https://ntrs.nasa.gov/search.jsp?R=19770018841 2020-03-22T09:49:27+00:00Z

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FINAL REPORT

RESEARCH ON INTEGRATION OF VISUAL AND MOTION CUES FOR FLIGHT SIMULATION AND RIDE QUALITY INVESTIGATION

NASA GRANT NGR 22-009-701

June 1972 through February 1977

PRINCIPAL INVESTIGATOR:

L.R. YOUNG

COINVESTIGATORS:
C.M. OMAN
R.E. CURRY

JUN 1977
RECEIVED
NASA STI FACILITY
INPUT BRANCH

MAN-VEHICLE LABORATORY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
CENTER FOR SPACE RESEARCH
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

(NASA-CR-153249) RESEARCH ON INTEGRATION OF VISUAL AND MOTION CUES FOR FLIGHT SIMULATION AND RIDE QUALITY INVESTIGATION Final Report, Jun. 1972 - Feb 1977 (Massachusetts Inst. of Tech.) 84 p HC A05/MF A01 CSCL 05H G3/54

N77-25785

Unclas
30402

FINAL REPORT

NASA GRANT NSG 22-009-701

June 1972 through February 1977

RESEARCH ON INTEGRATION OF VISUAL AND MOTION CUES FOR FLIGHT SIMULATION AND RIDE QUALITY INVESTIGATION

PRINCIPAL INVESTIGATOR:

Laurence R. Young

CO-INVESTIGATORS:

Renwick E. Curry

Charles M. Oman

Submitted: June 15, 1977

Man Vehicle Laboratory
Center for Space Research
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology

PREFACE

During the period of this grant (June 1972 through February 1977), models quantifying our theories of vestibular and visual motion processing have been developed and are now being tested. New experimental results concerning visually induced motion and its relationship to vestibular responses have been obtained. Most of this would not have been possible without the cooperation and help extended to us by the personnel of the Langley Research Center, especially our technical monitors, Dr. M.J. Queijo and Mr. Ralph Stone, Jr. They proved to be sincerely interested in our work and progress and offered every possible assistance towards the implementation of the research.

TABLE OF CONTENTS

INTRODUCTION

The use of ground simulation for research and training in the field of aviation has been undergoing a large growth in the 1960's and early 1970's. In the commercial airline operation field, the cost of the aircraft and its operation for jumbo jets made inflight training expensive and the risks inherent in this type of training made the use of inflight training on emergencies very questionable. Most prominent as a possible solution to this situation was the recent development of highly sophisticated ground-based simulators for this class of aircraft and their use as a means of augmenting flight training. In the general aviation area, the problem of overcrowded terminal areas and the relatively higher risks associated with flight by beginners served as the motivation for the continued development of ground-based light aircraft simulators to be used in the early phases of flight training as well as for instrument ratings. The difficulty in training private pilots to multi-engine and instrument ratings posed a severe threat to the continued health of the general aviation field, which could only be overcome by further simulation development.

Additionally, research and development on new aircraft with essentially unique flying characteristics required the use of inflight and ground simulation to assess the handling qualities and pilot ratings of the proposed vehicles. Although, strides had been made in the development of manual control theory for this last area, the final assessment by simulation was still a necessity.

Given this increased pressure for flight simulation, what are the technical problems which must be faced? Flight simulation, it must be realized, is always a compromise -- a compromise between the full six degree of motion freedom in the air and the limited motion in the laboratory; a compromise between the true visual scenes observed through the windshield in flight and the simulated scenes projected in the simulator; a compromise between the auditory and tactile cues of flight and those generated in thelaboratory. One of the purposes of the proposed research was to examine some of the guidelines for the minimum degree of motion and vision fidelity required for a given simulation. The stress was not one of how to achieve the best simulation, but rather how to combine the visual and motion cues to achieve a technically sub-optimum, but nevertheless, adequate simulation for the given purpose.

It must be recognized that the requirements for simulators differ greatly according to their application. The motion requirements for a simulator used in a refresher course on training for aircraft emergency procedures probably demand only that the motion cues remind the pilot of those which would be felt in flight and need not be highly accurate as to duration or magnitude. On the other hand, the motion fidelity requirement is clearly very great for a simulator designed for handling quality investigation of a proposed new vehicle, particularly one in which unstable behavior would lead to degraded pilot opinion. The motion fidelity needed for investigating ride quality and passenger acceptance is yet another case.

Although the entire range of simulator requirements would be considered in the research, the emphasis has been on assessing the required fidelity for different applications, and the ways in which this fidelity can be achieved with minimal motion and appropriate generation of visual scenes.

The basic approach to the problem was one of using models of the dynamic processing of sensory information for human orientation. We had, for some time, been developing mathematical models of the human vestibular system as an element of the dynamic spatial orientation process. These models relate the angular and linear acceleration of the pilot's head to his perception of orientation independent of any visual cues or knowledge of the experimental situation. From the point of view of motion cues only, the adequacy of a given simulator and its control circuitry could be assessed using the dynamic models with some modifications to tell whether or not the simulator motion "feels like" the aircraft motion to a sufficient degree of accuracy. In our research program, we planned to develop models of visual dynamic spatial information processing in a manner which will complement the vestibular models, fill in gaps in the vestibular model effort, investigate quantitatively the influence of other modes of stimulation which affect the sensation of motion and explore the problem of integration of visual, motion and other cues to achieve the most realistic sensation of simulator motion with the minimum amount of actual simulator displacement and visual scene generation equipment. The results of these studies would be foccussed on several specific application areas of interest to MIT and NASA.

The program proposed required considerable experimental work at different levels of simulator sophistication as well as analytical work on developments of models. Some of the experiments were carried out at MIT, while others were done with the more sophisticated equipment at NASA research centers.

BACKGROUND:

VESTIBULAR MODELS AND FLIGHT SIMULATOR MOTION WASHOUT TECHNIQUES

In the simulator industry, most of the designs for motion systems ultimately are constrained by the large travel required to wash out acquired linear velocities. It has been apparent for some time that improvement in the washout design procedure is necessary because existing techniques have resulted in considerable overdesign of motion capability in many cases. Unfortunately, however, attempts to improve the procedure have, until now, concentrated primarily on optimizing the ratio of simulator acceleration amplitude to actual vehicle acceleration amplitude per foot of simulator travel. The approach has been to design linear acceleration washout dynamics to give the most acceleration in the simulator for the least amount of base travel. Only a little thought has been given to the phase relationship between the aircraft and the simulator accelerations. Generally speaking, the relationship between actual inflight sensation of motion resulting from vestibular stimulation and that experienced in the simulator has been considered only qualitatively.

Review of washout techniques

The primary problem in producing motion cues in a simulator is that to exactly reproduce the linear and angular acceleration cues experienced by a man riding in a vehicle can require extremely large simulator travels. Physical or financial constraints often dictate that the designer is limited to angular motion capability only; and if linear travel is possible, it is often limited to distances on the order of 10 or 20 feet. In such cases, exact motion cue reproduction is clearly impossible, and designers have had to satisfy themselves with designing washout procedures within the acceleration, velocity and travel envelope that was available. The verisimilitude of the simulation was usually judged on the basis of pilot opinion, particularly for simulations of transport type aircraft. If pilots who had flown the actual aircraft said that the simulation "felt" like "a ride in the real thing", then the simulation was judged a success.

Proportional washout

The simplest washout technique consists of an acceleration command to the appropriate axis of the simulator that is a fixed percentage of the actual aircraft acceleration for the corresponding axis. The accelerations are only overridden when the simulator reaches the end of its linear or angular travel. An example of this may be seen in the succession of postwar flight simulators, where motion is limited to the three angular degrees of freedom. In these systems, roll and pitch displacements were limited to only a fraction of their values in the actual aircraft, although the actual values were shown on the simulator instruments. This was necessitated because, while it was necessary to give the pilot an angular motion cue for roll rotation when entering a turn, in the actual aircraft, once the turn rate is established, the total specific force vector acting on the pilot returns to the plane of symmetry of the aircraft. Such would not be the case in the simulator, since any roll angle produces side force on the pilot, as simulator linear accelerations are not available. As a result, the motion cue delivered to the pilot is a compromise, because:

a. The magnitude of the angular acceleration cue is diminished

b. There is a steady state side force component in a steady turn which is unrealistic

c. The magnitude of the total specific force cue is reduced.

Despite the shortcomings of the proportional washout technique, angular three degree of freedom motion bases have been quite successful in instrument flight training applications. In instrument flight training, the primary emphasis during the preliminary phases of instruction is on teaching the student to ignore the available motion cues when flying the simulator by reference to instruments. In such cases, exactly matching the actual motion cue seems to be of secondary importance, and instrument training received in these simulators seems to transfer fairly well to the actual situation.

"Onset" or "exponential" washout

As air carriers and the military developed a requirement for flight simulators to maintain pilot proficiency in aircraft which were too expensive to fly and difficult to maintain, more sophisticated techniques were developed. Fortunately however, while linear motion had to be added along several axes to achieve a reasonable degree of fidelity, the flight characteristics of some of the vehicles, such as large transport aircraft, made the problem easier, since sustained accelerations did not occur often. To date, six degree of freedom simulators have been built only for research purposes, and for training with newer aircraft. Six legged "synergistic motion systems are now in wide use. In the design of all these simulations, however, a major problem has been in dealing with the linear cues.

Proportional washout is clearly unsuitable for simulations involving linear motion. Flight maneuvers performed in one direction only may produce unacceptable displacement stand-offs from the center of its linear travel. An approach often taken is to interpose washout simulator dynamics of the form:

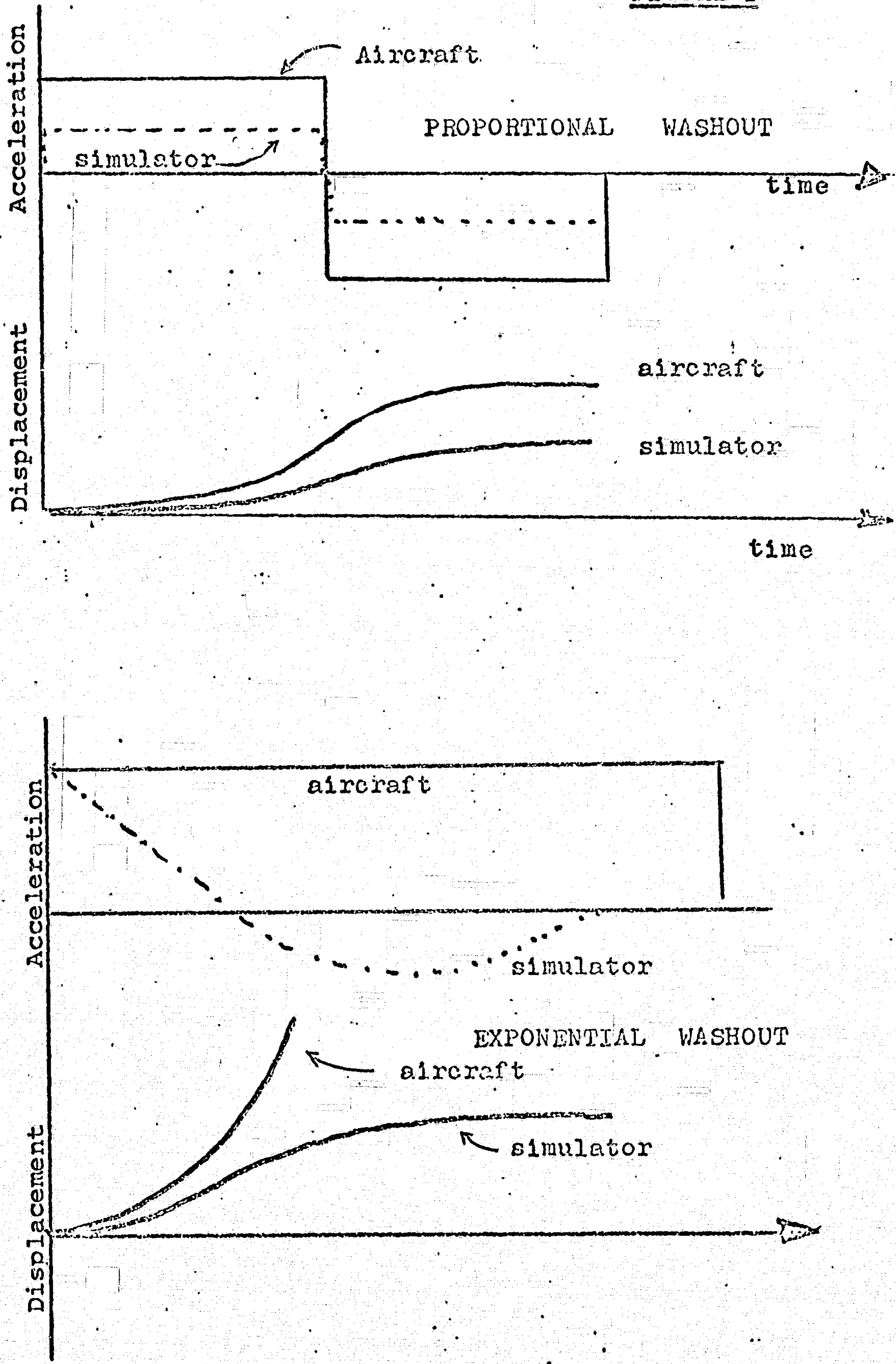
$$a_{simulator}/a_{aircraft} = s^2\omega_n^2/(s^2 + 2\zeta\omega_n s + \omega_n^2)$$

These dynamics effectively modulate the amplitude of the simulators linear travel at frequencies below ω_n, leaving the higher frequencies relatively undisturbed. These dynamics have the advantage that while the initial acceleration cue is exactly matched (as is its rate of onset), the final value of simulator position in response to any finite acceleration input is finite (see Figure 1).

