode in Self-Adaptive Systems," S.M. Thesis, M.I.T., September 1967

16. Young, L. R., "A Control Model of the Vestibular System," to be presented at the International Federation of Automatic Control Symposium on Technical and Biological Problems in Cybernetics, Yerivan, Armenia, U.S.S.R., September 1968

17. Young, L. R., "Functions of the Vestibular System in Human Guidance and Control," to be presented at the AGARD Bionics Symposium, Brussels, Belgium, September 1968

18. Young, L. R., "Motion Cues and Vestibular Models," to be presented at NEREM 68 in November 1968

19. Young, L. R., R. F. Brubaker, "Noninvasive Venous Pressure Monitoring by the Pressure Chamber Occlusion Method," 20th Annual Conference on Engineering in Medicine and Biology, Boston, November 1967

20. Young, L. R., "On Biocybernetics of the Vestibular System," Edsel B. Ford Institute Symposium on Biocybernetics of the Central Nervous System, February 1968; also Fourth Annual NASA-University Conference on Manual Control, University of Michigan, Ann Arbor, Michigan, March 1968

21. Young, L. R., "Recording Eye Position," chapter for McGraw-Hill Book Co., to appear in Medical Electronics and Engineering

22. Young, L. R., and J. L. Meiry, "A Revised Dynamic Otolith Model," Aerospace Medicine, Vol. 39, No. 6, p. 606-608, June 1968

23. Young, L. R., J. D. Forster, and N. Van Houtte, "A Revised Stochastic Sampled Data Model for Eye Tracking Movements," Fourth Annual NASA-University Conference on Manual Control, University of Michigan Conference on Manual Control, University of Michigan, Ann Arbor, Michigan, March 1968

24. Young, L. R., "Some Effects of Motion Cues on Manual Tracking," J. of Spacecraft and Rockets, Vol. 4., No. 10, October 1967, pp. 1300-1303