



MIT
@50

M A N - V E H I C L E L A B O R A T O R Y

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FRIDAY, SEPTEMBER 14, 2012

WELCOME to the



FRIDAY, SEPTEMBER 14, 2012

The MIT MVL (Man-Vehicle Laboratory) celebrates its fiftieth anniversary with a day-long symposium and celebration on the subject of human-vehicle interactions, on Sept. 14, 2012. The Symposium traces the people and research streams over a half century – from Doc Draper’s earliest desires to have us describe pilots as components of a control loop, through study and modeling of the balance mechanism of the inner ear and its role in aircraft and spacecraft control, to extensive space flight experiments. Over 200 graduate theses and over 900 publications have documented the research – and the MVL has emerged as a leading international force in space life sciences. (Details are available on the web site : mvl.mit.edu). Over those years we brought models of vestibular function to the control of moving base flight simulators. We developed devices and procedures to measure posture and eye movements. We used flight simulators to develop air traffic avoidance and pilot workload measures. We investigated human balance and biomechanical reactions on over a dozen space missions, from Shuttle and MIR to the ISS, and sent a member of our lab to space as America’s first Payload Specialist. We provided the human factors and life support for the record breaking Daedalus man-powered flight. We are developing a BioSuit™ prototype advanced space suit and applied artificial intelligence to assist astronauts doing scientific experiments. Together with our colleagues at the Charles Stark Draper Lab and at the Massachusetts Eye and Ear Infirmary we continue to explore advanced applications of control theory to human reactions – whether of patients or of astronauts.

Two of the three laboratory directors, Larry Young and Chuck Oman, (Y.T. Li passed away a year ago), along with current faculty (Dava Newman, Jeff Hoffman, and Julie Shah) and staff welcome a returning group of graduate alumni and distinguished friends from the aerospace field. In the course of panels, devoted to each decade, they place their experiences at MIT into the context of their professional development and their views of future challenges that would demand the attention of the modeling and basic psychophysics characteristic of the lab.

This celebration of the 50th anniversary of the founding of the MVL was made possible by the MIT MVL Fund, consisting of generous donations from alumni and friends. Lew Nashner, Aurora Flight Sciences, Zero-G Corporation, and MIT's Department of Aeronautics and Astronautics provided extensive support. Liz Zotos organized the event with her characteristic efficiency and care.

MIT
MVL@50
Friday, September 14, 2012
Bartos Theater, E15-070

PROGRAM
Panel Discussions

<i>Continental Breakfast</i>		<i>8-8:50 am</i>
Introduction and Welcome (Jaime Peraire, Head, Dept. AeroAstro)		8:50-9:00am
The '60s		9-9:40am
Chair:	Larry Young	
Co-Chair:	Greg Zacharias	
Panelists:	Ken Li and Wendy Spector (YT Li)	
	Philip Kilpatrick	
	Lew Nashner	
	Peter Benjamin	
	Howard Hermann	
The '70s		9:40-10:30am
Chair:	Chuck Oman	
Co-Chair:	Eli Gai	
Panelists:	Chas Burr	
	John Tole	
	Susan Riedel	
	Elazer Edelman	
	Sasha Efremov	
	Bob Renshaw	
The '80s		10:30-11:10am
Chair:	Steve Bussolari	
Co-Chair:	Bob Kenyon	
Panelists:	Anthony Arrott	
	Mark Kulbaski	
	Divya Chandra	
	Keoki Jackson	
	Mark Shelhamer	
	Ed Marcus	

The '90s 11:10-11:50am
Chair: Dava Newman
Co-Chair: Dan Merfeld
Panelists: Peter Diamandis (video)
Ted Liefeld
Chris Carr
Scott Rasmussen
Jason Richards
Mindy Gallo Eckman
Erika Wagner
Corinna Lathan

Lunch 11:50-12:50pm

The '00s 12:50-1:30pm
Chair: Andy Liu
Co-Chair: Kevin Duda and Alan Natapoff
Panelists: Allen Atamer
Berengere Houdou
Kristen Bethke (Wendell)
Jessica Edmonds (Duda)
Anton Aboukhalil
Jessica Marquez
Thomas Jarchow

The '10s 1:30-2:10pm
Chair: Jeff Hoffman
Co-Chair: Julie Shah
Panelists: Chris Oravetz
Roedolph Opperman
Alex Stimpson
Jaime Mateus
Thaddeus Fulford-Jones
Victor Wang
Allison Yost

Guidance from the Outside:

2:10-2:50pm

Chair: Steve Robinson
Co-Chair: Sasha Efremov
Panelists: Judith Burki-Cohen
Jim Lackner
Paul DiZio
John Tylko
Jay Buckey
Conrad Wall

Larry Young to present the Zero-G Award

Some Current Student Research:

2:50-3:30pm

Chair: Aaron Johnson
Co-Chair: Torin Clark
Panelists: Rita Domingues
Forrest Meyen

Current MVL students, introducing their posters to be shown at the reception

Reception, Posters and Tours of MVL

4:00-6:00pm

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Y.T. Li

THE FOUNDING OF THE MAN-VEHICLE LAB

**FREEDOM
&
ENLIGHTENMENT**

My Life As An Educator/Inventor

In China and the United States

Yao Tzu Li *

* Professor Emeritus, Massachusetts Institute of Technology
Member, National Academy of Engineering, U.S.A.

The founding of the Man/Vehicle Lab

During the late Sixties, my closest colleague was Larry Young. He had been a student of mine and had asked me to be the adviser for his doctoral dissertation with Dr. Draper as its Chairman. In fact, his experiment was conducted in the lab of Professor Stark of Harvard Medical School. It was a study of the movement and response of human eyes. He was the first to discover that human beings go through different stages of sleep, with each stage being marked by different patterns of eye movements. Thereafter, experts studying sleep often used the movements and responses of the eyes as a significant reference in their studies. Larry's discovery constituted an important contribution to the field of physiology. He was engaged as an Assistant Professor in our department soon after the completion of his dissertation.

At that time, I was interested in the relationship between man and the movement of a vehicle in which he is riding. Take for instance the biker. When he is biking, he can choose his direction by turning his front wheel while relying reflexively on the same front wheel to keep his balance. Indeed, riding a bike gives a sense of freedom. I was experiencing bothersome traffic jams during rush hour, and realized how we Americans had gotten used to driving big and spacious cars everywhere. It occurred to me that the length of the vehicle does not affect traffic jams as much as its width. But if we cut down the width of the vehicle too much, it would cause a series of problems in maintaining the needed stability, both static and dynamic. Finally, I made a donation to support one of my students, Bill Resner, to do a Master's thesis studying a three-wheeled vehicle whose two back wheels were capable of self-tilting and self-balancing. The tricycle should be able to stop without toppling over by adjusting itself automatically to the banking of the road surface and also to tilt automatically when turning the corner, just as the biker does. The principle involved is in fact not at all complicated - the gravitational force simply needs to negate the centrifugal force when the bike is turning a corner¹.

¹ I had published an article on "self-tilting tricycle" in a journal of the Society of Automotive Engineers. General Motors Company later on produced a model based on the article and displayed it at the EPCOT (Experimental Prototype Community of Tomorrow) center at Disney World in Florida. In 2000, I suddenly received a phone call inquiring if I was the person who had invented the self-tilting tricycle. The inquirer, whose name was Mitch Casto, then sent me an email. He told me that a group of amateur engineers had set up a club to study the tricycle and that according to their research I was the inventor of the self-balancing tricycle and was therefore welcome to keep in contact with them. It was a real pleasure for me to get this message.

Both Larry Young's experiment on eye movements and Bill Resner's thesis on the self-tilting tricycle showed that a variety of relationships do exist between the responses of the various organs of the human body and the movements of the vehicle he is riding. The responses of the human body are remarkably complex, including those of the body, the eyes, and the cochlea in the ear (which maintains one's balance). There is of course also the problem of the coordination of the eyes and the inner ears. In fact, there is a whole range of physiological reactions of the human body to its surrounding conditions. For example, while the driver usually is not affected, the passenger, who is in a passive state, tends to feel various degrees of motion sickness.

An airplane pilot's training often started in a flight simulator on the ground. This was then followed with flying low performance planes and then, gradually, high performance ones.

How to train an astronaut was a new agenda for NASA at that time. It was an area Larry was eager to explore and participate in. So I collaborated with him to submit a proposal to NASA seeking a grant to set up a Man/Vehicle Lab at MIT. To keep the program going, prior to the official approval of the funding, I provided financial backing myself, including paying the salary of Jacob Meiry, another Ph. D. candidate, who studied the performance of the man/vehicle function with an ordinary bicycle. (By then I had sold Dynisco, a business owned by my brother Shih Ying and myself, and therefore had money in the bank.)

During that period, the few of us had lunch together almost every day. We talked with great interest about the remarkable reflexes characteristically involved in human body responses. On the one hand, we tried to explain these responses, using the parameters frequently used in control systems. On the other hand, we were fully aware that control systems designed by humans have only a certain fixed set of functions and didn't have the intelligence or the reflexes to adapt themselves to changing circumstances in the same way as animals or human beings. Therefore, as we developed the Man/Vehicle Lab, we were also considering how to design a machine that could adapt itself to its circumstances, an area of study, which we named "Adaptive Control Systems."

I served as the Director of the Man/Vehicle Lab after its initial establishment, but much of the work was actually done by Larry. He was a very active and capable person and managed to set up the lab step by step, and at the same time publish volumes of scientific articles. I passed the role of Director of the Man/Vehicle Lab to him after just a few years, and felt greatly pleased that the Lab was still in operation at the time of this writing, some forty-plus years after its founding.

In the Sixties, Larry Young was not only my working partner, but also a good friend outside the office. He was a good athlete and was an amateur coach for downhill skiing in the winter. Mixing fun and research, I undertook a study of the body motions of skiers and extended it to the analysis of the simple function of man's walking.

The attempt led me to think about the physical parameters involved in our walking with two legs. Seen from a purely physical perspective, the two legs are actually a pair of "hanging pendulums." By the sheer force of the gravity of the earth, the "pendulums" acquire a natural frequency in their swing. The speed of their natural frequency matches the normal speed of a walking person. Therefore, the "pair of pendulums" functions like a wheel. The resistance it encounters is primarily in the friction of the hip joints, like the bearing of a wheel. If, however, the person wants to walk faster than the normal speed, matching with the natural pendulous frequency, he must use his muscles to increase the frequency of the "pendulums," which is quite tiring.

In a mechanical pendulum one can increase its natural frequency with the addition of a suitable spring, which can store kinetic energy and change it into potential energy and vice versa. But muscles are different. Walking upstairs and downstairs consumes energy either way. Thus I reasoned that if we equipped the two legs with a pair of springs to increase the restoring force acting on the equivalent of its pendulous effect, then we could walk faster without exerting ourselves too much.