Often the feedback gains which produce these second order dynamics have been chosen so that the system is overdamped, and the commanded response a sum of exponentials, but Hayden (1970) points out that a choice of $\zeta = 0.707$ is actually more appropriate. This results in simulator dynamics whose phase angle varies linearly with frequency for long period accelerations, with the net result that the form of the simulator acceleration follows that of the aircraft, though diminished in amplitude, and leading in phase. Hayden points out, however, that choice of the break frequency for each axis is more difficult. He proposes as a best approach a procedure involving analytic prediction of aircraft accelerations for the particular case in hand, and choice of break frequency for each axis so that the greatest simulator to aircraft ratio is achieved for the least amount of base travel. Hayden advocates second order dynamics and this design procedure for angular motion cue generation as well. Summarizing his recommendations:

Acceleration Cues Required to produce a
Constant Simulator Displacement Using
Conventional Washout Techniques

FIGURE 1



Axis	Break Frequency
X	> 0.5
Y	0.3
Z	0.5
ψ(yaw)	0.3
ϕ(roll)	0.3 (1.5 - 3.0 in fighter types)
θ(pitch)	0.5

Programmed techniques

While the second order dynamics of "onset" washout offer the distinct advantage that they are easy to implement on an analog device, they have several obvious drawbacks. These dynamics do not directly limit displacement, velocity or acceleration, and unless the pilot flies exactly the planned maneuvers, occasionally, the system limits will be reached. More importantly, the accelerations occurring during the washout phase are often needlessly (in terms of available travel) above the threshold of sensation to linear acceleration and negative motion cues result. A more efficient technique being investigated by the Canadian Aircraft Establishment (1969) is to use a digital computer to washout linear excursions by using predetermined accelerations and rates of change of acceleration during the washout phase. The approach makes better use of available linear travel in that lower washout accelerations normally result than is the case with a simple second order "onset" technique. This is because the computer continually predicts the velocity and displacement of the cab using the low washout accelerations, and in the event that the physical limits of the simulation system would be exceeded, higher values of washout accelerations are substituded before the limits are reached. This results in a reduction of the number of "negative cues" which the pilot receives, as compared with the "onset" approach.

Motion Cues and Vestibular Models

One persistent difficulty with existing techniques for establishing "optimal" washout techniques for a given aircraft/ simulator combination has been that it is difficult to calculate the degree of perceptual fidelity associated with each simulated maneuver. Since information on the pilot's subjective responses to simulated maneuvers is difficult to obtain in the quantitative sense, the approach generally taken in the optimization of simulator designs to date has been to simply compare the magnitude and phase relationship between simulator and aircraft accelerations. The optimum simulation in terms of perceptual fidelity, it has been assumed, is one with 0 db acceleration gain and zero phase lag. Analytical techniques such as Hayden's result in optimal washout simulations under this definition, given the constraint of the form of the washout dynamics chosen, and the physical limitations of the simulator. Phase relationships needed only to be in a band which is vaguely termed "acceptable".

The availability of models for the vestibular modality would enable one to carry the analysis one step further, and consider washout techniques developed to optimize the fidelity of subjective response directly.

VESTIBULAR PERCEPTION

The problem of modelling human perception of supra-threshold stimuli was divided into three parts. The first part consisted of modelling the afferent information available from the sensors and coupling this with a model of central processing suitable for noninteracting stimuli. The results of this effort were threefold:

1. Predictions could be made for the dynamic response to simple noninteracting stimuli
2. The best estimate of the head's rotational rate based upon information from the semi-circular canals and the best estimate of the directional magnitude of the specific force vector based upon otolith information was available for further integration for the case of interacting stimuli
3. A consistent mathematical framework had been developed for the central processor which incorporated a model of the _a priori_ information about the stimulus, a model of the sensory dynamics and a model of the variations in afferent firing, which

PRECEDING PAGE BLANK NOT FILMED.

indicated that at least in the use of otolith information, the central processor made a significant contribution to the total dynamic response.

The second part of this investigation centered on the perception of state orientation (no canal information) with respect to a constant specific force field. A thorough review of the illusions of static orientation indicated that they were consistent with a simple vector transformation which could be associated with differences in the processing of signals arising from stimuli in and stimuli perpendicular to the "utricular plane". Based on these observations, a model was developed which incorporated this difference in processing and which was capable of predicting the direction and magnitude of the experimentally determined illusions of orientation. Finally, it was observed that the alteration of saccular information required by the model was similar to the nonlinear response to static tilts seen in otolith afferents in the squirrel monkey. This similarity suggests that the mechanisms which give rise to these illusions may have at least part of its origin in the peripheral sensor.

Finally, the problem of integrating information from the semicircular canals and the otoliths for the general class of interacting stimuli was considered. The major difficulty encountered in modelling the perception of dynamic orientation for motions which involve rotations about a horizontal axis was the problem of deriving the transformation of canal and information which produces a perception of orientation with respect to the vertical. Once such a transformation is derived predictions for the other perceptual outputs (rotation rates, accelerations, etc) follow in a relatively straightforward manner. The model for the perception of the vertical relies primarily on the otolith sensors for low frequency (below 0.5 rad/sec) changes in orientation and on canal information which is confirmed by changes in the direction of the perceived specific force sensed by the otoliths for more rapid changes (greater than 0.5 rad/sec) in orientation. This spectral division of responsibility is quite reasonable in light of the frequency characteristics of the sensors and the problems associated with any attempt to differentiate between translational accelerations and a change in orientation with respect to the vertical. The response of the model to small variations in tilt angle with respect to the vertical in a 1 g environment indicate that under these conditions the perception of tilt should be essentially correct for frequencies from zero to about 3 radians per second. Accuracy in this region of operation should be expected since this is the region in which most head movements take place in daily life.

The model's usefulness in predicting, without detailed simulation, the qualitative nature of the response to be expected from relatively simple interacting stimuli was demonstrated with several examples. Furthermore, the accuracy of the model's predictions were shown for several stimuli for which data was available. The results of the simulations carried out indicate that the model in its present form should be very useful in predicting the perceptual response to a wide variety of stimuli which up until now could not be confidently predicted.

Much of this work is reported in the doctoral thesis of Charles C. Ormsby. This thesis (which also appeared as a NASA Contractor's Report) is abstracted below.

MODEL OF HUMAN DYNAMIC ORIENTATION

Charles C. Ormsby

Ph.D. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, January 1974; and also NASA CR-132537, 1975.

ABSTRACT

The dynamics associated with the perception of orientation were modelled for near threshold and suprathreshold vestibular stimuli. A model of the information available at the peripheral sensors which was consistent with the available neurophysiological data was developed and served as the basis for the models of the perceptual responses. As a preliminary assumption, the central processor was assumed to utilize the information from the peripheral sensors in an optimal (minimum mean square error) manner to produce the perceptual estimates of dynamic orientation. This assumption, coupled with the models of sensory information, determined the form of the model for the central processor. Comparison of model responses with data from psychophysical experiments indicated that while little or no central processing may be occurring for simple suprathreshold canal stimulation, a significant portion of the dynamic response to translational accelerations must

be attributed to the central processing of otolith information.

The fundamental mechanism which underlies the phenomenon of vestibular thresholds was studied experimentally by testing the response of subjects to a near threshold stimulus consisting of a velocity step-ramp proportional to the sum of the subject's velocity step and acceleration step thresholds. Experimental results indicated that canal thresholds could be accounted for by a model of central processing consisting only of afferent firing in additive noise with no necessity for peripheral dead zone linearities. Quantitative models of threshold detection were developed which correctly predicted threshold levels (75% correct detection) and response latencies for rotational stimuli. It was found that the same detector could be used to model the threshold responses resulting from translational stimuli.

The illusions of static orientation were studied and it was shown that they were consistent with a simple vector transformation which could be associated with differences in the processing of signals arising from stimuli in and stimuli perpendicular to the 'utricle plane'. A model was developed which incorporated this difference and which was capable of predicting the perception of orientation in an arbitrary static specific force environment.

The problem of integrating information from the semicircular canals and the otoliths to predict the perceptual response to motions which stimulate both organs was studied. A model was developed which was shown to be useful in predicting the perceptual response to multisensory stimuli.

One of the common techniques for use of limited motion flight simulators is the substitution of changes in orientation of the cockpit with respect to gravity for actual linear accelerations which are to be simulated. Another common technique utilizes the development of centripetal acceleration on a centrifuge to simulate vehicle lateral accelerations. In both cases, the success of the technique depends upon the perception of the orientation with respect to the specific force or gravito-inertial reaction force at each instant of time. A host of classical experimental data on the Aubert and Muller phenomenon is of only limited value in predicting the adequacy of step stimulations. In one portion of his thesis, Ormsby examined the quantitative relationship between perception of orientation and the applied specific force and succeeded in developing a relatively simple model which is successful in a wide range of applications in predicting this relationship. This model should prove of considerable value in the static orientation cases to be explored and has already been applied to the currently available simulation data including a simulation of a catapult aircraft launching. A summary of his work was presented by Prof. Young in an invited paper in Cologne, at the Symposium on "Mechanics of Space Orientation and Space Perception Related to Gravity". A summary appeared in a special issue of Fortschritte fur Zoologie in 1976. The abstract is presented below.

THE PERCEPTION OF STATIC ORIENTATION IN A CONSTANT GRAVITO-INERTIAL ENVIRONMENT

C.C. Ormsby and L.R. Young

Fortschritte fur Zoologie 23(1):288-294
1975

ABSTRACT

This paper examines the setting of the apparent vertical (subjective indication of the earth vertical) under quasi-static conditions, in which the effects of body angular accelerations are assumed to have decayed to a negligible level. A thorough review of the illusions of static orientation indicates that they are consistent with a simple vector transformation which can be associated with differences in the processing of signals arising from stimuli in and stimuli perpendicular to the average utricular plane. Based on these observations a model is developed which incorporates this difference in processing and which is capable of predicting the direction and magnitude of the experimentally determined illusions of static orientation (Aubert, Muller and elevator illusions). Finally, it is noted that the alteration of saccular informatin required by the model is similar to the nonlinear response to static tilts observed in the otolith afferents of the squirrel monkey. This similarity suggests that mechanisms which give rise to these illusions may have, at least, part of its origin in the peripheral sensor.

This article, in an expanded form, was also published in Aviation, Space and Environmental Medicine in 1976.

PERCEPTION OF STATIC ORIENTATION IN A CONSTANT GRAVITOINERTIAL ENVIRONMENT

C.C. Ormsby and L.R. Young

Aviation Space and Environmental Medicine
47(2):159-164, 1976.

ABSTRACT

The illusions associated with the perception of static tilt in various specific force environments have been reviewed and then classified in such a way that a simple perceptual model could be developed to account for the experimental data. The fundamental conclusion to be drawn from this model is that these illusions can be accounted for by a simple nonlinear transformation of the information primarily from the saccules.

The experimental work conducted at Langley in 1972 and the theoretical work on the neurophysiological signals associated with semicircular canal stimulation have resulted in a modified view of the angular acceleration threshold phenomenon. As commonly used in washout circuits, the threshold is viewed as an absolute level of angular acceleration or of angular velocity which must not be exceeded during the return of the simulator to its null position. In fact, as Ormsby pointed out, the probability of perception of linear motion cannot be viewed simply as an instantaneous one in terms of the entire stimulus. This sets other limits on allowable acceleration during washout for maintaining simulator fidelity. The results of this analysis are presented in the following paper, which has not been published.

THE FUNDAMENTAL THRESHOLD UNDERLYING ROTATIONAL THRESHOLD

C.C. Ormsby

ABSTRACT

This paper describes an experiment which was undertaken to determine the fundamental mechanism underlying vestibular thresholds. Two fundamentally different mechanisms were considered. The first hypothesis, called the 'simple threshold model' consisted of a dead zone nonlinearity associated with the peripheral sensor which blocked the response from any stimulus which was not sufficiently large. The second hypothesis considered was that the sensory threshold arose only because the stimulus generated afferent response was masked by the variations in afferent firing rate which are independent of the stimulus. These hypotheses could be distinguished experimentally by determining the threshold level (75% correct detection) associated with a stimulus which is proportional to the sum of a subject's velocity step and acceleration step thresholds. Such an experiment was carried out and the results clearly demonstrate that the second hypothesis, designated as the 'signal in noise' model, was to be preferred over the simple threshold model. Furthermore, the data indicated that the phenomenon of vestibular thresholds could be accounted for on the basis of a model of central processing of vestibular information consisting only of an optimal processing of afferent firing rates in additive noise with no necessity for peripheral dead zone nonlinearities.

The paper concludes by describing a quantitative model for the perception of near threshold rotational stimuli which is consistent with the signal in noise model. The results of Monte Carlo simulations are given which indicate that the model is adequate for predicting both the stimulus magnitudes at threshold and assoicated probabilities of detection as a function of time for arbitrary near threshold stimuli (rotational).

Finally, a summary of our model for the integration of semicircular canal and otolith cues was accepted for publication in the journal Mathematical Biosciences, and is in press (1977).

INTEGRATION OF SEMICRICULAR CANAL AND OTOLITH INFORMATION FOR MULTISENSORY ORIENTATION STIMULI

C.C. Ormsby and L.R. Young

Mathematical Biosciences, in press, 1977

ABSTRACT

This paper presents a model for the perception of dynamic orientation resulting from stimuli which involve both the otoliths and the semicircular canals. The model was applied to several multisensory stimuli and its predictions evaluated. In all cases, the model predictions were in substantial agreement with the known illusions or with the relevant experimental data.

INTEGRATION OF SEVERAL SENSORY INPUTS IN SIMULATION

A major portion of our research has been focussed on the problems involved in modelling the integration of the different modalities to give an overall sensation of motion. A particular area of interest has been in the phenomena of self-rotation and self-translation (circularvection (CV) and linearvection (LV)) in which a large moving visual scene is perceived as stationary by a subject who consequently experiences a corresponding strong sensation that he is moving in the opposite direction. By studying the phenomena for rotation in pitch and roll in collaboration with Drs. Dichgans, Brandt and Held, we have been able to document how inherently conflicting visual and otolithic information is resolved into a sensation of tilt. We have adapted our three degree of freedom Link GAT-1 trainer as a general purpose moving base simulator and have arranged the projection of patterns of moving stripes about any one axis on several windows in order to investigate the combined effects of visual-vestibular stimulation about a single axis. In an article by Dichgans, Held, Young and Brandt, which appeared in Science, it is reported that when an observer views a wide angled display rotating around his line of sight, he both feels his body tilted and sees a vertical straight edge tilted opposite to the moving stimulus. Displacement of the perceived vertical increases with stimulus speed to reach a maximum (averaging 15 degrees) at 30 degrees/second. The Science article is abstracted below.

MOVING VISUAL SCENES INFLUENCE THE APPARENT DIRECTION OF GRAVITY

J. Dichgans, R. Held, L. Young, T. Brandt

Science 178:1217-1219, 1972

ABSTRACT

The observer's visible surround influences his orientation and localization in space. Most investigators of these phenomena have been concerned with the effects of tilted scenes on the apparent vertical. They have interpreted their findings as the outcome of a conflict between spatial coordinates given on one hand by the dominant orientation of visible contours and, on the other hand, by the direction of gravity.

We now report that a visual surround rotating around the observer's line of sight induces tilts of the apparent upright ranging up to 40 degrees. The moving visual displays entailed no cues to visual orientation that could conflict with those of gravity, consequently the motion as such caused tilt. Shortly after initiation of the motion, the observer felt his body rolled laterally and saw a stationary edge turned in the direction opposite to the movement of the display. Accordingly, the effect of the moving surround was equivalent to displacing the direction of gravity in the direction of rotation. It can be accounted for by assuming that neurally encoded signals of visual motion modulate signals from the graviceptors at some level of the nervous system, an interpretation which is consistent with neurophysiological results.

Young, Dichgans, Murphy and Brandt have studied the interaction of semicircular canal stimulation and visual stimulation in more detail using the modified GAT-1 device. Otolithic information conflicts were avoided by stimulating the subject visually to the left or right, while rotating him about an earth vertical axis. A paper, abstracted here, reports the main results of these experiments.

INTERACTION OF OPTOKINETIC AND VESTIBULAR STIMULI IN MOTION PERCEPTION

L.R. Young, J. Dichgans,
R. Murphy, Th. Brandt

Acta Otolaryngologica 76:24-31, 1973

ABSTRACT

The sensation of self rotation (circularvection) was produced by rotation of a stripe pattern to the left or right at constant angular velocity. During circularvection, subjects were randomly accelerated in constant acceleration steps. The major experimental findings were:

1. Thresholds for detection of angular acceleration are raised when this acceleration is opposite to the direction of circularvection. Times to detect these accelerations are similarly increased.

2. Magnitude estimations of angular velocity show the effect of visually induced offset which is increased slightly by vestibular responses in the same direction and decreased markedly when the vestibular responses are in the direction opposite to self-rotation.

> 3. Many of the effects of angular acceleration on perceived velocity are accurately predicted by the Laboratory's model of the semicircular canals. However, an important nonlinear interaction exists whereby rapidly occurring conflicts between visual and vestibular sensation, especially those involving direction disparities, result in a precipitous decline in circularvection and temporary domination by the vestibular response.

During his sabbatical year in Zurich, Professor Young continued experiments on circularvection using an optokinetic drum. He studied the effects of repeated stimuli in the same direction on response habituation, and also the effect of the orientation of the head with respect to gravity. Preliminary results indicated that for pitch stimuli, where the subject is not directly observing the visual axis of rotation, the resulting sensation may be one of linear translation in addition to or instead of pitch vection.

We began to assemble a hierarchical model for the treatment of simultaneous vestibular and visual stimuli. More recent efforts have been focussed on extending the multi-axis visual stimulation situation, studying simultaneous pitch, roll and yaw pattern motion. Unfortunately, this could not be accomplished in the GAT-1 due to the inherent limitations of the system. Nor could it be done at any existing facility at MIT or Freiburg. Construction of such a display was briefly contemplated, however, it was found that the computer controlled projection system of the NASA

Langley Dual Maneuvering Sphere was suitable for this purpose and this facility was made available to us through the efforts of our Technical Monitor, Mr. Ralph Stone.

The first series of experiments were carried out in July of 1972 and were possible only because of the extraordinary technical assistance given by the personnel of LRC, especially those invovled in the operation of the DMS and computer programming.

All experiments were carried out in a Dual Maneuvering Sphere. A set of blank projector globes were prepared by randomly afixing irregularly shaped pieces of black tape, approximately 3/4" on a side, on a pair of clear hemispheres. The black/white ratio was on the order of 25%. The angle subtended by each of the black areas was approximately 3 to 4 degrees. The contrast achieved with this sphere was noticeably superior to that used in the earlier pilot experiments, but was still not as sharp as those used for circularvection experiments at MIT and Freiburg.

The entire test procedure was run under computer control. During each of the tests, a minimum of four subjects participated. One was seated in the cockpit and the others remained standing on the platform below and to the side of the cockpit. The subject in the cockpit indicated his perceived pitch angle, roll angle, and yaw rate using the control stick and rudder pedals. Pitch and roll angles were displayed to him on the heads-up display and yaw rate was indicated on the rate of climb indicator. In addition, the subject in the cockpit and those on the platform continuously recorded their sensations of pitch, roll and yaw rates and steady tilt angle offsets on tape recorders. Synchronization marks for timing were included to allow later analysis of the taped comments. As will be seen in the discussion of the specific experiments, the results were qualitatively the same for the subjects in the cockpit and those on the platform. The major quantitative difference was a stronger sensation of circularvection, especially in roll and pitch, experienced in the cockpit, compared to that experienced on the platform.

The experiment was documented on an 8 channel chart recorder which indicated the gimbal roll, pitch and yaw rates and roll and pitch Euler angles. It also had three subject indications of perceived roll angle, pitch angle and yaw rate, starting with the calibration of these quantities.

Constant yaw rate-circularvection calibration

The experiments started each day by calibrating the subject's sensation of circularvection. A series of thirty second constant angular yaw rate patterns at different rates were randomly presented. Each subject was asked tp estimate the initial speed of the stripes as well as to note circularvection. Subjects generally showed high accuracy in identification and were never in error by more than one step in the judgement of velocity.

Experiment #1

Experiment #1 consisted of constant roll rate for 40 seconds with a pause of 20 seconds between tests. Clockwise and counterclockwise roll rates of 5, 10, 20, 40, and 60 degrees per second were presented randomly. The resulting steady state displacements of the apparent vertical showed the same pattern for each of the four subjects. In each case, the perceived roll angle increased more or less linearly from a relatively modest value at the slow speeds, up to 20°/sec. Above approximately 20°/sec, roll angle remained constant up to the maximum spped tested (60°/sec).

The magnitude of tilt sensation appeared to be a strong function of position in this experiment. Both subjects whose ouputs were recorded while they were in the cockpit and viewing the pattern from the roll axis, experienced far larger sensations of tilt and roll circularvection when they were in the cockpit than when they were observing the same pattern from the platform.

An interesting additional finding during the constant roll rate experiments was a tendency to associate a constant pitching down angle with the roll circularvection. The pitching down sensation appeared to develop as roll circularvection increased. An obvious interpretation of this pitch down sensation is a resolution of the conflict inherent in a sensation of constant rotation about an anterior-posterior axis without the confirming otolithic cue that would be associated with rotation about this axis horizontally in a gravitational field.

Experiment #2

Experiment #2 was similar to #1 with the exception that the constant rotation was in pitch rather than roll. The same general effects of tilt circularvection and constant deviation of the perceived vertical were noted as in the roll experiment. An increase in the amount of perceived pitch with pattern rate was noted. The major differences between the pitch and roll experiments was the marked asymmetry in directions observed for pitch. In almost every case, the sensation of pitching down sensation was stronger than the pitching up sensation. In one extreme, the subject reported 40 to 50° pitching down and no noticeable pitching up.

An explanation for this pitch asymmetry is not readily available. Two possible explanations involve the difference between upward beating optokinetic nystagmus and the possible retinal field placement variation of movement sensors in terms of their sensitivity and directional specificity. Both of these, however, is highly speculative.

The disparity between pitching up and pitching down sensations in relationship to the Coriolis phenomenon has been noted before. These observations were all that the magnitude estimations associated with pitch down sensations resulting from Coriolis stimuli were greater than those for pitch up sensations.