This idea somehow aroused the interest of the Quarter Master Research Laboratory of the U.S. Army in Natick, Mass. They invited me to make a demonstration of my concept, which I did. I made a simple apparatus with a bundle of thin steel rods used as a torsion spring. I strapped them around

my waist with the two ends of the spring coupled to the upper ends of a pair of control levers, and their lower ends fastened onto the ankles of my two legs. Thus I could adjust the stiffness of the swinging action between my two legs.

Then they asked me to step onto their treadmill to carry on with the experiment. They put a mask over my nose to measure the amount of oxygen I consumed while I was walking. According to the procedure, I first walked for half an hour, which allowed my body to attain a certain state of equilibrium. Then I undertook four walking tests, with each test lasting half an hour. The four tests differed in terms of using, or not using, the spring and also in terms of walking at two speeds, 3.5 and 4 miles per hour. The experiment showed that the spring could reduce the amount of oxygen consumed by some 20% when the walking speed was 4 miles per hour. The researcher at the center said the result was quite remarkable and invited me to go back to repeat the test, since the first test involved the failure of some parts that had to be fixed at their shop. I promised to try again, but did not follow it up for various reasons. Nevertheless, I already felt quite satisfied because my hypothesis had been proved to my own satisfaction.

Creative Engineering Symposium

The experiment mentioned above was based on a parameter analysis approach. Thereafter, I frequently reminded my students that when they came across an industrial product with particularly good performance, they should make it a point to analyze it and figure out the parameters that made it so.

One day I read a report concerning an invention by Lockheed Aircraft Co. about a new type of helicopter called the "rigid rotor helicopter," i.e., a helicopter with a fixed rotor. The report claimed that the new helicopter was much more maneuverable than the conventional "hanging" type that was commonly being used. This common type had its body "hanging" under the rotor by a universal joint. This was necessary because the rotor of the helicopter, while floating in the air, is very much like a piece of wood floating on the water. Being always swung by air currents, it tends to rock constantly, and sometimes violently. It would be very uncomfortable if the cabin

was rigidly attached to it. By "hanging" the cabin under the rotor, one could reduce the rocking of the cabin and give the riders a better sense of smooth sailing. But this type of helicopter is lacking in maneuverability and could never hope to be as nimble as a fighter plane.

The new type of helicopter invented by Lockheed, instead of "hanging" the body under the rotor, fixed the rotor onto the body rigidly. This enabled the helicopter not only to move up and down or to slide forward and backward but also to roll and tumble like an airplane and yet keep itself as stable and balanced as the "hanging" type in rough weather. When I told the news item to the students, they were all very interested. I then suggested that it would be fun to find out how the new type of helicopter could fix the rotor to the body, and yet solve the rocking problem.

In fact, the report did mention that the special feature of the rigid rotor was a very simple dumbbell installed above the rotor to adjust the pitch angle of the blades of the rotor. The smartest part of the design was the simplicity of the structure of the "gyroscope." It looked just like a horizontal rod with a ball on either end, which turns synchronously with the rotor. When the dumbbell-shaped rod "senses" that the rotor is being tipped by the air currents, it immediately adjusts the pitch angle of the blades of the rotor to neutralize the effect of the wind. The report was not very specific about how the rod worked, but this vagueness served precisely my purpose of inspiring the students and giving them some sense of what innovation and creativity means in a practical sense.

When I was introducing the report to the class, a student raised his hand and said that he actually had flown that new type of helicopter and therefore knew pretty well the remarkable performance being described in the news. The student's name was Joe Tymczyszyn. His father was a test pilot at Lockheed and he himself had a pilot's license. He had flown the new type of helicopter with his father. This unusual coincidence prompted me to think seriously about going to Lockheed to learn first hand about the construction of the new helicopter.

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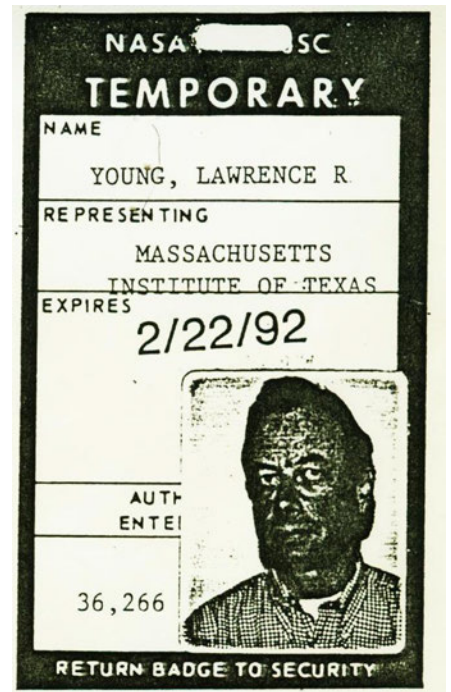
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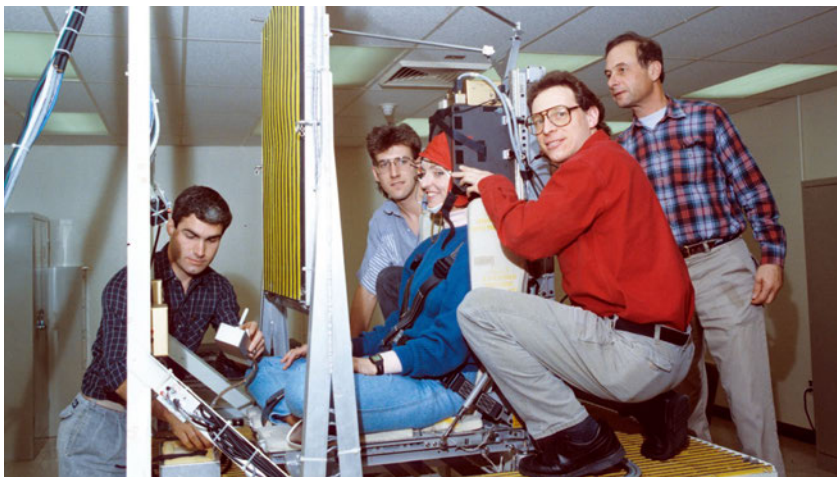
MVL's three Directors: Chuck Oman, Y.T. Li, Larry Young 2009



MVL Founder Y.T. Li's 90th Birthday



The Man from "MIT", Larry's JSC Security Badge 1992



Space Lab SLS-1 Sled JSC-BDCF Johnston, Hughes, Fulford, Merfeld, Young 1991



MY TWENTY-FIVE YEARS
with the
MIT MAN-VEHICLE LABORATORY
(1962-1987)

Laurence R. Young

THE BACKGROUND AND THEMES OF OUR LABORATORY

MY TWENTY-FIVE YEARS WITH THE MIT MAN-VEHICLE LABORATORY

by Laurence R. Young

The Background and Themes of Our Laboratory

The history of a laboratory, even of a small university laboratory, is the story of the people who grouped together, the ideas that evolved and led to successes or to dead ends, and the technology that enabled certain developments and stood in the way of others. Although the detailed history is primarily of interest to those involved in the adventure, it may be of interest to those who follow the ebb and flow of research and development as it really occurs, rather than as it is depicted in journal articles or in the popular press. On the occasion of the twenty-fifth anniversary of the Man Vehicle Laboratory at MIT, I have put together a very personal account of this first quarter-century of our activities. Because of my close association with the faculty, staff and students in the Laboratory over these years, this narrative touches on the work of most of my colleagues - but it remains a personal and, therefore, biased account. I apologize to those whose accomplishments have been dealt with inadequately or who have inadvertently been omitted in this account. Memories fade - even important ones. No slight is intended.

The fundamental theme of the Man-Vehicle Laboratory during its first 25 years has been the use of control theory in understanding biological systems with particular applications to the aerospace environment. Through the years, the fundamental research area has evolved and the applications have led or followed changes in technology and in the interests of the aerospace community and our faculty. One theme that has been visible throughout this period, however, is the emphasis on human spatial orientation as affected by the motion environment and the visual surround. Other continuing themes have been pilot and astronaut human factors, eye movements and bioinstrumentation. In this informal and very personalized set of recollections, I will try to point out the intellectual tree, including many of the dead branches, which links together the research of our Laboratory from the background of its founders before 1962 to the 25th anniversary in 1987. The Research Roadmap is my view of the intellectual pathways and dead-ends we have undertaken during the evolution, growth, and false starts of this interdisciplinary group. Two of these themes are discussed more extensively below; others appear as they come up in the chronology.

A Continuing Theme: The Role of Gravity in Human Orientation and Posture

From the beginning of the Man-Vehicle Laboratory, one of our continuing themes has been the role of gravity in human orientation, posture and manual control. My particular interest in gravity-sensing is based upon the nervous system's resolution of the ambiguity in gravito-inertial sensing. Clearly, no "graviceptor", including the otolith organs, can distinguish between gravitational acceleration and any other linear acceleration. Nevertheless, we are usually able to distinguish between head tilt and lateral acceleration, and normally do not lose our balance under self-generated acceleration. It seemed clear that the nervous system makes use of information from other sources, particularly the semicircular canal (sensing rotation), tactile and proprioceptive static orientation cues, and makes special use of visual information to supplement the other sensory orientation inputs. Furthermore, the role of an internal model of body motion, including

the treatment of the efferent copy of motor commands must determine the expectation of body orientation with respect to gravity and influence the interpretation of the signals from our internal linear accelerometers. Failure of the system to correctly interpret the otolith signals can result in illusions which can be amusing as in carnivals or dangerous as in pilot disorientation episodes. The problem becomes even more challenging and dramatic in the weightlessness of orbital flight, when the otolith organs respond only to linear acceleration and are unaffected by static head orientation relative to the vertical.

The principal tools for the study of acceleration responses in humans are the measurements of eye position, body and trunk stabilization, perception of spatial orientation, and manual control. To the extent possible, animal neurophysiological experiments, which have a direct tie to human eye movement and perception experiments under similar stimuli, are particularly useful. Asymmetries in responses to linear acceleration, especially those associated with differences between up and down or forward and back motions, are particularly interesting to study.

Investigation of responses to linear accelerations and their interactions with angular accelerations and visual stimuli is consequently a dominant theme of our Laboratory throughout its history. The NE-2 multi-axis simulator obtained from NASA in the early 60s was similarly used to compare human control performance in roll (involving gravity tilt cues) and in yaw. When our yaw-axis rotation chair was placed on the arm of the Instrumentation Laboratory centrifuge in the late 60s, it was to investigate the role of a rotating gravitoinertial vector on eye movements and to distinguish the contributions of the rotation and linear acceleration sensors. When we became actively involved in study of visually induced motion in the late 60s and 70s, our interest quickly extended to the basic facets of linearvection in all cardinal axes. We investigated the interaction between angular and linear stimuli on monkey eye movements within a study of off-vertical rotation with Henn in Zurich. A collaborative research activity with Berthoz in Paris produced a moving stripe projection system for generation of linearvection for investigation of linear visual-vestibular interaction on another moving cart. Our investigations of rollvection, beginning with the collaboration with Held, Dichgans and Brandt at MIT, were based upon the role of the graviceptors in the inhibition of visually-induced motion. Our later related experiments with Dichgans in the large dual-maneuvering sphere at Langley established the relationship between head orientation and visually induced roll, further supporting the critical role of the graviceptors in the interpretation of visual signals. This latter line of research set the pattern for our "rotating dome" series of visual-vestibular interaction experiments on Spacelab beginning in 1983 and scheduled to continue into the 90s. The Link Trainer was modified for rear projection of moving stripes on the windows and used to determine the basic characteristics of vertical and forward/backward linearvection, including the important asymmetries. The influence of gravity on the caloric response, begun in the work of Steer on basic physical characteristics of endolymph and extended by Oman in his experiments on changing head orientation suddenly during caloric stimulation was another theme involving the influence of gravity during the spatial orientation sensors. (This last theme was to achieve considerable notoriety when our German colleagues investigated the caloric response in weightlessness on Spacelab 1.) Vertical linear acceleration had always been the most difficult to study because of the physical constraints involved in sustained acceleration. We modified a hoist in the basement of the Center for Space Research to use it for our first vertical motion device. In an attempt to achieve considerably more vertical

motion, I collaborated with Melvill Jones, of McGill University, in a study of the detection of vertical accelerations carried out as the final experimental series on the NASA venerable and vibrating outdoor linear accelerator. These experiments, building on Meiry's earlier work, led to a simple theory for linear motion detection and formed the basis for part of our Space Sled experiments eventually carried out in 1985 on the D-1 Spacelab mission. Our second laboratory linear acceleration device, the MIT sled, was constructed by Lichtenberg in preparation for our Spacelab experiments and continued to be a workhorse for protocol development, astronaut training, pre- and postflight data collection, and newer studies of linear visual-vestibular interaction as reflected in perception of motion and optokinetic nystagmus as well as ocular torsion. Brief vertical linear acceleration was achieved by Wicke in the laboratory by dropping subjects over distances of only one to two feet, with varying accelerations controlled by counterweights, supplementing the work of our McGill colleagues on our Spacelab experiments. Our most exotic linear acceleration experiments, short of the actual space flights, were conducted in NASA's KC-135 airplane during parabolic flight.

Nearly all of our Spacelab experiments directly involved investigations of the role of linear acceleration before, during and after space flight in the human spatial orientation and postural control system. Our plans for future Spacelab and other space shuttle experiments similarly concentrate on the interesting asymmetries in interactions between the linear acceleration sensing system and visual and tactile stimuli. Thus, the apparently simple question of how the nervous system sorts out the difference between tilt of the head with respect to vertical and linear acceleration has led us through a series of experimental and theoretical developments using a wide variety of linear and angular acceleration stimulus devices in an effort to clarify the situation.

Eye Movement Instrumentation

In the course of our work on eye movement modelling, we developed a number of eye movement instruments and improved others. At the time of my thesis, Alan Sandberg, Larry Stark and I improved on an infra-red reflecting technique originally developed in Switzerland by Pfaltz and Richter to perform photo-optical measurement of horizontal eye movements. I later extended this to vertical eye movements and made it relatively immune to ambient light. When MIT expressed no interest in a patent, I worked with Joel Newman for a patent and commercialization of this instrument which has since been a product line that has been sold and resold many times. Hans Lukas Teuber, then Chairman of the Psychology Department, recognized the need for a wide field two-dimensional tracking system for human eye movements in the mid-60s. David Sheena, then a doctoral student in electrical engineering, worked under Sam Mason and myself to develop an image dissector primitive scanning system for eye movements and first came across some of the problems of determining the center of the pupil when it was not fully visible. Sheena went on to perfect this system as a modification of the oculometer, originally developed at Honeywell, and brought it into widespread commercial use for a company originally part of Whittaker Corporation and now Applied Sciences Laboratory. I had the pleasure of working with Sheena throughout this period, and at one time we used the instrument for reading studies at our lab at MIT. Josh Borah went from our lab to join Sheena, and has developed the video device into a helmet mounted eye view monitor which is coming into increasing use in modern flight simulator applications.

It is somewhat ironic that electro-oculography, which we early eschewed because of its noise and drift, is now the most common technique we employ in the lab. The availability of low noise, temperature insensitive, high-input impedance, drift-correcting operational amplifiers, along with convenient pre-gelled electrodes, has changed the status of this method. The automatic impedance checking introduced by John Tole has not proven to be necessary in practice with newer electrodes.

By far the most difficult challenge in eye movement recording which we encountered, however, was associated with ocular counterrolling. This torsional rotation of the eye about the visual axis, in a direction to compensate for head tilt, is of little functional importance in man and received relatively little attention until recently. Ocular torsion is however, one of the only unique indicators of otolith function in man and consequently assumes great significance in studies of otolith organ physiology especially in weightlessness. The lack of an adequate accurate fast and reliable means of measuring ocular torsion has limited its clinical application although interest in the technique is high. Our interest in ocular counterrolling measurement began with our proposal for experiments on assessing otolith function in weightlessness, submitted in 1976. We needed to measure torsion in two experiments, during linear acceleration on the space sled and during observation of the rotating dome portion of our visual-vestibular interaction experiment. In order to achieve a measure of certainty for these important measurements we sacrificed analysis time and sampling frequency. The method we used was to take a series of 35 mm flash photographs of the eye, using a motor-driven camera and a special ring flash to avoid presenting a linear after-image. The analysis method, patterned after that used by Woellner, Miller and Graybiel at Pensacola, was to determine the rotation of landmarks in the iris relative to a reference picture. To increase contrast, Lichtenberg experimented with a variety of films and illumination. The very helpful and knowledgeable Doc Edgerton dropped by the lab one day and helped to work out the flash and exposure. After looking at photos of eyeballs taken with infrared, ultraviolet, enhanced infrared, and other films, we decided that conventional Ektachrome gave the best results. The film story did not end there. In order to save several hundred grams at a time when mass was being severely restricted during Spacelab-1 preparation, we agreed to use a new motorized 35 mm camera being developed by Nikon especially for the space shuttle. This camera, similar to an enhanced version of the Nikon F-3 development, had so many interlocks to prevent double exposure that it was almost guaranteed to jam or hang up in a state from which recovery was difficult if not actually impossible without exposing all the film. Furthermore, to enable us to fit 250 exposures onto a roll of film, we had to resort to the use of thin based film, which required a special order through NASA to lay on our desired emulsion. In the end, we used ASA 180 thin-based film purchased by NASA in great quantities for the Skylab mission some ten years earlier and pushed the film in the development process. Training of the astronauts on operation of the camera was the most difficult part of the training task, and even Bob Renshaw and I, most familiar with the camera, frequently needed a refresher course between training and simulation sessions. We taught the crew to "field strip" and reassemble the camera completely blindfolded as a challenge. Ironically, during the Spacelab-1 flight, the camera failed during its very first use, due to a flash malfunction, and was replaced by an alternate method for the entire flight. This alternate method, using Spacelab closed circuit TV, was enabled by the judicious use of a special adaptor designed and insisted upon by Lichtenberg as a backup to the camera and only accommodated on the mission over the objections of management, but with the support of our technical representatives at the Johnson Space Center.

(This is but one of many examples where the presence of a trained scientist on board can save an experiment both in the planning and in the execution phase.)

Well before the Spacelab-1 mission took place, the backlog of film to be analyzed from our sled and dome experiments was becoming dangerously large. Undergraduates were hired to work as "scanners" which consisted of sitting for several hours in front of a screen placing a cursor repetitively on the same iral landmark on each successive frame of film and doing the same for a pair of fiducial marks attached to the skull by a biteboard. This process took about one minute per frame and the entire process of taking the picture, developing, scanning it, and running it through a computer, cost between \$1 and \$2 per data point. In an effort to improve upon this situation, we embarked on a series of studies of automatic ocular counterrolling measurement computer techniques. Oman and Edelman developed a prototype video-ocular torsion system. Kenyon then took over the problem and with Tony Parker, a radiologist at the Beth Israel hospital, pursuing his Ph.D. in biomedical engineering, worked on the signal processing problem and developed a workable method for analyzing ocular torsion automatically to an accuracy which exceeded the best of the scanners. The technique depended upon x-y localization of two landmarks by comparing successive two-dimensional Fourier transforms. Yoshi Nagashima further improved the procedure and got it to run in one minute on a VAX 780. We are currently in the process of getting this algorithm to run faster and less expensively on our own in-house computer. In order to increase the robustness of the method and make it easier to identify landmarks by computer or human scanner, we developed a technique using specially marked soft contact lenses. Such lenses normally float freely on the surface of the eye and would be unsuitable for measurements of this type. However, a serendipitous observation was made by Oman one day after skiing in the rain in New Hampshire. (We do that in New England, you see.) He found his soft lenses stuck to his eye and deduced that it was the fresh water which caused them to change their curvature or change the osmotic pressure. Kenyon, Oman, Tony Cavellerano and Edelman further explored both the mechanisms of sticking contact lenses to the eye and ways of safely marking them with a line which would remain sharp and visible and yet be non-toxic and acceptable by the human use committees of MIT and later of the Johnson Space Center. We proceeded from the use of a human hair sandwiched between two lenses, introduced by Edelman, to special dyes tested and found safe by Bausch and Lomb, to cooperation between Kenyon and Leroy Meschel, an ophthalmologist in San Francisco who produced the appropriate lens shapes and curvatures for us for our spacelab missions. E.R., who had begun working with us as an undergraduate on the problem, did his Master's thesis on a video-based monitoring system using lines in a contact lens. (He established a student longevity record in the lab by continuing to pop in during his years as a Harvard-MIT medical student.)

In an attempt to rid ourselves of the burden of data reduction of eye movement photographs and video tapes, Bob Kenyon and students worked on a series of real-time ocular torsion transduction devices in the early 1980's. Most of these devices required the attachment of some marker or transducer to the eye by means of a contact lens, as always affixed with drops of distilled water which sufficed to stabilize the lens for periods of approximately five minutes. One early device used a polarizing material sandwiched between two contact lenses, but the mechanical implementation proved incompatible with a comfortable lens. Another used a division of the contact lens into a white and a black half which was then detected photo-optically by small photodiodes, much in the manner of our limbus tracking device. Most recently, Kenyon employed the technique originally developed by Robinson and later used by Collewijn, of attaching a small pickup coil out of the

plane of the cornea, extending from a contact lens, which detected rotations in the magnetic field of large coils which surrounded the subject. Although methods have been improved, and Collewijn and his group have recently published significant findings on basic ocular torsion characteristics, much of the required fundamental and clinical research awaits the development of a practical and low cost continuous measurement system.