A frequent report during the pattern pitching up stimulus was an additional perception of translation or continuous descending in addition to the pitch rate. The interpretation of the moving visual pattern as a linear descent rather than a constant pitch rate is an additional possibility for resolving the conflict referred to above.

<u>Experiments #3, #4, #5</u>

Experiments #3 (roll), #4 (pitch) and #5 (roll) all involved sinusoids of various frequencies. The perceived peak roll agnle was a function of both stimulus frequency and amplitude and seemed to increase with the peak angular velocity of the pattern, and, for the low frequencies, integrated up to a high tilt angle even at relatively low angular velocities.

Experiment #6

Experiment #6 consisted of a constant yaw rate pattern with superimposed sinusoidal roll rates. The yaw rotation lasted 30 seconds prior to the initiation of the superimposed roll. During this time, the subjects built up a circularvection of 15 to 20°. Within the first cycle of the roll, the roll vection began with the feeling of both continuous roll rate and also deviation from the vertical in the direction of the roll rate. Most subjects indicated a stronger sensation of roll in the direction of the yaw circularvection than in the opposite direction.

The average pitch sensation throughout the experiment was going down as far as 20 or 30° during the roll in the direction of the yaw circularvection and rarely exceeding a pitch angle of 5° up for the opposite roll direction. In general, the roll component was stronger then the pitch component by a factor of 1 to 1 1/2 or more. Generally, the direction of pitch sensation associated with simultaneous yaw and roll was given by the cross product of the roll rate into the yaw rate.

Experiment #7

Experiment 7 was similar to 6. It began with a constant yaw rate, to which, after 30 seconds, was added a sinusoidal pitch rate. When it did occur, the resulting perception of roll was consistent with the findings of experiment 6. The directions were consistent during the first trial and the right hand rule seemed to operate. On the following day, however, with a larger pitch sinusoid, the opposite tendency was noted occasionally. In any event the roll circularvection was very slight during the runs on the second trial, although the pitch sensations were quite marked.

Experiment 8

Experiment 8 was an attempt to quantify the pseudo-Coriolis phenomenon induced by making an active head movement about an axis orthogonal to that of circularvection. Yaw circularvection was induced by a sustained constant rotation of the pattern in the yaw axis. After about 30 seonds, subjects were asked to make a head movement to the right shoulder first and then to the left shoulder and to report on any sensations of pitching. In a later repetition of these experiments, subjects were asked to move their heads forwards and then back and report any sensation of roll. The results of these experiments were inconclusive. Many subjects did experience a sensation of pitch with rolling head movements. The directions are not as consistent as we might have expected, however.

Two papers were written on the knowledge gained from these experiments. One was presented at the Tenth Annual Conference on Manual Control.

INFLUENCE OF HEAD POSITION ON VISUALLY INDUCED MOTION EFFECTS IN THREE AXES OF ROTATION

L.R. Young and C.M. Oman

Proceedings of the Tenth Annual Conference on Manual Control, pp. 319-340, Wright Patterson Air Force Base, Ohio, April 1974.

ABSTRACT

The sensation of self-motion based on rotating visual fields was investigated in pitch, roll and yaw axes using large visual field motion in a high performance aircraft simulator. The development of roll tilt angle and steady state yaw velocity, for constant speed roll and yaw stimuli respectively, was consistent with earlier reports. Steady pitch offset was also discovered, increasing with pitching field velocity up to 40°/sec. The induced pitch was markedly stronger in the forward than in the backward sense.

Pitch and roll effects were found to depend strongly on head position. The tilt magnitudes were increased for the head 90 deg to the side and for the head inverted, but decreased for the head pitched 25 deg forward. These

results support a hypothesis that the visually induced tilt is limited by conflict with the otolith information which fails to confirm this tilt. They are consistent with the observations by other investigators that uncertainty in orientation based on graviceptor cue increases as the major utricular plane is tilted out of the horizontal.

Peripheral field stimulation was shown to be the adequate stimulus for the self-motion rotation about all three axes. The upper visual field was fcund to be dominant in the generation of pitch sensation. Any moving scene containing sufficient moving visual borders, including a realistic picture of the earth (but not the blank sky), was able to generate the self-motion.

The other paper on the subject was published in Aviation Space and Environmental Medicine.

INFLUENCE OF HEAD ORIENTATION ON VISUALLY INDUCED PITCH AND ROLL SENSATIONS

L.R. Young, C.M. Oman and J.M. Dichgan

Aviation Space and Environmental Medicine 46:264-268, 1975.

ABSTRACT

Observers viewing rotating scenes in their periphery frequently experience self-motion in the opposite direction. A full field (360°) flight simulator projection system was used to investigate the sensations resulting from pitch, roll and yaw stimuli at various head orientations. Steady yaw rate (circularvection) and development of a constant roll tilt angle, for the head erect and constant velocity yaw and roll stimuli, confimed previous reports. Pitch stimuli were also found to produce a sen-

sation of tilting to steady pitch angle, which was much stronger for pitch forward than backward. Pitch and roll effects were strongly dependent on head position, increasing for the head rolled 90° to the side or inverted, and decreasing for the head pitched 25° forward. These results support a hypothesis that visually induced tilt is limited by conflict with otolith information.

Our continuing emphasis on the effects of motion perception with moving visual fields led us naturally to the question of whether such repeated stimuli would sensitize or inhibit the response to a true body acceleration. To the extent that our hypothesis of the visually induced motion sense mimics a true vestibular stimulus is correct, we would expect to see habituation both of subjective sensation and of nystagmus transferred from the visual to the vestibular case. Such a finding would have considerable significance for the operational use of visually induced motion sense in flight simulation. A series of experiments on normal subjects was run in Zurich with positive results. A paper was published in Acta Otolaryngologica in 1974 which summarizes this investigation.

SELECTIVE HABITUATION OF VESTIBULAR NYSTAGMUS

L.R. Young and V.S. Henn

Acta Otolaryngologica 77:159, 1974

ABSTRACT

The effect on vestibular nystagmus of repeated exposure to unidirectional rotating visual field was studied in ten subjects. A visually induced sensation of self-rotation (circularvection, CV) about a vertical axis was repeated 30 times for each subject. Post-stimulation rotation with eyes closed showed a significant 40% reduction in vestibular nystagmus intensity in the direction of the circularvection, measured by cumulative displacement and no significant reduction in the opposite direction.

To tie in these results with our neurophysiological studies on monkeys (described below), we tested nystagmus of monkeys before and after OKN stimulation in a similar manner with similar results. The findings were reported in Acta Otolaryngologica and are summarized below.

SELECTIVE HABITUATION OF VESTIBULAR NYSTAGMUS BY VISUAL STIMULATION IN THE MONKEY

L.R. Young and V.S. Henn

Acta Otolaryngologica 82:156-171,1976.

ABSTRACT

Four monkeys were exposed to a series of unidirectional rotating visual fields, of the type known to produce circularvection in man. As in the human case, the vestibulo-ocular reflex for rotation in the direction of the optokinetic nystagmus and circularvection during the preceding visual stimulation - was markedly decreased following that visual stimulation, whereas that in the opposite direction was increased. This finding corresponds to the results of nystagmus and psychophysical circularvection studies on man. It suggests a link between single unit studies performed under identical conditions in monkey and psychophysical investigations.

Neurophysiological studies on the mechanism of visual vestibular interaction

In an effort to gain insight into the basic physiological results we have been measuring, on sensations of movement based upon moving visual fields and their interaction with true vestibular stimuli, Young began work on single unit recordings in primates during his sabbatical year in Zurich. The initial results of this collaborative work with Dr. Henn, a neurologist at the Kantonsspital in Zurich, were extremely encouraging and led to the discovery of units in the vestibular nuclei that respond to moving visual fields and to the motion of the animal in much the same way that the psychophysical responses of subjective sensation in humans respond to these stimuli. An abstract of this work was presented at the German Physiological Society in September 1973 and a paper was published in Brain Research in 1974.

VESTIBULAR NUCLEI IN ALERT MONKEY ARE ALSO INFLUENCED BY MOVING VISUAL FIELDS

V. Henn, L.R. Young, C. Finley

Brain Research 71:144 (1974)

ABSTRACT

The sensation of self rotation about an earth vertical axis can be induced even without vestibular stimulation by a moving visual

surround viewed peripherally. This sensation, known as circularvection, is indistinguishable from true body motion, suggesting neuronal convergence of vestibular afferents and visual pathways on certain neurons. Such units should reflect the highly nonlinear interaction of visual and vestibular stimuli in generating the sensation of body motion. In a series of experiments on alert monkeys, units in the vestibular nuclei were explored using various combinations of true body rotation and rotating visual fields. This report will be confined to units responding unequivocally to vestibular stimulation. All such units proved to respond also to moving visual fields, independent of the strength of the optokinetic or vestibular nystagmus.

Visual influence on the firing rate of vestibular units has been reported in the vestibular nerve of the goldfish and in the vestibular nucleus of rabbits and goldfish. The converse, vestibular influence on visual systems, is also known. In addition to the large psychophysical literature, especially on head orientation with respect to the vertical, there have been recordings in the visual cortex showing the influence of vestibular stimulation on single units. Our aim was to investigate whether the activity of vestibular units could be modified by pure visual stimuli of the type which would induce circularvection in humans. The approach was to identify vestibular units by their activation on ipsilateral or contralateral accelerations about a vertical axis. Such units were then tested under three stimulus conditions: pure vestibular, pure visual, and combined visual vestibular.

In connection with the research discussed above, we had the opportunity to investigate semicircular canal/otolith interaction in the development of nystagmus in monkeys through the use of so-called "barbecue-spit" stimulation and the more general off-vertical stimulation. The appearance of steady state sinusoidally modulated nystagmus when the rotation was about an axis only a few degrees off-vertical was documented and will be useful for further studies on the nature of this nystagmus. The significance of this study to flight simulator design involves the perception of rotation as well as the nystagmus that results from exposure to a rotating linear acceleration vector, such as in counterrotation at the end of a centrifuge arm. This material was also presented by L.R. Young at the Symposium on the Mechanics of Space Orientation and Perception Related to Gravity in Cologne, 1973.

NYSTAGMUS PRODUCED BY PITCH AND YAW ROTATION OF MONKEYS ABOUT NONVERTICAL AXES

L.R. Young and V.S. Henn

Fortschritte fur Zoologie 23:235-246, 1975

ABSTRACT

Nystagmus produced by constant angular velocity rotation about nonvertical axes was studied in the Rhesus monkey. Both horizontal nystagmus resulting from rotation about the longitudinal axis and vertical nystagmus resulting from rotation about the lateral axis of the head were explored as a function of rotation speed and angle of the spin axis. A comparison with human data is presented.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

RELATIONSHIP BETWEEN TILT SENSATION INDUCED BY MOVING VISUAL FIELDS AND THOSE PRODUCED BY ACTUAL BODY TILT

A study was undertaken involving the more complex situation of visual fields which rotate about a vertical axis. Using subjective sensation of tilt rather than vestibular nystagmus as the dependent variable, Tang found significant interaction between the two stimuli. The results were reported in his Master's thesis, and are abstracted below.

INTERACTION BETWEEN VISUALLY INDUCED AND REAL LATERAL TILT

J.T. TANG

M.S. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, February 1974.

ABSTRACT

Other investigators have recently reported that a rolling visual field can induce a sensation of lateral tilt. Two aspects of the interaction between this visually induced tilt and actual body tilt were investigated. In the first series of experiments, four subjects were given a rolling visual stimulus (±36°/second) and small body tilts (±6°) in separate procedures. These responses were then compared to those obtained when the rolling visual field was added to pre-existing tilts. The results showed that, at small tilt angles, the measured steady state response to combined visual and nonvisual stimuli was approximately the sum of the responses to the individual stimuli. However, the time required to reach steady state response to combined stimuli depended on the phase relationship between the individual stimuli.

PRECEDING PAGE BLANK NOT FILMED.