General Background

The Laboratory has always been small, usually totalling 15-25 people, and has been primarily populated by graduate students and faculty, with a few dedicated staff and occasional post-docs. It began in the infancy of what is now called biomedical engineering, and retained a basic theme with varying application areas over 25 years. The collaborative effort, which became known first as the Man-Vehicle Control Laboratory and later as the Man Vehicle Laboratory (as we lost "control" in 1968), began when I joined the faculty of the Aeronautics and Astronautics Department in 1962.

The laboratory was founded by Professor Yao Tzu Li and myself to pursue applications of biomedical engineering relevant to aeronautics and astronautics. Professor Li, who at that time was head of the Aero Department's Division of Instrumentation, Guidance and Control, is an extraordinarily imaginative and versatile engineer and entrepreneur. His talents have been brought to bear on problems ranging from building an underground airplane engine factory in China during World War II to developing the first practical adaptive control systems applied to optimizing the performance of aircraft engines, in collaboration with Dr. C. Stark Draper. He has started two successful transducer companies and the MIT Innovation Center. He continues at this time as Chairman of the Board of Setra Systems, and pursues the application of several other innovations, chiefly the realization of a practical low-cost water purification and desalinization system. In recognition of his achievements and contributions, he was elected to the National Academy of Engineering in 1987. Li's earlier involvement in bioengineering included inventing and serving as the only test subject for a device consisting of springs to increase the undamped natural frequency of the leg in order to permit people to walk faster without increased effort. (Apparently the springs worked, but nearly were the undoing of Y.T., as he ran with them on a treadmill at the Army Natick Laboratories in a test chamber that was set for the temperature and humidity necessary to evaluate jungle clothing.)

My own interests in the late 50's were in control systems. My background was in physics, electrical engineering and mathematics. When the space age began with the launching of the first Sputnik, I was on the SS Liberte sailing to France for a year of studying mathematics and computers. The relevance of space only became apparent to me when I returned to the Instrumentation Laboratory (now the Draper Laboratory) in 1958 to work on an inertial navigation system for use in a predecessor of the Space Shuttle, the DynaSoar program of the Air Force, which was later cancelled. Most of the work surrounding me, and the thesis topics of my peers, was concerned with aspects of inertial/doppler/stellar navigation systems including the questions of compensating for instrument errors and adapting to changing noise conditions and component failures. The cancellation of the DynaSoar program was certainly one contributor to my interest in a different area for my thesis.

My interest in eye movements came from a chance discussion with my wife's friend, Howard Hermann, in 1959 and a meeting with Larry Stark who was about to move from Yale to MIT. I recognized the potential for treating the human eye movement control system using the same tools as we were using in the Instrumentation Laboratory for analysis of fire control systems. Stark had just completed his pioneering research showing the utility of linear servomechanism theory in explaining several important aspects of the response of the pupil system to variations in light. He was excited by the idea of extending this work to analysis of the eye movement system as a control system. Stark agreed to make that part of the work of the new laboratory, which Jerry Wiesner and Gordon Brown helped him establish in Cambridge. The idea was growing that engineering had something to contribute to biology besides instruments. The blessing of Norbert Wiener and the contributions of Warren McCulloch and Jerry Lettvin created a stimulating atmosphere for a new enterprise.

I had learned enough about eye movements to recognize the potential of a thesis in this area and approached Dr. Charles Stark Draper with the idea of pursuing it in the Instrumentation Laboratory. He was incredibly supportive. Doc chatted with me in his office, crowded with awards, on the top floor of the old shoe polish factory at 68 Albany Street, and told me in no uncertain terms who to keep out of the lab if I was to stay in his favor. He reminded me of his undergraduate background in psychology at Stanford and arranged to support my thesis research in RLE and the Servomechanisms Laboratory with his own "instrumentation fund" accumulated from book royalties. He was generous enough to include me as an author of an article on men vs. machines with Phil Whitaker, and then to bring me to the IAF in Warsaw to share his limelight.

Draper continued to offer encouragement and suggestions as well as support throughout my doctoral program and later career. Win Markey was given the task of tracking the project, even to the extent of verifying the seriousness of my winter in Puerto Rico with Jose Del Castillo, studying the eye movements of land crabs during rotation. (Only after one bit me during a test, and refused to let go, did I develop a taste for crabs as prepared in the special Puerto Rican manner.) To pursue the thesis, I had to develop a means of measuring eye movements. No adequate techniques were available at the time. I, therefore, began a career-long involvement with the development and use of eye movement measurement devices and proceeded to perform the set of experiments which led to the sampled data model for eye movement control. The major innovations which led to this model stemmed from control systems, including on-line computer control (a novelty in those days) and experimentally manipulating the eye movement loop gains. Gerhard Vossius, a German physician then visiting Stark, worked alongside me in the dark basement of RLE as we struggled to find a common language (English) and common ways of expressing ideas of homeostasis (servomechanism theory). Walter Wrigley, the long-time head of the Instrumentation Program, served as academic supervisor with admirable tolerance for all my aberrations.

The Beginning of the Laboratory, 1962-66

When Draper invited me to join the Aero/Astro faculty in 1962 to establish a bio-engineering activity in the department, it was a new departure. (I later heard that the Department Visiting Committee had discouraged any involvement with medicine. That would have been all that Draper needed to proceed!) Li and I began our work in the field of manual control. These studies of the human operator as

an element in a closed-loop control system concentrated on adaptive control and non-linear characteristics. The emphasis then was still on single loop, single-output control systems. With the endorsement of Jerry Elkind of Bolt, Beranek and Newman (BBN), for whom I was consulting, we quickly obtained NASA support for this activity. In 1966, with the support and guidance of NASA's Roger Winblade, MIT hosted the second in the formalized series of "Annual Manuals" (Annual Conferences on Manual Control). Among the more unusual manual control activities, Lew Nashner developed an automatic stabilization system for a motor bike, and risked limb and arrest as he tested it around the athletic fields. The bike was Y.T.'s own property - and fit in with his interests in developing safe, inexpensive personal transportation appropriate for developing countries.

Our interest in inertial systems and their relationship to the human operator problem naturally led to aerospace applications concerning the role of motion cues in piloting. The question we posed in 1964 was to keep us busy for nearly twenty years: What effect do motion cues, sensed by the vestibular apparatus, have on the pilot's rating of an aircraft, its stability and his performance? To study this problem, we obtained from NASA Ames Research Center an NE-2 moving base flight simulator, through the assistance of Mel Sadoff and John Stewart. Jacob Meiry, the first of a series of Technion graduates to join us, and I installed this all-analog device, powered by welding generators and a train of rotating motor generators, in building 17A. (Y.T. was so pleased and surprised when we completed the job and tested it one Saturday morning, that he took Jake and me to lunch at Locke Obers, despite our greasy hands and work clothes.) A series of master's students used this simulator to demonstrate the importance of motion cues in lead generation for pilots. The theme that began to emerge was that pilots would make use of the acceleration cues from motion if they were needed to overcome destabilizing delays or phase lags in the system, but that the cues were unneeded for very well-behaved vehicles. Vieko Vuorikari, from Finland, showed the importance of motion cues in the early and correct detection of a failure in the automatic landing systems of a transport aircraft resembling the Caravelle. Peter Benjamin explored the role of motion cues in the piloting of a helicopter without stability augmentation. In the mid-60s, much of the Aero-Astro world was concentrating on Apollo issues, and we were no exception. Phil Kilpatrick studied the (negative) influence of high frequency bending mode motions upon the emergency manual control system of the first stage of the Saturn Five rocket. (As finally designed, but never used, the manual control stick had to be heavily filtered to prevent the pilot from chasing the bending modes.) Our close ties with the Instrumentation Laboratory, which was designing the guidance systems for Apollo, involved several students in the human factors problems which were facing Jim Nevins, my former supervisor. Ivan Johnson first looked at the problem of human tracking of a stroboscopic beacon for orbital rendezvous. Charlie Duke (who was later to walk on the moon) and Mike Jones studied the same problem for potential lunar emergency rendezvous.

As our interest in the mechanisms of motion cuing increased, we turned to research on the dynamic modeling of the vestibular system. It was quickly evident that the existing data concerning semicircular canal function could be put in control theoretic terms rather easily, but the linear acceleration sensing aspects, including the otolith organs, required additional basic data.

In the middle 1960's, we met Ashton Graybiel, the senior American vestibular scientist, who became interested in our work and helped us to obtain NASA funding for basic research into semicircular canal function. The fluid motions in the

vestibular apparatus during so-called "Coriolis accelerations" were central to his interests. We enlisted the help of an eminent fluid mechanician in the department, Eric Mollo-Christiansen and a doctoral student, Bob Steer, went to work on the problem. Although the exact solution lay beyond the scope of that 1967 model, Steer established the fluid mechanics basis for the torsion pendulum model of canal function and, by careful measurements of the density, viscosity, and thermal coefficient of expansion of endolymph, provided a rational basis for the classical caloric testing of Barany. Graybiel came to MIT one summer, along with his colleague Al Fregley and a contingent of labyrinthine defective subjects and a control group of sailors to serve as controls for our tests. We were unprepared for the degree of adaptation made by the patients, or for the disappointment of the young sailors when we informed them that Scollay Square had been replaced by Government Center. The research demonstrated the relationship between otolith function, as revealed by ocular counterrolling, and linear acceleration detection thresholds on our "cart".

Meiry joined the faculty in 1966 and turned his interest to display and control problems of deep submergence rescue vehicles and to voice recognition control systems. Instrumentation development continued in the area of head and eye movement measurements with the development of ultrasonic and optical head trackers.

A New Building - 1966-1970

By 1966, we had made the case that man in space was to be a continuing topic of importance and were assigned space in the new Center for Space Research by Jack Harrington, its founding director. Up until this move in 1968, all of the students were housed in the "barn", a large dreary room in N-52, up Massachusetts Avenue. Our research space was in Building 17a and my office was in a third building. We all walked a lot. The new building brought us all together. The move to Building 37 entailed detailed planning with the Center for Space Research and the architects concerning our requirements for the foreseeable future. The centerpieces of our new facility were our PDP8/GPS hybrid computer, NE-2 simulator, single-axis rotating chair, and hydraulically-driven posture platform. Looking back 20 years later, most of these requirements were short-term and overly specific as none of these 'centerpieces' exist in 1987. The first linear acceleration cart was left in Building 17A because no space was available in Building 37, and was dismantled shortly after our move. The computer was a new and rather advanced hybrid model consisting of a PDP-8 (one of the very first off the production line (we later purchased a PDP 11/34 - serial number 39)) with "DEC tape drives" and a GPS analog system chosen because of its megacycle bandwidth amplifiers. The rationale for a hybrid computer was based upon the contemporary trend toward digital computer data logging (researchers were building their own "Linc-8" computers) and our perceived need to introduce digital computers into real time control of our experimental devices including flight simulators. Flight simulators, up to that point, were almost entirely driven by analog computers. The particular choice of the high-bandwidth GPS analog system turned out to be a mistake, based upon my perception of the importance of dual time simulation and my underestimation of the advances in speed and convenience of digital computers. (The high speed did enable us to draw simple shapes on CRT's - mostly cubes which rotated - but we were still far removed from practical computer graphics.) Our manual control interests at the time emphasized adaptive manual control and we employed a model reference parameter tracking system to solve for the parameters of the human operator transfer function during adaptation to changes in the con-

trolled plant. Hybrid flight simulation at the time used analog integrators and amplifiers for rapid solution of the linear equations of motion and relegated to the digital computer some of the non-linear computations and the setting of parameters for the analog system. Both of these applications required minimal phase lag contributions from the amplifiers, hence the choice of our advanced (but poorly supported) analog computer. The hybrid system was used well into the late 1970's, principally for control of our Link trainer, but the amplifiers and integrators were later used largely as signal conditioners.

The single-axis rotating chair, enclosed in a wooden box, was originally constructed by Gerry Katz for investigation of semicircular canal dynamics and was to serve future students for 15 years. It was brought out to Bedford, MA in 1967 for its most exciting rides. Bob Steer and I were interested in the newly-discovered phenomenon of "barbecue spit nystagmus" whereby horizontal nystagmus continued with a DC or bias component as well as a modulated component during constant angular velocity rotation about the longitudinal axis horizontal. In order to study this phenomenon without the interference of gravity or the dynamic response of the semicircular canals to rotation, we required a stimulus which would permit the gravito-inertial vector to rotate around a non-rotating subject at constant velocity. To accomplish this, we mounted our rotating chair at the end of the arm of the MIT Instrumentation Laboratory's 50-g centrifuge at its Bedford Flight Facility. This centrifuge, normally used for testing inertial navigation systems, had never previously been used for a human experiment. In those days, prior to the existence of a committee on the use of humans as experimental subjects or formal man-rating procedures, we used engineering analysis, testing and common sense to ensure the safety of our system. As the centrifuge rotated, the chair counter-rotated at the same rate so as to achieve our desired stimulus. Eye movement recordings of nystagmus modulation as a function of depth and frequency of g-variation were employed in development of a model for barbecue spit nystagmus. Steer used these results to propose a "roller pump model" for steady pressure against the cupula of the semicircular canals under a rotating specific force vector. (However, later animal experiments in other labs showed that the otolith organs, rather than the semicircular canals, were probably responsible for the continuous compensatory nystagmus during this sort of bizarre motion.)

Steer's thesis also led him into the world of biophysical measurements and into a continuing, if sporadic, collaboration with the Massachusetts Eye and Ear Infirmary. From Herb Silverstein, he obtained small frozen samples of endolymph, and was able to determine the important parameters of viscosity and thermal coefficient of expansion necessary to complete the simple model for semicircular canal mechanics. In conjunction with Al Weiss, he demonstrated the comparability of human nystagmus thresholds to angular acceleration and to caloric stimulation.

The NE-2 simulator was moved into 37-146, our main laboratory space, and required a special concrete base. Because of its size, it was installed prior to completion of the building and the internal walls. It served as a workhorse until 1985 for our series of studies on the effects of motion cues on flight simulation and pilot performance, culminating in the Ph.D. thesis of Dick Shirley and the follow-up Master's Thesis of Peter Dinsdale. Shirley explored the influence of roll motion cues for a wide variety of vehicle dynamics by comparing pilot describing functions with an attitude instrument only versus roll plus an attitude instrument in the presence of external disturbances. He was able to demonstrate the importance of roll motion cues in moving up the open loop crossover frequency which was especially important for control of marginally-stable vehicles and with higher

frequency disturbances. Dinsdale extended this work to a comparison of roll and yaw motions with the head upright and supine in order to parse out the contribution of the linear acceleration sensors relative to the angular velocity sensors. (Dinsdale's "can-do attitude" extended to shorting out all of the safety interlocks on the NE-2 simulator minutes before demonstrating it to the MIT Visiting Committee and senior administration, because the system had been acting flaky. Like many of us, the NE-2 didn't work well in warm weather, and paused for a break every ten minutes during hot spells.) Shirley went on to continue this work while running a major portion of the NASA Ames flight simulator facility, before returning to the Boston area to head the Human Factors Department of Foxboro Corporation. Dinsdale, after a stint in the Southern California aerospace industry, returned to run his family farm in Oregon.

Our adaptive manual control work, meanwhile, moved into a new phase of looking at simple cases of human learning of manual control situations. Al Preyss, then an active duty Air Force pilot, returned to MIT for his Ph.D. program and did his thesis on identification of the phases of learning manual control technique. Al was one of many pilots in the lab who brought his first-hand flying experience and instincts to bear on manual control problems. His interest in the process of learning skilled tasks extended to the area of air-to-air combat and electronic aids for the pilot. Eventually Al and his MIT student friend Rick Willes went on to the faculty of the Air Force Academy and proposed an advanced 'snap-shoot' gunnery display which Jake Meiry's company went on to develop. T.T. Chien followed this work with a Master's Thesis which concluded this branch of study of human learning for us. Y. Nozawa foresaw some of the later issues concerning testing and reliability with his thesis concerning optimal pre-launch test durations.

Our interest in advanced displays for manual control began in the late 60s. We explored several aspects of three-dimensional displays and worked on displays whose perspective and orientation changed as one walked around them. This necessitated techniques for measurement of head orientation as well as primitive graphics systems implemented with great difficulty on the PDP-8. Vector rotations were achieved with algorithms borrowed Wally Vander Velde's work in the field of strapped-down inertial guidance. Chuck Oman solved the hidden surface removal problem. We never made much of an impact on the still infant computer graphics field, primarily because of the primitive graphics hardware available to us at the time. It is interesting to see our early figure showing a 3-D projection still appearing (unreferenced) in contemporary computer graphics texts. For head movement measurements, Jim Deckert developed an ultrasonic system which measured the difference in time delay between the receipt of a click on the pilot's helmet at different fixed microphones. (He went on to run a digital control group at Draper Labs.) With Jim Nevins, we also developed a non-contacting optical head tracker and used simple flexible shaft measurements of head movements. Robert Vircks studied the importance of head movements in generating depth cues using these facilities. Our interest in head movements as a way of generating stereo vision continued for several years, until the hardware limitations brought it to an end. Head movement and eye movement driven simulator scenes are now at the cutting edge of flight simulator research in the late 1980's, with improved hardware.

Our work in the late 60s was supervised by Jacob Meiry, Y.T. Li and myself. We had two capable staff engineers, John Hatfield and Henrietta (Mimi) Galiana. Our paper studies of life sciences technology for NASA during that period carried us as far afield as closed food, water and atmosphere systems for spacecraft. Mimi

and I bought a biotelemetry unit for measurement and transmission of leg muscle EMG's to a computer where they would be superimposed upon stick figures of patients walking for the purpose of gait analysis, in collaboration with Don Pierce, an orthopedic surgeon at MGH. (We had hoped to be the first to measure and interpret the muscular activity of skiers during turns, but by the time we got the equipment for EMG telemetry working all the snow had melted. Dan Mote at Berkeley later beat us to it.) The obvious inadequacy of the PDP-8 for this purpose led us to our first use of the Adage AGT-30 computer, an advanced 32-bit special purpose machine which required a high degree of specialized programming skill. Although this machine resided in Building 35 in the Electronics Systems Laboratory (now LIDS), the MVL bought part of its memory in a special arrangement with Prof. George Newton. The machine, under the watchful eye of Mark Connolly at ESL, was to serve us well in a variety of human factors experiments over the next five years.

Meanwhile, the manual control problem became more focused on ways of delivering several parallel signals to the human operator without overloading him. George Friedman wrestled with the multi-loop manual control problem associated with helicopters. Pitu Mirchandani conducted a study of the use of auditory feedback for parallel processing of compensatory tracking cues with encouraging results. Philip Noggle, a Marine pilot back for graduate study, investigated the utilization of kinesthetic feedback by making the control stick force against the operator's hand represent a function of the error signal to be nulled. Anticipating the advent of the "glass cockpit" by 15 years, we began investigation of integrated displays for aircraft controls in the late 1960's, still using the PDP-8 and the Adage graphics computer. Predictor displays had already been introduced for submarines and we attempted to show their utilization for a difficult aircraft control problem. Gordon Kemp, from the Canadian Armed Services, developed an interesting and effective "bottom window display" for VTOL. In addition to the usual moving grid pattern representing the land, his display employed a "down pointer", like a searchlight shining out the bottom of the aircraft, which, along with a predictor display vector, greatly simplified the task of stability during hover. Finally, along this line, Noel Van Houtte, from Belgium, developed a threedimensional integrated display landing aid which permitted even inexperienced operators to land an STOL simulation at 17-degree glide slopes. This "telephone pole glide slope" was the last major display activity on the PDP-8. As happens so often, the concepts were ahead of the technology and made relatively little impact.

Basic research on eye movement and vestibular models grew in importance during the late 1960's. Jack Forster and Noel Van Houtte worked to convert my deterministic sampled data model for eye tracking movements into a stochastic system with random sampling to better explain the observed ranges of eye movement responses to target pulses and steps. Syozo Yasui, a Japanese control engineer who did his Master's Thesis with us on adaptive control systems, returned to MIT for Ph.D. work and chose this area. (Yasui was the first of several graduate students, all excellent, who were sent our way by Prof. Washizu of Tokyo University, who directed a similar laboratory.) He began a major study of the dynamics and modeling of pursuit eye movements, optokinetic nystagmus, and visual-vestibular interaction, making use once again of the single-axis rotary box. Yasui was known for his irregular hours (he believed that a 24 hour cycle was inefficient), his confidence that he could solve any complex problem by thinking about it hard enough, and his tendency to save money on switches by twisting bare wires together. Anil Phatak from USC spent two fruitful years with us working on the problems of adaptive manual con-

trol. Yuri Plotnikov, of the Moscow Institute of Aviation was the first of our Soviet visiting scholars.