In a second group of experiments, eight subjects were given standardized tests of rolling visual field field (36°/second) or a tilt stimulus (30°) between intervening exposures of 10 minute constant velocity rolling visual display or 30° tilts. Adaptation effects resulting from the exposure were investigated and evaluated by means of statistical analysis. Very significant reduction in response to a rolling visual stimulus after an intervening body tilt exposure was found. In both experiments, Aubert phenomena were observed in response to tilt, and an asymmetry in responses to visual stimuli in different directions was proved significant.

Further studies in this direction were devoted to the relationship between visually induced tilt and the ocular counterrolling associated with the visual stimulus or actual head tilt. A preliminary report was presented at the fifteenth annual meeting of the Psychonomic Society, Inc. in Boston, Massachusetts, November 21-23, 1974.

INTERACTION OF VISUALLY-INDUCED AND LABYRINTHINE-SENSED POSTURAL TILT

J. T. Tang, R. Held, L. R. Young

ABSTRACT

Sensed roll movement of the body can be produced either by real tilt or by large rotating visual fields. Settings to visual vertical and extent of counterrolling eye movements were measured. Results show that real tilt constrains and directionally biasses visually-induced tilt, although the latter mimics most of the effects of real tilt.

LINEARVECTION STUDIES

Previous observations in the Link GAT-1 trainer showed that linearvection could be developed in horizontal and vertical axes and precedence in the literature was found as far back as Mach in the 1870's. Two parallel research efforts were launched using equipment having different capabilities. At MIT, the GAT-1 was modified to permit investigation of fore and aft motion sensation based on moving visual stripes on the side windows and its interaction with pitch stimuli. In Paris, in a collaborative effort between L. Young and A. Berthoz at the Laboratoire de Physiologie du Travail, a limited motion four-wheel cart was developed. It carried with it a moving film and mirror system which generated translating visual scenes on side windows and through an overhead view. In general, linearvection seems to follow the same interaction laws as for circularvection. Confirming direction cues result in the adoption of the linearvection sensation of sustained constant velocity; opposing direction cues lead to a transient acceptance of the vestibular response.

Interactions between fore and aft linear acceleration and true body pitch effects seems to be second order, based principally upon the asymmetry in the visually induced pitch associated with motions in the upper visual field. Two papers were prepared based upon the portion of the work performed in Paris. One preliminary paper describing these results appeared in Compte Rendu of the Academy of Science. The other paper was presented at the European Brain and Behavior Society Workshop in Pavia, Italy in April 1974.

ROLE DE LA VISION PERIPHERIQUE ET INTERACTIONS VISUOVESTIBULAIRES DANS LA PERCEPTION EXOCENTRIQUE DU MOUVEMENT LINEARE CHEZ L'HOMME

B. PAVARD, A. BERTHOZ, L. YOUNG

Compte Rendu Acad Sc Paris 278 (Series D) 1605.

ABSTRACT

A quantitative investigation of linear self motion (linearvection) induced by moving visual fields was undertaken. The wellknown illusion of self-displacement induced by the motion of a neighboring train was studied in an appartus which projected the image of moving visual fields to two side windows and an overhead screen. The subjects, viewing the forward-backward uniform field motion peripherally, were seated on a cart which could also be accelerated along the anterior posterior axis. Field and cart velocity were separately controlled by a computer to be varied independently or together, in confirming or conflicting directions. Separate influences of visually induced and vestibularly induced motion were calculated. The interaction between simultaneously applied body acceleration and visual field motion revealed a pattern of steady state subjective velocity dominated by linearvection, with transient vestibular dominance associated with conflicting visual-vestibular interactions. Similarity to the rotary (circularvection) situation is discussed.

A more recent paper on the results was published in Experimental Brain Research.

PERCEPTION OF LINEAR HORIZONTAL SELF MOTION INDUCED BY PERIPHERAL VISION (LINEARVECTION): BASIC CHARACTERISTICS AND VISUAL VESTIBULAR INTERACTIONS

A. BERTHOZ, B. PAVARD, L. YOUNG

Experimental Erain Research 23:471-489, 1975

ABSTRACT

The basic characteristics of the sensation of linear horizontal motion have been studied. Objective linear motion was induced by means of a moving cart. Visually induced linear motion perception (linearvection) was obtained by projection of moving images at the periphery of the visual field. Image velocity and luminance thresholds for the appearance of linearvection have been measured and are in the range of those for image motion detection (without sensation of self motion) by the visual system. Latencies of onset are around 1 sec and short term adaptation has been shown. Thy dynamic range of the visual analyser as judged by frequency analysis is lower than for the vestibular analyser. Conflicting situations in which visual cues contradict vestibular and other proprioceptive cues show, in the case of linearvection a dominance of vision which supports the idea of an essential although not independent role of vision in self motion perception.

In the course of the literature search, we were very impressed by the depth shown by the research of Ernst Mach and Volker Henn and Laurence Young prepared a paper detailing Mach's contributions to the field.

ERNST MACH ON THE VESTIBULAR ORGANS 100 YEARS AGO

VOLKER HENN & L.R. YOUNG

Oto Rhino-Laryngoligica 37:138-148, 1975.

ABSTRACT

Ernst Mach (1838-1916) performed pioneering research on vestibular function 100 years ago. His experiments were mainly psychophysical and included measurements of threshold and study of the vestibular visual interaction. Contrary to general belief, he concluded that the adequate stimulus for the semicircular canals must be pressure. He presented evidence against the sustained endolymph flow theory of Breuer (1974) and Crum Brown (1874), with which he is frequently associated. Excerpts from his publications are given and their relevance to current research is discussed.

Additional work on the response to linearvection is summarized in the master's thesis of Mr. William Chu.

DYNAMIC RESPONSE OF HUMAN LINEARVECTION

William H.N. Chu

M.S. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 1975.

ABSTRACT

The function of human visually induced sensation of linear motion (linearvection) was examined. The experiments performed were mainly designed to investigate the frequency response of the human linearvection mechanism. It was shown that both the gain and phase exhibited steady decrease for increasing frequency. Asymmetry in response was also studied. It was shown that visually induced downward moving sensation was stronger than the sensation of upward motion. There also seemed to be a stronger backward moving sensation than a the forward one. The break frequency was found to be approximately 0.1 Hz.

APPLICATION OF THE VESTIBULAR MODEL FOR PERCEPTION OF ORIENTATION BASED ON MOTION CUES: OPTIMUM SIMULATOR MOTION CONTROLS

Application of the Ormsby vestibular model to motion requirements for a coordinated turn in the LINK trainer

Modern aircraft simulators often have multi-degree of freedom motion capabilities, but compared to an aircraft are severely restricted by position, velocity, and acceleration limits. A strategy must be devised for attenuating or "washing out" the vehicle motions so that they fall within the simulator constraints. The task, then, is to duplicate or approximate the sensations produced by some motion history when only a much more limited motion is available.

The motion parameters available to a person for use in sensing motion are basically specific force and angular acceleration. These quantities can influence the tactile sensors at points of the body in contant with the vehicle, proprioceptive sensors when muscles are stretched or compressed, and the small inertial mechanism in the inner ear known as the vestibular system.

Although physiological thresholds and sensitive frequencies are considered and are used in "tuning" existing washout circuits, the basic attempt is still to minimize error in specific force and angular acceleration presentation. This

PRECEDING PAGE BLANK NOT FILMED.

has been the logical thing to do because these quantities have been the available, measurable parameters most closely related to motion perception. The human biological system, however, is not a perfect transducer of specific force or angular acceleration, and often does not even respond to these vectors in a linear fashion.

A physiological model, providing a reliable estimate of human perception during a given motion history, would be a very promising tool for simulation technology. Human perceptions in the simulator and aircraft could be objectively compared to gauge simulation fidelity, since it is the match up of overall perception that actually defines "realism".

So far, we have only considered the use of real motion to produce the feeling of movement. This feeling, however, is also influenced by the movement of the visual field. It seems that the peripheral visual field is especially important in creating motion sensations, and can also effect the perception of spatial orientation.

Use of visual illusions such as circularvection and linearvection may help create the desired sensations of motion within the simulator.

Analysis of a coordinated turn simulation

We have attempted to simulate a coordinated turn in our three degree of freedom Link GAT-1 trainer using the Ormsby model of human dynamic orientation to predict the non-visually induced sensations of a passenger during the maneuver. The model has been adapted to provide a gauge of simulation fidelity by using a simple, intuitively logical scheme for assigning penalties to incorrect perceptions. An incorrect perception is defined as any difference between the perception in the simulator and the perception in the aircraft. This penalty or cost index analysis is then used to choose a motion profile for the Link that is most like the optimum simulation for a particular turn. For use in the physiological model and experiments, a specific coordinated turn profile was needed. Most convenient for this work is an idealized profile that is as simple as possible while retaining the basic elements that make coordination difficult to simulate. One of the most important things to note about a coordinated turn is the behavior of the specific force vector, which rolls with the cockpit and increases in length. It may deviate slightly from cockpit vertical now and again, but to an observer in the craft it does not indicate cockpit roll angle or roll rate. In a three-degree of freedom device, with only pitch, roll and yaw motion available, it is not possible to create this situation. Even in a multi-degree of freedom simulator, with lateral motion capability, it is not possible to sustain a roll angle very long without allowing the specific force vector to realign with earth vertical. It is this aspect of the turn which should be emphasized in the idealized version to be analyzed with the physiological model.

The basic parameters chosen for the idealized turn are a 30° bank, 85 knot, constant altitude coordinated turn, maintaining airspeed during roll-in and roll-out. This will yield a 7°/sec turn rate, considerably faster than the standard 3°/sec turn. It is, however, by no means unreasonable and the steep bank angle will emphasize the effects of coordination.

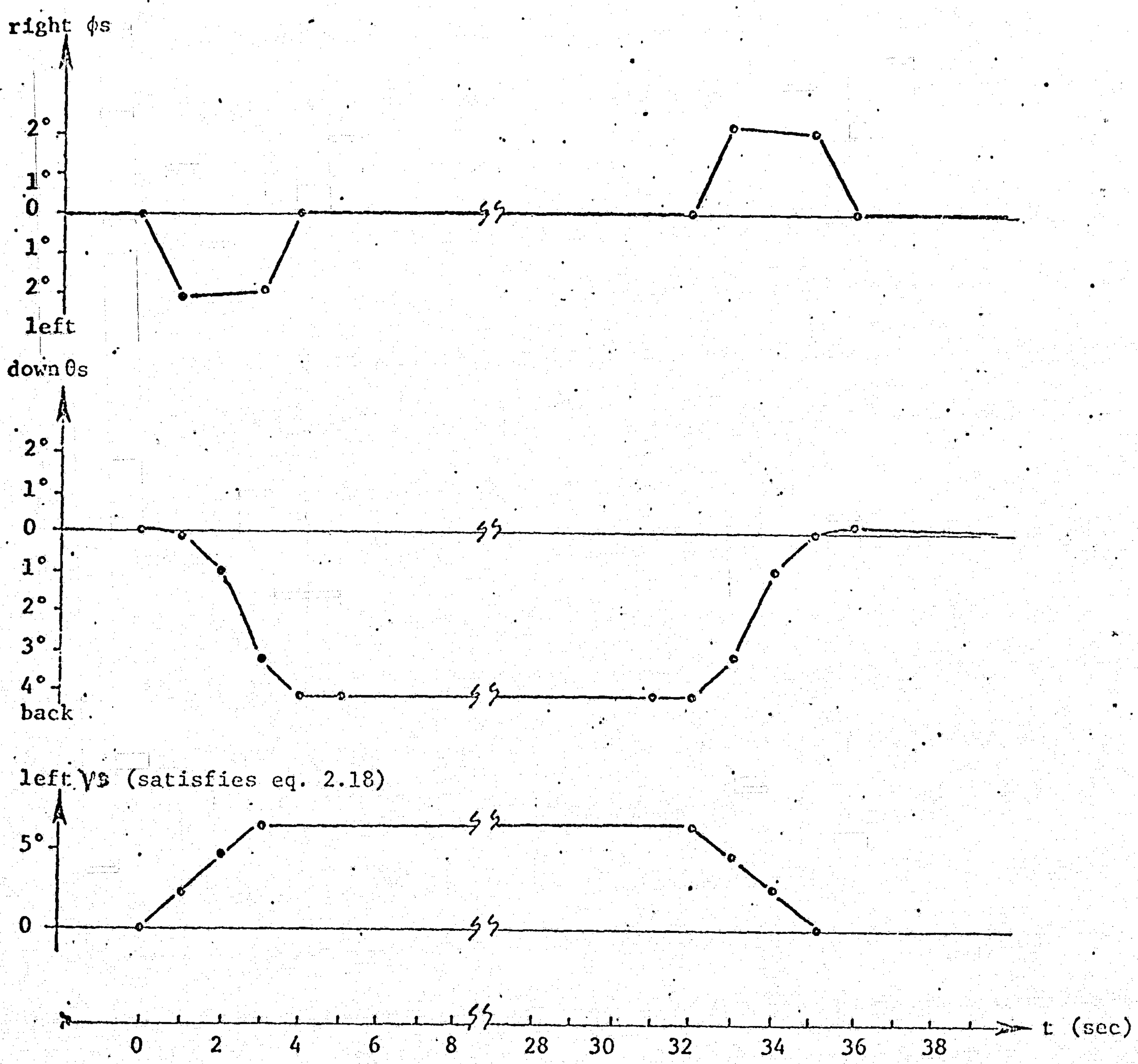
Model predictions for a coordinated turn

In order to apply the Ormsby model to the coordinated turn, let us assume that the aircraft roll axis passes directly through the origin of the occupant's head axis system. Also assume that the vehicle and head axes always remain parallel. The first and most obvious observation is that the canal and otolith responses will be contradictory. Since the specific force remains in the same direction with respect to the subject, the otoliths indicate no change in roll attitude. The canals, on the other hand, are sensitive to the angular velocity produced by roll in.

Although the specific force vector has not been rotated, it has elongated and therefore brings into play the saccule nonlinearity. The expected result is an "elevator illusion" of being tilted backwards. During a coordinated turn, people will feel only a small change in roll attitude compared to their true roll, and a roll rate that may be somewhat more pronounced, and a slight pitch back as specific force increases.

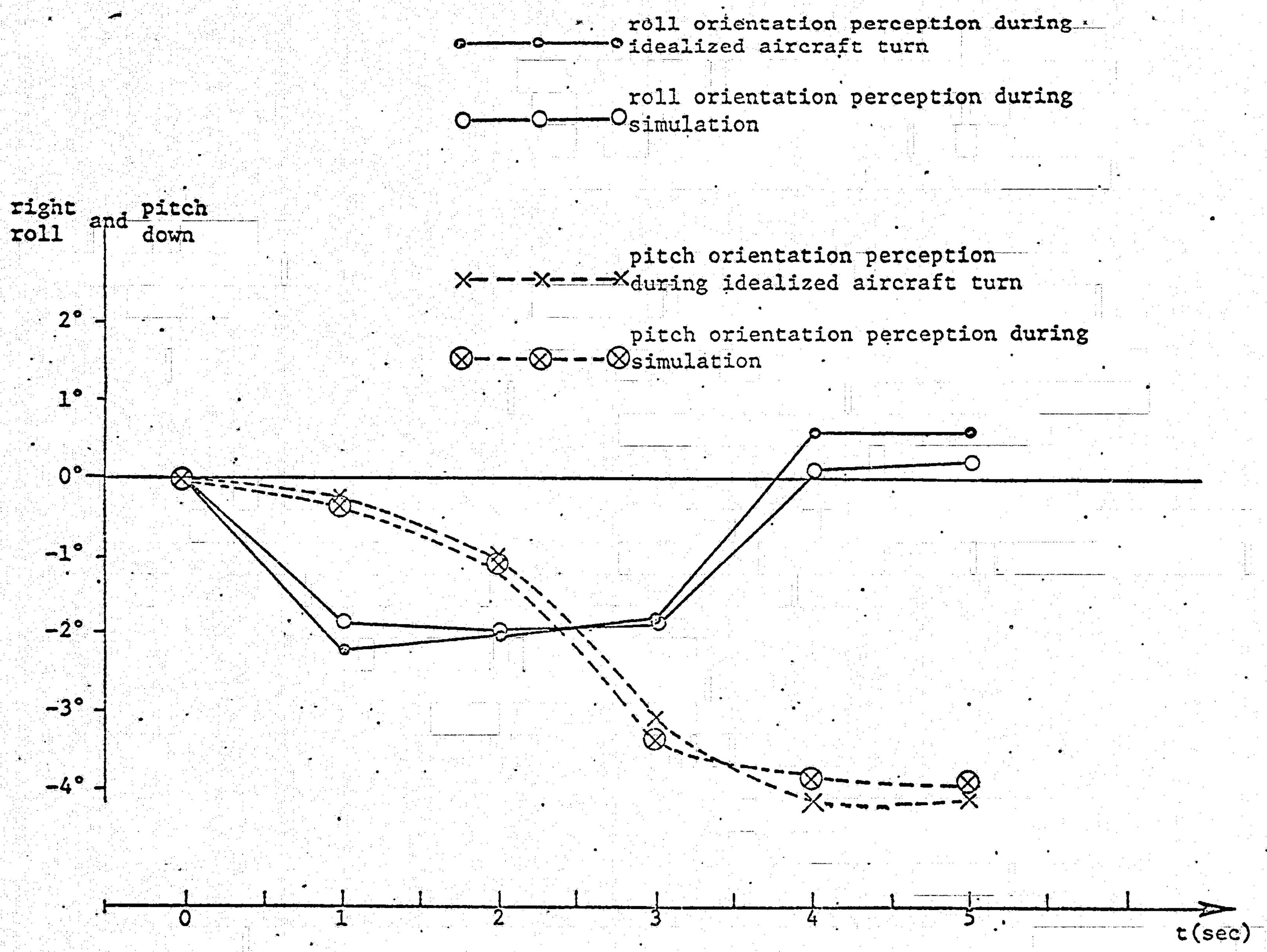
Simulation fidelity analysis

If we assume that the Ormsby model is giving a meaningful estimate of human perceptions, it should be useful in gauging the effectiveness of a given simulation. It makes sense to look at some function of the difference, at each sampling instant, between model outputs for the real motion and the simulator motion. Figure 5 shows a coordinated turn simulation profile for the Link trainer based on our model motion drive logic. Model predictions for motion perception during these profiles are shown in figures 6 and 7. Model predictions for the aircraft turn are superimposed. According to the model, proper attitude perception has been virtually duplicated, although there has been some expense to the pitch and roll



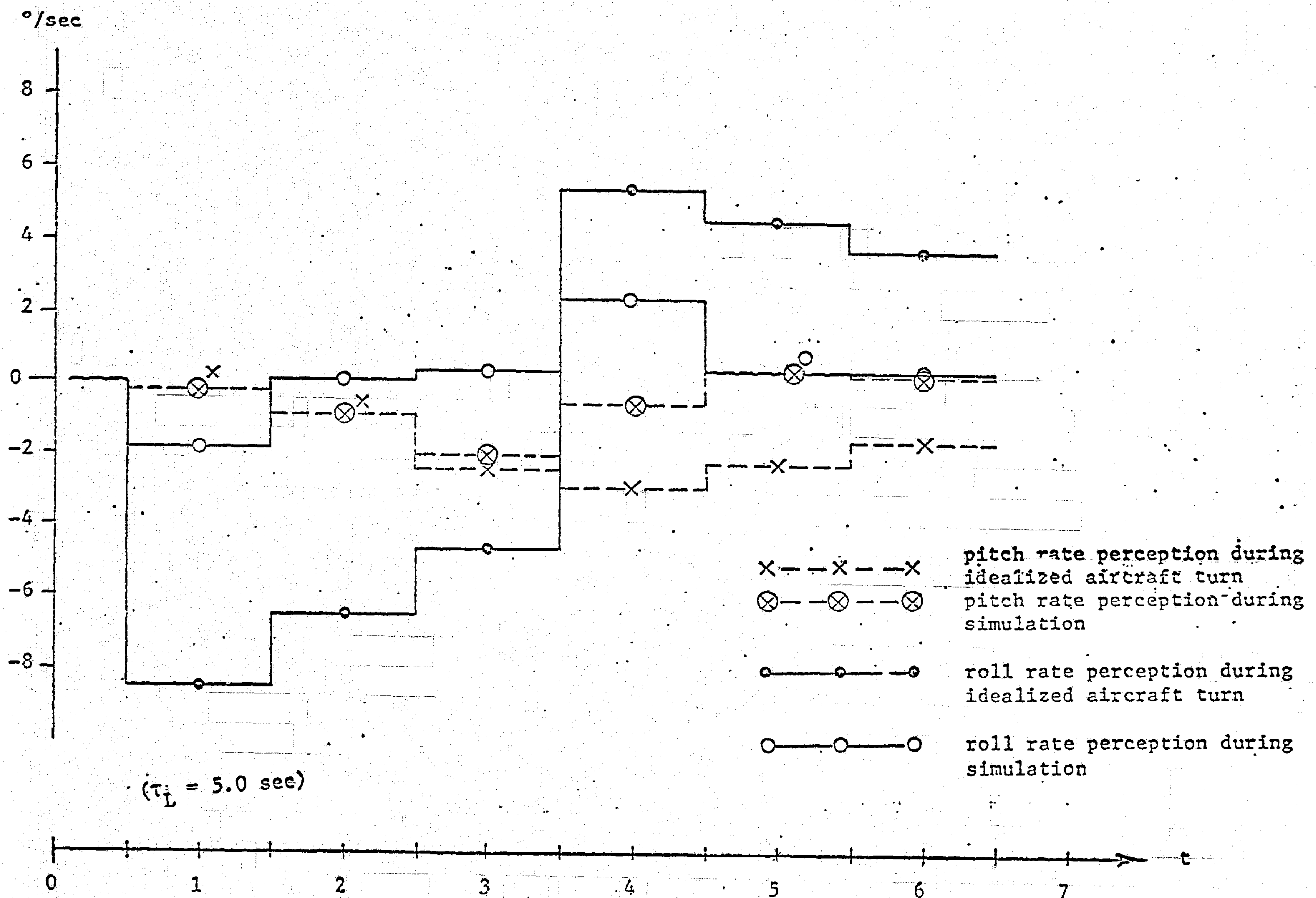
A coordinated turn simulation profile for the Link trainer

Figure 5



Pitch and roll rate perceptions during a simulation of the idealized coordinated turn.

Figure 6



Pitch and roll perception during a simulation of the idealized coordinated turn.

Figure 7

angular rate perception as anticipated. Figure 8 shows the results of cost index calculations for the simulation of figure 5. Weighting factors have been taken as 1, and τ_L has been taken as 5 seconds. Figure 9 shows the case of zero τ_L.

When flown with its own "factory" logic, the Link GAT-1 trainer employs a proportional roll and over a certain range, maintains roughly 1/6 of the imaginary aircraft roll angle. When a motion history based on this logic is input to the fidelity index program, the following results (shown in Figure 10) are obtained.

Use of the circularvection display

The modified Link trainer is outfitted with a visual display system capable of projecting moving horizontal stripes on the translucent cockpit side windows. When τ_L is greater than zero, the model predicts an angular roll sensation, during the coordinated turn roll-in and roll-out, that simply cannot be generated by Link trainer motion without producing a grossly incorrect attitude perception. Perhaps, the "missing" velocity sensation or some part of it could be produced visually.