A long-lasting influence on the Laboratory began with the appearance of Chuck Oman as a new graduate student from Princeton in 1966. I had noted that the torsion pendulum model of the semicircular canal in the literature required an additional low-frequency adaptation term to explain subjective responses for long-duration measurements. In his Master's Thesis, he completed this modeling and extended it to nystagmus. The adaptation model was subsequently adapted by Jay Goldberg and Cesar Fernandez in their landmark physiological studies and has become very widely known. Chuck also worked on our early "anti-vertigo display" in the rotating chair, based on a moving stripe display driven by a model of the semicircular canals. (This was to be the forerunner of our extensive investigations of visual-vestibular interactions over the past 15 years.) For his Ph.D. Thesis, Chuck went on to further develop the fluid mechanical model of semicircular canal function and to establish the thermal response characteristics of the semicircular canal as reflected in caloric testing by sudden changes in plane of the head after the thermal system had reached equilibrium. Chuck's device for rapidly pitching a subject through 90 degrees represented a solution to low budget motion devices which could only have been invented by a top sailor. Although the thermal modeling work went relatively unnoticed until the German Spacelab experiments 15 years later, the semicircular canal modeling paper showing the minimal deflections of the cupula during normal head movements created immediate and continuing interest. Chuck also worked with Larry Frishkopf at RLE for part of his Ph.D. Thesis, exploring the responses of the lateral line organ, and continued thereafter with basic studies of the mechanics and afferent encoding characteristics of the semicircular canals of the skate in conjunction with Frishkopf and Moise Goldstein at RLE and at Woods Hole. The continued refinement of mathematical models of the semicircular canals has been a theme of Oman's research over his entire association with the laboratory and has led to the most advanced models in use.

Another major activity in the late 1960's was the first work on posture platforms in our laboratory conducted by Lew Nashner for his Ph.D. Thesis. Lew's original two-degree-of-freedom platform was the beginning of a major international interest in posturography and modeling of the various components associated with human stability. A direct descendant of this platform, totally rebuilt and redesigned but using the original mechanical frame, is used in our facility at the Kennedy Space Center for testing astronaut stability. Nashner, meanwhile, became the world leader in posturography, in Portland, Oregon and supplies the clinical and research community with commercial platforms.

Alan Natapoff joined the Laboratory in the late 60s for the purpose of blending his theoretical work on human brain evolutionary studies with our work on pilot cockpit decision-making. His earliest contributions relating symmetry in mathematics to human mental function led instead to a fruitful avenue of research in novel techniques in mathematical pedagogy which became the mainstay of his work. In later years, Natapoff became the biostatistics consultant to students and staff of the Laboratory, thereby fulfilling an essential need. (My close friendship with Alan goes back forty years - to basketball games and math puzzles in Junior High School).

Diversification During A Recession: 1970 - 1975

The period of the early 1970's was a depressed and depressing one for the aerospace industry, and our laboratory stood out as one of the few areas of growth in the Department. Between the effects of the recession, student post-Vietnam dissatisfaction with technology, the Draper Lab diversification, and the post-Apollo letdown of interest in the space program, our department's undergraduate enrollment fell to a low of 17 new sophomores, from a steady level of 60 in the late 1960's, and compared to 140 in 1986. One of the plans for reorganization of the School of Engineering would have combined Aero/Astro with Mechanical Engineering. We were encouraged to extend our expertise to relevant problems which might lie farther from the field of aeronautics and astronautics.

For diversification we sought additional paths for application of our skills in the application of control systems to biomedical problems. It was in this atmosphere that we grew into clinical applications, basic psychophysics, physiology and aviation safety.

We began a long series of experiments involving visually-induced motion which continues through to our space experiments in the eighties. We also launched a series of activities in aviation human factors which extended beyond the single loop manual control problems which had occupied us during the 60s. Ren Curry was recruited to leave Cornell and join our department faculty. He concentrated primarily on this latter area. Ren had written his Ph.D. dissertation on optimization, estimation and quantization in our department under Wally Vander Velde so that he was already familiar with MIT. At that time, NASA had established one of its principal research centers, the Electronics Research Center, in Cambridge in temporary facilities in Tech Square. The proximity of this center and their interest in guidance and control systems developed an optimism concerning long-term large government/university research programs. (Alas, these hopes were short-lived as the ERC succumbed to political pressures and was abolished before it could move into its new facilities, now occupied by the Department of Transportation Research Center in Kendall Square.) The Link GAT-1 served as a test platform for a project on PWI (Pilot Warning Indicator or Proximity Warning Indicator depending upon whom one was addressing). National concern with midair collisions led NASA to consider a low-cost alternative to the expensive cesium clock collision avoidance system then being developed. This low-cost system was based upon optical detection of the beacon of other aircraft and would only be of use when visibility permitted it. However, since almost all of the midair collisions involving light aircraft occurred during VFR, this was not considered a significant shortcoming. Our portion of the project was to develop a display for the single pilot aircraft to tell him where to look for potentially dangerous traffic. We began with a localized auditory display in which the sound source would appear to emanate from the direction of the target, but abandoned the effort because of the ambiguities associated with reflections inside a small cockpit. Curry, John Hatfield and I eventually developed and patented a simple clock face, multisector LED display for this purpose. The determination of the element sizes and spacing was accomplished as the Master's Thesis of Basil Smith. To permit an adequate simulation with outthe-window search behavior in conjunction with the PWI, we moved the Link Trainer from the Main Laboratory to the basement of Building 37 where we surrounded it with a large wooden hemisphere to serve as a dome projection screen. Targets were projected on the earth/sky dome to simulate other aircraft, matched for detection time. Although the PWI display never did become a reality, it led us into a long-term and fruitful joint activity with the Flight

Transportation Laboratory, the Electronics Systems Laboratory, and eventually Lincoln Laboratories in the area of traffic warning displays. The initiative for this extensive program lay with Tom Imrich, then a graduate student of Bob Simpson's. The basic idea was to improve safety, reduce the frequency of aircraft communications, and shorten delays in the terminal areas by provision in each cockpit of the relevant portion of the air traffic control situation. To implement the development and experiments, Tom arranged a gift from Boeing of its then-surplus supersonic transport wooden cockpit mockup which was cut in half to permit it to enter Building 35. Once reassembled, it was linked to the Adage computer which accepted its controls, calculated the equations of motion of a Boeing 707 transport, and generated electronic displays of both the conventional aircraft instruments and the newer traffic warning display. The first of our human factors experiments conducted under the supervision of Curry, was the Master's Thesis of Robert Anderson, who worked on the traffic warning indicator format. David Melanson wrote his Master's Thesis on the traffic situation display as it related to aircraft detection and solved many of the knotty programming problems associated with the simulation. Later studies were to cover the ability to predict potential collisions from intermittent updates.

Curry built on his interest in human factors in aviation to initiate a research grant from NASA's Ames Research Center on the role of the pilot in automatic landing, following up on a theme we studied with Vuorikari ten years earlier. Curry's emphasis on the workload versus reliability issues continued long after his association with MIT, and established him as the nation's leader in this field at Ames. Workload evaluation and pilot workload reduction became a theme in the manual control field and stayed with us in the MVL for some time. Pitu Mirchandani demonstrated the effectiveness of a supplemental auditory cue for a subject performing challenging multi-axis tracking. Basil explored an analytic technique for control of multi-loop systems. It was already clear that the earlier emphasis on single-axis, single loop continuous control would pass into history in the manual control field. The end of the 1960's and beginning of the 1970's marked the end of our activity in manual control as it had originally been defined. The single loop pilot control problem for compensatory or pursuit tracking seemed to be adequately handled by the "crossover model" developed and refined by Duane McRuer and his colleagues at Systems Technology Inc., based upon classical control frequency response methods. Extensions to deal with care for multiloop and inner-loop control and for instrument scanning seemed straightforward, and did not promise any revealing insights into the nature of human control. My own line of research on modelling the human as an adaptive manual controller, which had begun in the early 60s in conjunction with Jerry Elkind at Bolt, Beranek and Newman and with Dave Greene, then a psychology professor at MIT, seemed to have run its course and became largely an exercise in on-line parameter identification. Our interest in man-in-the-loop models in the future was to lie primarily in the modelling of motion cue and wide field visual cue influences on pilot control performance.

Our work on visually-induced motion had begun in the late 60s with the development of our "anti-vertigo display" which was an early and not terribly effective attempt to provide moving visual cues to reduce the conflict between vision and the vestibular input. The background for this notion goes back to the "Kinalog", a concept developed by Larry Fogel, then at General Dynamics. He thought that pilot disorientation could be reduced by having the attitude indicator gradually switch from "outside-in" to the conventional "inside-out" as the vestibular cues changed during a turn in an airplane. His idea never came to fruition, but I

reasoned that a more compelling visual horizon or indicator of lateral motion could be more effective. In our first attempt Oman and I built a vestibular model-stabilized display and demonstrated that control performance could be either enhanced or reduced depending upon the phase of the moving visual scene with respect to the motion of our single axis rotating chair, and arrived at ideas of sensory conflict in motion sickness which paralleled those of Steele and especially of Reason.

A major jump forward for us resulted from the presence in our laboratory for one year of Johannes Dichgans, then an assistant to the famous neurologist, Richard Jung of Freiburg, Germany. Dichgans shared our interest in visually induced motion, properly termed "vection" and had already explored many of the parameters of yaw vection with Thomas Brandt. His year at MIT was spent performing three full-time research affiliations; with us, with Dick Held, and with Emilio Bizzi, in addition to playing the violin and skillfully racing Tech Dinghies on the Charles. During this time, we made considerable modifications to the Link Trainer to permit it to serve as a general-purpose motion system of great utility for our basic experiments on vection. The Trainer was turned into a general purpose three-degree-of-freedom motion device by controlling its servos through the hybrid computer one floor above. Bob Murphy equipped the Trainer with a generalized pattern motion generator consisting at first of two moving film planes to project Moire patterns. Later we added a simple servo-driven moving film projector, augmented by a motorized dove prism to rotate the pattern. By using this relatively simple system to back-project stripes on the front and side windows of the trainer, we were able to explore many aspects of visual-vestibular interaction over the ensuing decade. Thomas Brandt, also a neurologist from Freiburg, came to our laboratory and, along with Dichgans and myself, worked out the influence of yaw vection on perception of true body rotation. Meanwhile, Dichgans found both in the Link Trainer and independently in his setup with Dick Held in the Psychology Department, that visually-induced roll motion produced a paradoxical steady tilt. (The paradox consists of the sensation of continuous movement without any sensation of going anywhere - a phenomenon which is well known to MIT graduate students!) We proceeded to study this phenomenon in the Link Trainer by the first of a long series of experiments using the motion nulling technique in which the subject attempts to balance out a motion disturbance in the presence of a visual signal.

My own interest in human reactions to motion stemmed not from a fascination with the vestibular systems for its own sake, but rather from the opportunity to explore human control strategies at the sensory-motor level. Behind most of our experiments was the thought that the brain somehow managed to blend multiple (noisy) dynamic measurements in a possibly optimum fashion, and to discard unreliable inputs when needed. The adaptive and self-repair properties of human spatial orientation were clearly accessible in terms of perception and eye-movements in response to vestibular, tactile and visual inputs. The temptation to find out how the brain solved the adaptive control and self repair problems in control was irresistible, and kept our lab involved in multisensory integration at a time when most researchers were working on one sensory modality at a time. My particular interests grew in the subject of visual-vestibular interaction over this period and I worked on models based upon conflict detection and conflict resolution. In the ensuing years, we made great use of the moving stripes on the Link Trainer to develop visual-vestibular interaction grew basic data analysis for vertical self-motion detection (Alfred Chao) and fore-aft motion detection with its associated asymmetries (William Chu). Not until the end of the decade, with

the work of Greg Zacharias and then Jen-Kuang Huang, were we to develop satisfactory models for the interaction of visual and vestibular cues in human perception of spatial orientation in all axes.

Another vestibular motion processing theme which became of increasing interest was that of otolith-canal interaction. Our work went back to Bob Steer's thesis and built on the data presented by Steer, by Melvill-Jones, Alan Benson and a number of others to determine the basis for "barbecue spit nystagmus." Among our contributions were the identification of the frequency response of linear acceleration-induced nystagmus (L-nystagmus); a topic which was to reappear as a formal Spacelab experiment more than ten years later.

A desire on my part to learn the techniques of single-unit recording in awake primates, along with the hope that the underlying mechanisms of visual-vestibular interaction could be clarified, led me to take my first sabbatical year in Zurich in the Neurophysiology and Neurology Laboratory of Professor Gunter Baumgartner. (Prof. Max Anliker, who had just left the Aeronautics and Astronautics Department at Stanford to set up a Bio-engineering Institute at the ETH in Zurich, arranged for me to be a Visiting Professor, with minimal teaching responsibilities.) I was privileged to work with Volker Henn, a German neurologist/neurophysiologist who had just returned from a fruitful collaboration with Bernard Cohen in New York. Together we set up a laboratory for primate visual-vestibular oculomotor research, concentrating in that first year on single-unit recordings from the vestibular nucleus during simultaneous rotation and optokinetic stimulation. We modified the clinical optokinetic facility so that we were able to have parallel human experiments with the same stimuli. By measuring eye movements of the monkeys and the humans, recording human subjective rotation sensation, and recording monkey vestibular nucleus activities, we were able to make the jump from human perception to neurophysiological responses in the brain stem. We were fortunate enough to find this correlation during our first few experiments and to establish the basic relationships among perception, slow phase of nystagmus, and various types of vestibular nucleus neuron responses. Henn carried this work further after I returned to MIT, with Walter Waespe and others, and built an extremely productive primate neurophysiology laboratory. Our basic vestibular stimulation device in Zurich was a gyroscope test table I obtained surplus from the Draper Laboratory and modified to carry a primate chair and transmit neurophysiological and eye movement signals through slip rings. Since the rotation axis of this chair could be rotated from vertical down to horizontal, we were able also to use it for a study of otolith-canal interactions in the monkey by "off-vertical rotation." This data complemented the fragmentary information on human responses to such stimuli and laid out a data base for the modelling of the interaction between gravito-inertial force and rotation in the development of nystagmus modulation and bias. Back at MIT, we pursued the canal-otolith interaction problem with humans, looking primarily at perception of orientation. A major study of the interaction between linear and angular acceleration was conducted by Chuck Ormsby for his Ph.D. Thesis. This research began our changed pattern of using outside simulators for some of our research purposes. Ormsby performed many of his experiments in the six-degree-of-freedom large moving base device at NASA's Langley Research Center in Virginia. This device, originally developed to permit astronauts to practice the Gemini/Agenda docking maneuver, permitted him to investigate the detection threshold on the basis of changing angular velocity steps and impulses, as well as to mix linear and angular stimulation. The models in Ormsby's thesis, covering a "signal and noise" formulation for thresholds and a non-linear gravito-inertial signal processing model to explain perceived orientation relative to the vertical,

proved of longlasting value and were frequently quoted in the vestibular research community. Ormsby remained in the area to head a systems group at TASC, where he has hired other MVL alumni.

Chuck Oman joined the faculty in our division in 1972 upon completion of his Ph.D. thesis and proceeded to work on vestibular models and displays as well as to extend his work with Larry Frishkopf under NIH sponsorship to study vestibular mechanics in the skate. This work extended to a series of important endeavors in the 80's extending understanding of the physical processes underlying semicircular canal function.

Sherry Modestino was hired as a secretary in the laboratory in 1972 during my sabbatical. Sherry previously had been a doctoral student and instructor in Chemistry at WPI, and clearly was over-qualified for the position. Over the following 15 years, she assumed ever more responsibility for laboratory affairs and acted as our Editor-in-Chief, Reference Librarian, Personnel Director, Fiscal Officer, Travel Coordinator, Computer Systems Manager, Researcher on Astronaut pre- and post-flight visual-vestibular interaction, and MVL Hostess with the Mostest. The importance of continuity and dedication in administration, represented by Sherry, at its best, cannot be overestimated in an academic laboratory.

Larry Leifer, a Visiting Scientist from NASA Ames, spent a year with us contributing to our expertise in electromyography, and developing his new interests in robotics and design. Leifer followed me with Anliker in Zurich and now leads a highly successful program in the latter area at Stanford.

By 1970 our interest in space research passed from the general utility of microgravity for vestibular investigation to a number of specific applications. The nearly annual symposia organized by Ashton Graybiel on the role of the vestibular organs in the exploration of space, generally held in Pensacola, brought together a stimulating international community focussed on this problem. We were accepted into this group and made regular contributions. Soon it became apparent that the MVL, because of our location in a Center for Space Research and our engineering approach to space vestibular problems, was in an excellent position to pursue space experiments as well as modelling. Jim Tang, Oman's first student, conducted a study of the interaction between head tilt angle vection and ocular torsion. This was the precursor of activities that led to major studies of the influence of otolith signals on visually-induced tilt, leading eventually to our Spacelab rotating dome experiments in the 80s. I wrote on the problems of vestibular stimulation during various motions in a rotating spacecraft. (Artificial gravity had been a hot topic during the 60s, and a subject for frequent discussion at the Pensacola symposia. By the early 70s, however, NASA apparently decided that human adaptation to long duration flight would be without problems, even on return, and research on rotating spacecraft and the physiological consequences was discontinued. Now, 15 years later, the questions of the necessary and tolerable rotation rates and radii for artificial g are once again being studied in preparation for possible multi-year missions and travel to Mars.)

We began investigations of "natural control" of astronaut body position and posture during extra-vehicular activities. Lonnie von Renner first performed this study by looking at the ability of a subject to stabilize his body position through the natural vestibulo-colic reactions of head stabilization. This was relatively unsuccessful when we relied upon neck electromyographic signals for the control. Consequently, Bernard Chouet developed an electrooptical head tracking

system to allow us to measure head orientation and drive the Link Trainer attitude accordingly. Although this technique did not prove practical for EVA control, it did allow us to determine the describing function for head movement control as an effector. Sherman Vinograd, who was then Director of Biomedical Research at NASA Headquarters, spent a year with us in 1974-75 as a Visiting Scientist, to expose us to the biomedical instrumentation needs for space flight and to refresh his clinical skills at the Beth Israel Hospital. Vinograd had earlier organized a very successful one-week summer course with me at MIT, calling on many of the outstanding experts in Aerospace Medicine of the time.

In 1973, Oman and Tole participated in a collaborative project with Walt Hollister and Art LaPointe of the Measurement Systems Laboratory, experimentally studying skill degradation among 50 randomly chosen private pilots from the New England area. The study used both written exams and in-flight observations. Statistical analysis supported the view that skill covaried with the log of total flying time and also with the average number of flight hours flown during the previous month, as determined from computer analysis of logbook records. The findings did not totally support the then-current regulatory push for biannual flight reviews among private pilots, which may explain why the FAA paid little attention to the results.

Animal research has always presented a problem for our laboratory. I had done some gross behavioral/eye movement work on crustacea during my doctoral studies but did not return to any animal research until my collaboration with Henn in Zurich. I returned in 1973 convinced of the value of a laboratory in which closely-related experiments on animal neurophysiology and human behavior were performed. The animal of choice for vestibular-oculomotor studies, beyond the end organ, was clearly the monkey, which presented enormous practical difficulties for any work in the Center for Space Research. I was therefore forced to abandon the effort or look for outside collaboration. Fortunately in the middle 70s Dick Held, Emilio Bizzi and I taught a course in sensory/motor systems which placed considerable emphasis on plasticity. Out of that course grew a collaborative research effort with Bizzi to investigate the limits of geometrical plasticity in the vestibulo-ocular reflex by using rotating prisms on monkeys. Lionel Greene came to us from NASA Ames Research Center as a post-doctoral Fellow to perform this work using Bizzi's animals and facilities in the Psychology Department. The results of two animal experiments, showing an absence of cross-axis plasticity, were at variance with information that was emerging from other laboratories dealing with similar experiments in humans and the cat. These experiments were not followed up after Greene's departure and that aspect of our collaboration came to an end. The physical distance between laboratories and the fact that our experiment was a "guest" in another laboratory possibly contributed to the failure to establish a long-term close tie between our human spatial orientation work and related monkey experiments at MIT. I did, however, continue to work with Henn, both in further analysis of the material we gathered in 1973, and in a distant collaboration on some newer experiments dealing with VOR frequency response.

Our longest-running animal experiment program was that of Howard Hermann, a Research Associate and psychiatrist, who worked with us for many years in his small neurophysiology laboratory. He was able to take advantage of the quiet isolation of the basement of Building 37 to set up a minimum-vibration cage for doing both intra-cellular and extra-cellular recording in the oculomotor pathways of the fish. The intra-cellular work proved too difficult, but the thorough anatomical and neurophysiological study of the oculomotor pathways finally produced a

comprehensive oculomotor wiring diagram for the fish. With the completion of Hermann's work, there was no successor in the laboratory and the apparatus was dismantled. Oman's experiments on the lateral line and the isolated end organ have already been mentioned. That work was carried out in the Research Laboratory of Electronics. Lindsay Harkness, who came to the MVL with her Kennedy fellowship from Oxford, filled her lab space with chameleons and the crickets upon which they fed. (Her photo of a chameleon wearing prism spectacles, which were used for her study of distance judgments, made the cover of Nature in 1977.) Harkness' drawings enlivened the atmosphere and her crickets remained for many months, after her departure, chirping away from the walls. A token frozen chameleon lives on in the MVL refrigerator to this day. Our only subsequent venture into animal research in the MVL did not take place until 1985 when Bob Kenyon prepared a space experiment on chick embryo vestibular development. My conclusion is that animal research related to human performance, though desirable, requires such a heavy commitment of facilities, animal care, specialized techniques and specialized interests, that it is not feasible in one small engineering laboratory primarily concerned with human research.