The Link stripes can be made to move up on one window and down on the other producing an optokinetic roll display. It has been shown that this display

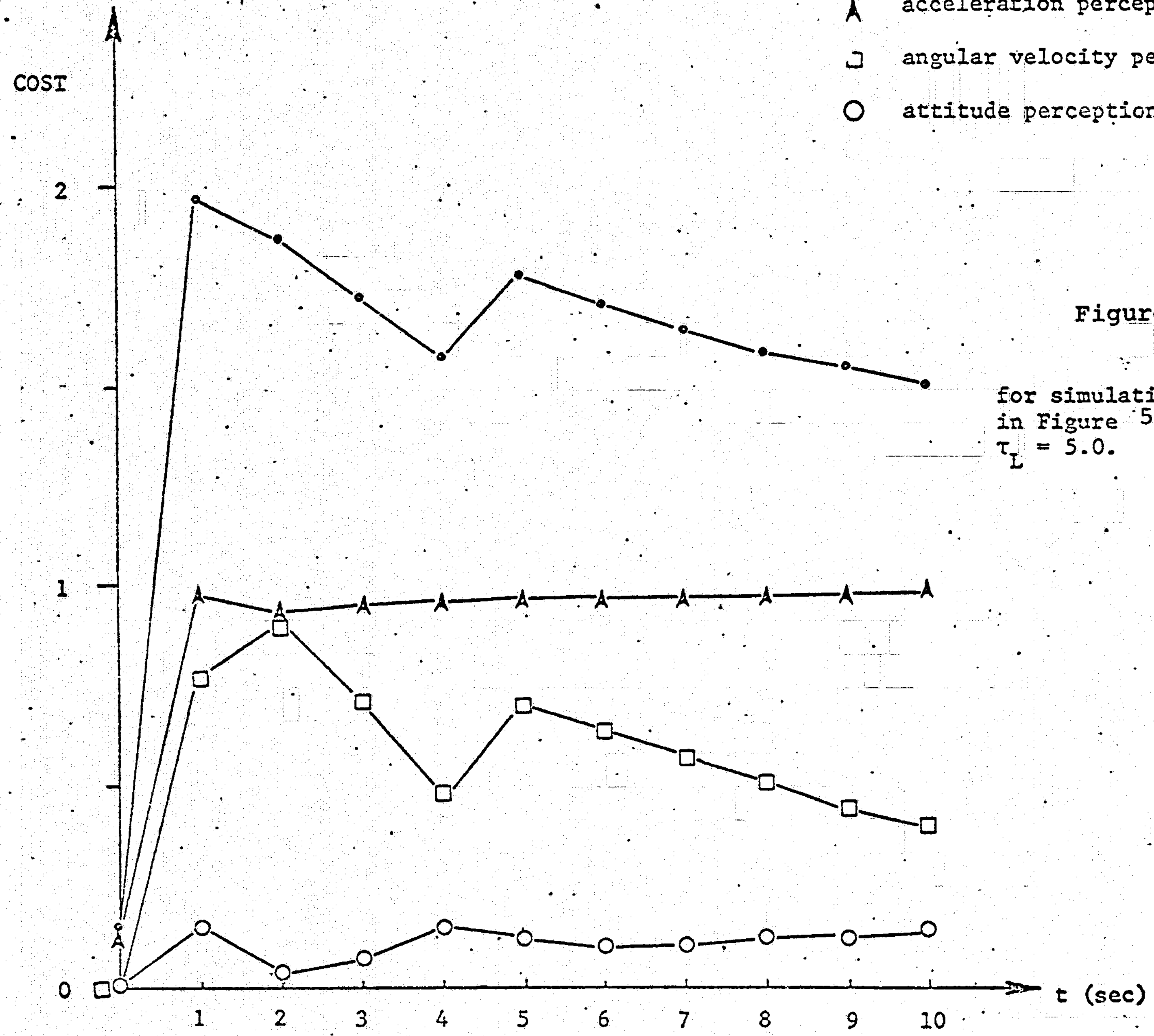
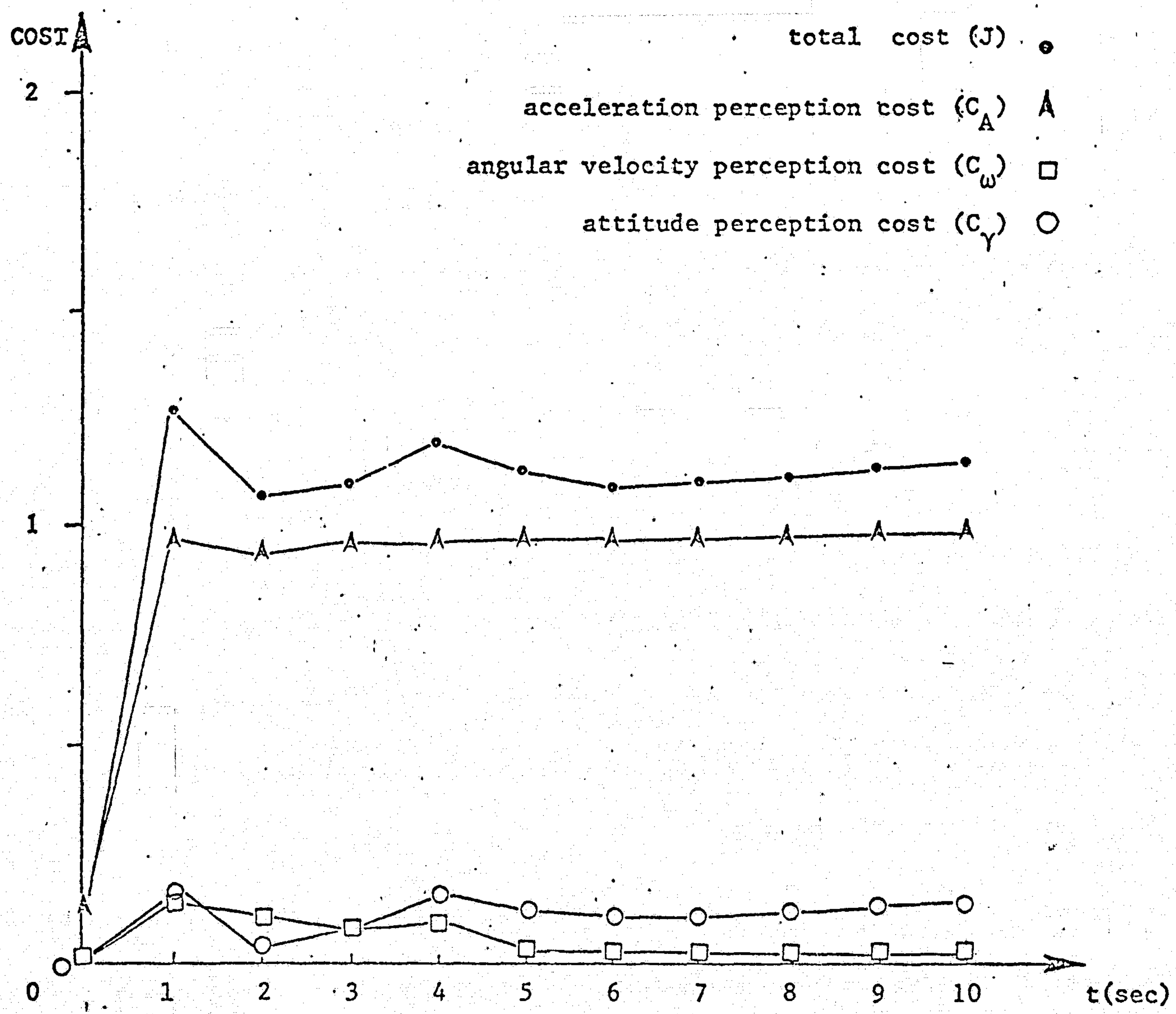


Figure 8

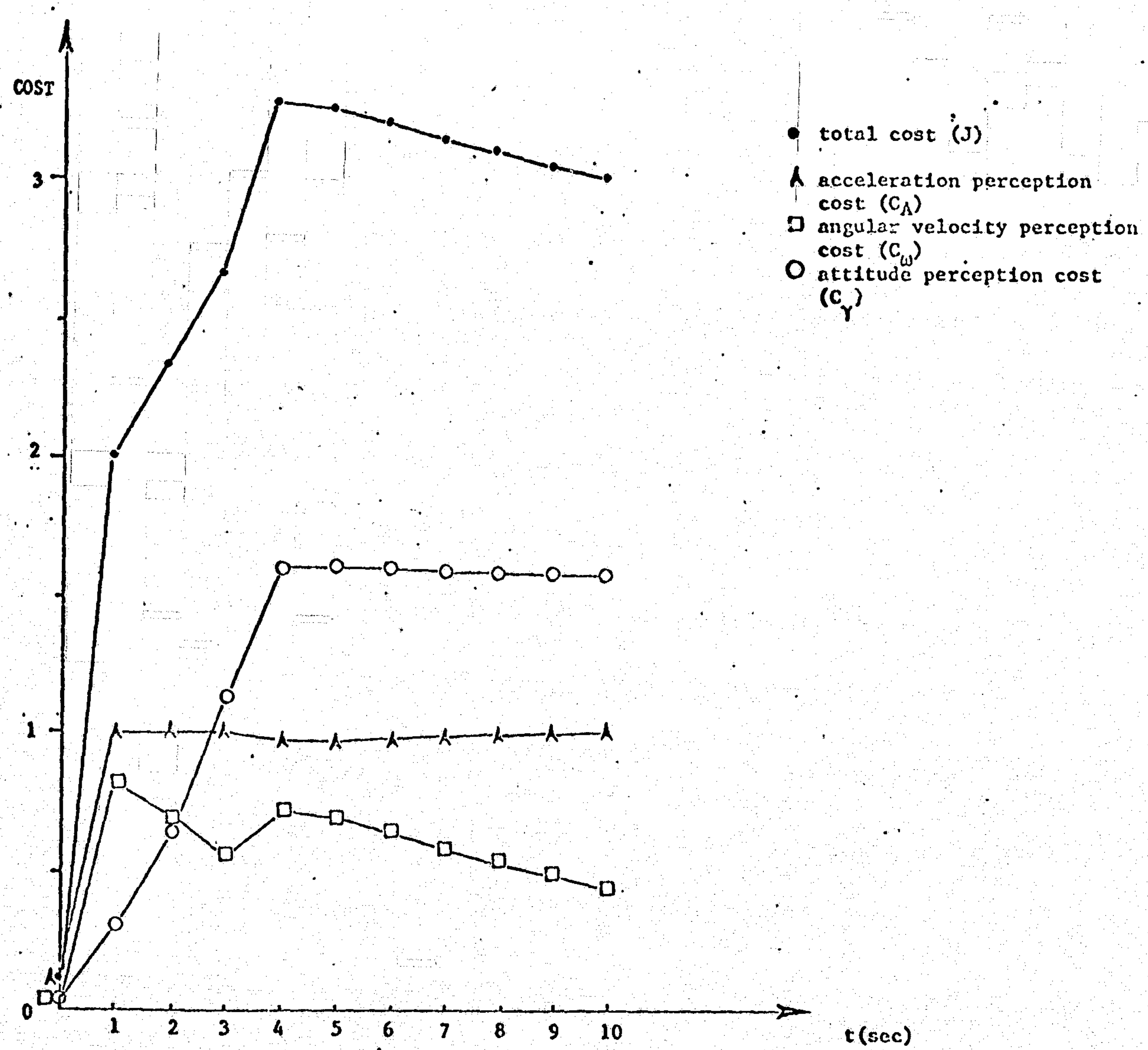
Cost computation for simulation profile shown in Figure 5 assuming $\tau_L = 5.0$.



Cost computation for simulation profile shown in Figure 5, assuming $\tau_L = 0$.

Figure 9

Figure 10



Cost computation for simulation profile based on proportional roll stragegy.

can produce the paradoxical illusion of constant roll velocity and a constant tilt with respect to the vertical.

For the coordinated turn simulation, the most logical display strategy is a stripe roll velocity profile that is proportional to the roll velocity profile of the actual turn. This may enhance the roll velocity sensation produced by onset of Link roll, thereby bringing the roll rate perception closer to that of the actual turn. Previous work suggests that attitude perception will possibly be affected; however, the true attitude profile can always be appropriately adjusted. The most serious problem here is one of onset time. Circularvection takes anywhere from 3 to 10 seconds to onset, and the roll into the idealized coordinated turn takes only 3 seconds.

Discussion of results

Roll magnitude estimates

During a series of constant velocity rolls between 1 and 10°/sec, with 2.5 to 14° excursion, and in the presence of a superimposed low level noise, subjects are able to produce continuous magnitude estimates, the peaks of which correlate very highly with stimulus velocities. Input-output functions appear to be linear relations, in most cases not significantly different from

$$RESP = B_1(STIM)$$

By setting a 5 response equal to 5°/sec as a modulus for this experiment, B_1 was effectively set to 1.

The proportional relationship above is somewhat surprising since psychological scaling laws are commonly log functions or power laws. The data may represent a small segment of a much larger log or power curve, or may be a reflection of the response scale and modulus employed.

Two axis tracking

There is considerable variance among subjects in the gain with which they estimate their orientation using the continuous vertical tracking task. For excursions ranging from 2.5 to 14°, some subjects consistently overestimated their roll and pitch angles, in one case by as much as 100%, while others consistently underestimated these angles. Subjects are quite self-consistent, however and within subjects, changes in indicated orientation angles correlate well with true attitude changes. Simultaneously tracking different profiles on the pitch and roll axes does not significantly affect performance.

The overall implication is that the two dimensional tracking task is a very useful tool for obtaining attitude perception information so long as the frequency range of interest is low.

Optokinetic display and visual effects

The moving stripe display had little if any effect on either roll orientation or roll velocity estimate during the experiments, with two possible exceptions. When the data from all subjects is pooled, roll rate magnitude estimates during 2-3°/sec stimuli in experiment 1 show a mean that is 0.82°/sec higher for SP4 stripe motion than for stationary stripes. Although the effect is significant it is very small and represents a bias that is below the standard deviation of the responses.

Implications for the Ormsby model

The high correlation between roll velocity estimation and true stimulus value in experiment 1 is supportive of the model. The data is too noisy, however, to allow much comparison of the response dynamics with the model. When we look at the model predictions for stimilar stimuli, we can see that in the model the roll rate perception peaks within a fraction of a second of stimulus onset and then begins to decay. When the stimulus returns to zero, the rate perception undershoots by an amount equal to the previous decay. The entire decay and overshoot effect amounts to less than 1 degree. This is below the accuracy of the peak responses in the data.

The high stimulus-response correlation in the vertical tracking data is also supportive of the model. The variance across subjects is certainly noteworthy, but the model cannot be expected to predict this. Ideally, the model should represent the population norm or mean. As mentioned previously, the responses usually follow the shape of the profiles more or less faithfully, but beyond this, the model predicts no dynamic effects of a large enough magnitude to be seen through the noise of the data.

The only finding that is contrary to the model is the frequent failure to detect the two roll motions toward the vertical. Perhaps a threshold effect is being observed. The comptuer model used here does not consider thresholds. The motions involved are above generally accepted threshold values, but these thresholds are usually applied to deviations from zero under optimal detection conditions, and often employ longer accelerations than those used here. Another possible explanation is a blocking effect in which the second pair of motions is not being observed due to the nature of the response task.

Finally it is possible that the Ormsby model should be modified to account for this result. It could be done by adding a lag somewhere to make the system behave more like an integrator of the short duration roll stimuli.

However, this would contradict responses observed during the calibration profile and some of the other experiments. It would mean that these responses should be more gradual than those observed. The most probable explanation, then, is a combination of the detection threshold inherent in perception and an added probability of detection failure introduced by the response task itself.

Implications for Simulation

When subjects experience the Link trainer motion profile considered most likely to be the optimal simulation of a coordinated turn maneuver, their responses differ somewhat from the attitude and angular rate perceptions predicted by the Ormsby model. If the computer model in this work represents a signal farther back along the pathway, than the observed output, then it is a useful tool for gauging simulator fidelity. Unfortunately, the experiments performed so far are not sufficient to unambiguously answer this question. Further work, especially the often mentioned idea of recording actual aircraft motions and analyzing these using the model, is needed.

This work was carried out by Joshua Borah and reported in detail in his Master's thesis.

HUMAN DYNAMIC ORIENTATION MODEL APPLIED TO MOTION SIMULATION

Joshua D. Borah

S.M. Thesis, May 1976, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology

ABSTRACT

The Ormsby model of dynamic orientation in the for of a discrete time computer program has been used to predict non-visually induced sensations during an idealized coordinated aircraft turn. It was found that attitude and angular rate perceptions may be contradictory and furthermore in a three rotational degree of freedom simulator, it is impossible to duplicate both simultaneously. To predict simulation fidelity, a simple scheme was devised using the Ormsby model to assign penalties for incorrect attitude and angular rate perceptions. With this scheme, it was determined that a three degree of freedom simulation should probably remain faithful to attitude perception even at the expense of incorrect angular rate sensations. Implementing this strategy, a simulation profile for the idealized turn was designed for a Link GAT-1 trainer. Use of a simple optokinetic display was proposed as an attempt to improve the fidelity of roll rate sensations.

Two open loop subjective tasks were designed to obtain attitude and roll rate perception indications. A series of experiments were performed in our modified Link trainer to test the effectiveness of the tasks and to check the model predictions and visual display effects.

The subjective responses were self-consistent and both tasks are considered to be useful for obtaining low frequency information. An unexpected difference was found between subjective

indications and model predictions for the turn simulation. It can probably be explained by the response lag inherent in the task (low bandwidth) plus consideration of dynamic detection threshold effects; but this must be verified by further work. The optokinetic display was found to be insufficient to signficantly improve roll rate perception fidelity in the turn simulation, probably due to the short durtion of the movements involved.

Although not designed for the purpose, the predetermined simulation profiles were rated for realism by two pilots. The results did not contradict model predictions, although support was weak. A dynamic simulator motion logic was proposed, incorporating the strategy derived from the model. Its use would enable pilots to "fly" the simulator and may provide more convincing data for use in evaluating and revising the fidelity prediction scheme.

VISUAL CUES IN APPROACH TO LANDING

An important aspect of the development of models for motion sensing based on visual cues is the effort evolving from the Bayesian-processor interpretation of the perception of visual fields. The effort consists of preparing simplified scenes of an approach to landing. These will be used to measure the perceptual response of pilots. The Bayesian model is particularly suitable to this type of work as it allows the incorporation of multiple simultaneous cues in the model and in the subsequent data analysis. This is especially important when one considers that the experiments cannot be performed by removing visual cues from the scene to determine their importance; the experiments must be performed with all of the cues being considered present.

Glideslope/Aimpoint Thresholds

The primary goal of this experiment is to obtain the perceptual response of humans to deviations in glideslope and aimpoint using the Langley TV visual attachment. A secondary goal is the refinement of psychological scaling techniques for flight simulator stimuli. Complicating factors in these measurements are (a) the long times required to present the stimuli, (b) the number of stimuli required to obtain measurements, and (c) the response perseveration which is magnified by presenting sequentially correlated stimuli.

PRECEDING PAGE BLANK NOT FILMED

Video tapes of landing approaches were made under the supervision of Dr. Queijo with the Langley Landing Scene Generator. The approaches were made with random variations in distance, glideslope, and flight path angle to be appropriate for psychophysical testing. Approximately ten seconds of each approach at each distance are shown. The tape begins with a set of 21 scaling runs to help the subject calibrate his magnitude estimation scale for both glideslope and flight path at each of the three distances used. Then follows 81 presentations of the factorial combination of three glideslopes, three flight paths and three distances, with three replications each.

These video tapes are used in conjunction with the Boeing Cockpit simulator and an Amphicon video projector to give an image with the proper scaling and field of view as seen from the pilots window.

Thus far, this work has concentrated on overcoming a number of technical problems, including proper alignment of mirrors, tape/projector compatability, proper darkening of the simulator room to obtain adequate contrast. Several pilot studies have been completed and the results incorporated into new tapes.

The preliminary results obtained from these pilot studies indicate that this approach will provide a useful method for obtaining the importance of various visual cues.

COMPARISON OF LINEAR AND NONLINEAR WASHOUT FILTERS USING A MODEL OF THE HUMAN VESTIBULAR SYSTEM

This portion of our research represents a recent effort to discover what information the model of the human vestibular system can give about the effects of washout filters on a pilot's perception of motion. A qualitative evaluation of linear versus nonlinear washout filters as used in aircraft simulators shows that the nonlinear filter provides a "better" representation of actual motion than the linear filter. This subjective pilot response seems to be due primarily to the fact that the nonlinear filter eliminates the false rotational rate cues presented by the linear filter. Hopefully, the model of the vestibular system will allow more objective results to replace the rating of "better", thereby providing a more quantitative method for predicting simulator performance.

Using our model of the vestibular system in the form of a Fortran program to be implemented on the lab's PDP-11 computer and data recorded during subjective tests at Langley, we hope to analyze the data from linear and nonlinear filters and quantify the pilot ratings.

THESES PERFORMED UNDER THIS GRANT

ORMSBY, C.C., 1974, Model of human dynamic orientation, Ph.D. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology.

BORAH, Joshua, 1976, Human dynamic orientation model applied to motion simulation, S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology.

CHU, William H.N., 1976, Dynamic response of human linearvection, S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology.

TANG, James T., 1974, Interaction between visually induced and real lateral tilt, S.M. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology.

THESES ORIGINATING UNDER THIS GRANT AND CONTINUING UNDER OTHER GRANTS

ZACHARIAS, G. - Visual-vestibular interactions in the yaw axis (Ph.D.)

ACREE, W. - Visual cues in landing (S.M.)

REIDEL, S. - Washout circuits (S.M.)

PRECEDING PAGE BLANK NOT FILMED.

PUBLICATIONS AND PRESENTATIONS UNDER THIS GRANT

YOUNG, L.R., OMAN, C.M., 1973, "Visually induced sensations of motion" (Abstract) Ninth Annual Conference on Manual Control, MIT.

Young, L.R., Dichgans, J., Murphy, R., Brandt, Th., 1973, "Interaction of optokinetic and vestibular stimuli in motion perception", Acta Otolaryng 76:24-31.

BERTHOZ, A., YOUNG, L.R., PAVARD, B. 1974, "Role de la vision peripherique et interactions visuovestibulaire dans la perception exocentrique du mouvement lineare chez l'homme", Compte Rendu Acad Sc Paris 278(Series D): 1605.

HENN, V.S., YOUNG, L.R., FINLEY, C. 1974, "Vestibular nucleus units in alert monkeys are also influenced by moving visual scenes", Brain Research 71: 144-149.

YOUNG, L.R., OMAN, C.M. 1974, "Influence of head position on visually induced motion effects in three axes of rotation", Proceedings of the Tenth Annual Conference on Manual Control, Wright Patterson AFB.

YOUNG, L.R., HENN, V.S. 1974 "Selective habituation of vestibular nystagmus by visual stimulation" Acta Otolaryng 77:159.

HENN, V.S., YOUNG, L.R., FINLEY, C. 1974, "Unit recording from the vestibular nucleus in the alert monkey" Abstract presented at the 1974 Workshop Meeting of the European Brain and Behavior Society on Vestibular Functions and Behavior, Italy.

ORMSBY, C.C., YOUNG, L.R. 1975 "Nonlinear model for the perception of static orientation", Fortschritte fur Zoologie 23:288-294.

YOUNG, L.R., OMAN, C.M., DICHGANS, J.M. 1975, "Influence of head orientation on visually induced pitch and roll sensation", Aviat. Space Environ Med 46:264-268.

BERTHOZ, A., PAVARD, B., YOUNG, L.R. 1975 "Perception of linear horizontal self-motion induced by peripheral vision (linearvection): Basic characteristics and visual-vestibular interactions", Exp Brain Res 23:471-489.

PRECEDING PAGE BLANK NOT FILMED.

HENN, V.S., YOUNG, L.R. 1975 "Ernst Mach on the vestibular organs 100 years ago", Annals Oto-Rhino-Laryng 37:138.

HENN, V.S., YOUNG, L.R., FINLEY, C. 1975, "Vestibular nucleus units in the alert monkey are also influenced by moving visual fields", Fortschritte fur Zoologie 23:247-250.

ORMSBY, C.C., YOUNG, L.R. 1976, "Perception of static orientation in a constant gravitoinertial environment", Aviat Space Environ Med 47:159-164.

YOUNG, L.R., HENN, V.S. 1976 "Selective habituation of vestibular nystagmus by visual stimulation in the monkey", Acta Otolaryngol 82:165-171.

ORMSBY, C.C., YOUNG, L.R. (in press, 1977) "Integration of of semicircular canal and otolith information for multisensory orientation stimuli", Journal of Mathematical Biosciences.