Ren Curry spent a productive year as a visiting scientist at the NASA Ames Research Center working with their Manned Vehicle Division. Upon his return, we began devoting more effort to a theme which has been with us on and off ever since, that of interactions between the pilot and automatic systems in a cockpit. Techniques such as maximum likelihood estimation, signal detection theory and multi-dimensional scaling were borrowed from psychophysics to apply to modeling human decision-making in the cockpit. The traffic situation display activity on the Adage computer served as a source of several fruitful problems in this regard. Two Israeli doctoral students produced important theses of this type. Eli Gai applied signal detection theory to the problem of pilot estimation with time-varying uncertainty, represented by the problem of detecting the probability of mid-air collisions with intermittent radar updates. (Gai is still associated with the Department, and has risen to Division Leader in the Draper Laboratories.) Arye Ephrath looked at the problem of information requirements for precision landing under 0-0 conditions. These tasks, of necessity, required estimation of pilot mental workload. He explored physiological as well as "side task" techniques to this purpose. Because of our familiarity with eye movement instrumentation, fixation direction was seized upon for workload estimation, and Ephrath used it to monitor attention. Much later, he and John Tole used eye movement measures in a flight simulator at NASA Langley to estimate pilot workload from the irregularity of the scan pattern. Ephrath stayed squarely in the aviation human factors field, building up his flying hours and doing research at NASA Ames, teaching at the University of Connecticut, and leading a group at Bell Labs.

Clinical applications of our research had always loomed as a possibility and came to fruition during this period. Our clinically-oriented vestibular research had several brief extensions into new areas of stimulation. John Tole investigated galvanic stimulation whereby weak currents could stimulate vestibular responses as a possible adjunct to the more common caloric tests. Charles Burr, in his Master's thesis, extended the galvanic stimulation to tests carried out on a posture platform to attempt to quantify the relationship between galvanic stimulation neck position and postural reactions. Dr. Alfred Weiss, Otoneurologist at Massachusetts General Hospital and Massachusetts Eye and Ear Infirmary, was particularly active with us during this period of exploration of clinical test methods. The galvanic stimulus remained a poorly understood and diffuse stimulus which has not come into widespread use clinically. We discontinued our research in this

field except for a brief episode some years later in which it was utilized by Oman and Barry Linder to study the vestibular-evoked response. Nashner's posture platform was considered for patient testing.

To further the clinical applications, we seized the opportunity to help establish an NIH funded Biomedical Engineering Center for clinical instrumentation in the Harvard-MIT Health Sciences and Technology program. Our own area was for clinical vestibular tests and interpretation, computerizing and refining the variety of test protocols and eye movement analyses conducted on a patient complaining of disorientation, dizziness or vertigo. John Tole completed his Ph.D. thesis on a closely-related area, including the development and evaluation of a system for delivering caloric stimulation with air rather than water, and became our Project Engineer in the Biomedical Engineering Center. One of the principal accomplishments was the reduction to a microcomputer of the latest version of our original programs for nystagmus eye movement analysis by detection and removal of the fast phases of the signal. The requirements for this system were well conceived and the algorithms were implemented on an MIT-built special purpose microprocessor using STOIC, a new programming language derivative of FORTH, developed by John Sachs who subsequently left MIT and wrote LOTUS 1-2-3. The choice of a homebuilt, rather than off-the-shelf, microprocessor and a unique language was, in retrospect, a severe mistake. Programmers were not available who knew the language, the system was difficult to maintain and update, and it could not be exported to other users. Finally, after showing the utility of this approach, we watched as industry in the US and Europe proceeded to develop practical commercial versions which implemented similar ideas. In the course of this development, John Tole, ably assisted by our staff engineer, Bill Morrison, designed and constructed a servo-driven rotating and tilting chair for performing clinical rotation tests. This chair remains in use in the lab at this time for motion sickness and vestibulo-ocular reflex research. The project was handed over to John Tole when he left MIT to go to Worcester Polytechnic Institute, as we became increasingly occupied with Spacelab responsibilities in the late 1970's.

In another clinical investigation, we began a long-lasting collaborative effort with colleagues at the Children's Hospital Medical Center to use our biomechanical test equipment for the study of spasticity. Some of the impetus for our extension into the motor control side of things, after our concentration on sensory modelling, was the appearance in our lab of John Allum, a graduate student from England studying on a Kennedy fellowship. Allum was interested in limb movement biomechanics, and built an "arm bender" capable of determining limb mechanical impedance even during active movements. He collaborated with John Tole in a version of "MITNYS", the MIT nystagmus analysis program, and later brought out a commercial version of the eye movement analysis device in Germany. (Allum stayed in the field of clinical applications and currently is on the faculty of the medical school in Basel, directing a clinical research laboratory in otolaryngology.) Among other applications, this device enabled us to directly measure limb mechanical impedance by a frequency response method. We then began an extended period of collaboration with Dr. Sheldon Simon, an orthopedic surgeon originally trained as a mechanical engineer, then heading the Gait Laboratory of the Children's Hospital Medical Center. Alfred Chao, and then Eddy Barak, worked with the device at Children's Hospital to implement limb motion range tests of use in assessing the efficacy of treatment. Not unexpectedly, the major problems were associated with patient interface and patient acceptance of the instrument. It was later further modified to act as an ankle spasticity tester. Our posture platform underwent a similar evolution from basic research device to clinical applications, also in

conjunction with Dr. Simon. The posture platform was included in the clinical vestibular test battery at the Biomedical Engineering Center. Under Tole's direction, and with the able assistance of Bill Morrison and Jay Gould, an Electrical Engineering undergraduate, it was converted to microprocessor control and moved to Children's Hospital for further evaluation. There, as part of the Master's Thesis of David Israel, a Canadian physician who was retraining in Biomedical Engineering, it was applied to the measurement of possible vestibular disorders associated with idiopathic scoliosis. Within the limits of the determinations available from posturography, no correlations could be found which would support a Swedish speculation of vestibular disorders leading to this spinal curvature in teenagers. It did become clear, however, that appropriate use of both fixed and moving posture platforms for vestibular diagnosis required considerable basic research as well as extensive study with well-diagnosed patient populations. Following this exposure, and after the effective work of David Loo, a Mechanical Engineering Master's Degree student, in tying the posture platform to the Gait Laboratory analysis system, our further applications of posturography were restricted to looking at astronaut post-flight postural disturbances. By now, the posture platform was controlled by pneumatic rather than hydraulic systems, for cleanliness and acceptability in the hospital, and had its control sequence and data logging accessible to a special-purpose microprocessor. The platform was returned to MIT for further development and became an important part of our Spacelab testing at the Dryden Flight Research Center and at Kennedy Space Center in the 1980's.

The Biomedical Engineering Center was but one of several activities within biomedical engineering in which we participated in the 1970's. My academic responsibilities as Chairman of MIT's Committee on Biomedical Engineering extended to an active role in the planning of the Health Sciences and Technology program, including the development of a clinically-based PhD program later to become the Medical Engineering and Medical Physics (MEMP) program. This major initiative in joining the physics and engineering strengths of MIT with the medical strengths of Harvard was difficult at first and continually time-consuming, but did accomplish the bridging of several large gulfs administratively and chasms of misunderstanding between the professions. I retreated from several of the administrative responsibilities, including membership on the Administrative Committee, as Spacelab duties required more of my time and more travel in the late 1970's.

By the mid-1970's, our interests in motion requirements brought us to the notice of the flight simulator community. I became involved in the determination of motion requirements for US military simulators. An exchange scholar from Russia, Alexander (Sasha) Efremov, Associate Professor in the Moscow Institute of Aviation, spent a year with us to work on simulator motion requirements. His personal project was an attempt to provide additional phase advance in the visual display to make up for the lack of phase advance which would be provided by a motion system. Sasha provided many fascinating lunchtime discussions and social interactions, and was a continual source of vodka, propaganda, and good fellowship. Some of his most outrageous stories of manipulation of visiting scholars and misdeeds of the intelligence agencies, for which we roundly mocked him, lately have turned out to be true.

Ski injury research began in the early 1970's and has continued as a minor personal offshoot of the main theme of the laboratory. At first, my involvement was limited to analysis of the Waterville Valley accident data. I was an active ski patrolman and worked with Henry Crane, the surgeon in charge, in determining the relationship between injury risk and skier factors. When it began, Chuck Oman

was looking for a project for his statistics course and this fit perfectly. As the years went on, our Waterville Valley studies became frequently recognized, received the United States Ski Association Award, and led to the involvement of myself and our laboratory in establishment of ski binding, boot, ski standards through the American Society of Testing and Materials (ASTM). I continued a variety of research projects relating to skier injury mechanisms and means of reducing them, largely working with MIT undergraduates during Independent Activities Period programs at Waterville Valley. For several years, this activity fed into an undergraduate seminar on engineering in skiing that I offered. It continues to be a pleasurable diversion within the general context of human postural control and biomechanics. The ski injury research has led to a number of UROP, IAP and undergraduate thesis projects, with modest funding from the binding industry. I have resisted the temptation to follow major funding and research in this field because I feel that it is too limiting for graduate study.

Simulators, Clinical Engineering, and A Touch of Space - 1976-1980

Our flight simulator research had, by 1976, turned to the optimization of motion drives based upon vestibular models and to the incorporation of visually-induced motion cues into simulator drive algorithms. The overall concept was to minimize a vector difference between perception or vestibular efferent signals in the simulator and those that would be experienced in flight. Ormsby's models, based largely on the monkey afferent signal recordings and analysis by Jay Goldberg and Cesar Fernandez at the University of Chicago, served as our starting point. Josh Borah, in his Master's thesis, applied the human spatial dynamic orientation model to the problem of the coordinated turn in a three-degree-of-freedom simulator, using our Link Trainer as the test device. (Borah also resumed his career as a weekend ski instructor later, so that many of our most enjoyable research reviews took place on the slopes of Waterville Valley - often to the consternation of our friends.) Susan Riedel used a comparison of washout filters in an experiment conducted at the NASA Langley Research Center to try to understand the adequacy and failings of linear and non-linear washout by means of human orientation models. (She went on to Systems Technology Inc., in California, to continue work on the flight simulator design problem and later to also work in the space motion sickness field before going on to teach and do further graduate work in Wisconsin.) By this time, the Link Trainer was largely in use for basic visual-vestibular interaction experiments. In Greg Zacharias' Ph.D. thesis, he looked at the interaction between yaw circularvection and true yaw motion of the Link Trainer as reflected in operator nulling of perceived trainer motion. He introduced the notion of the dual-input describing function to deal with the interactions of two competing and sometimes conflicting stimuli. That work formalized some earlier notions of mine about the relative priority in the brain's treatment of different sensory cues, and produced a "conflict model" for determining when visual cues were suppressed in favor of vestibular information. (Zacharias also stayed in the field and in close association with the lab. He forged another link with Bolt Beranek and Newman (where he went to work on human control of aircraft and simulators) by leading a joint MVL/BBN softball team in the MIT leagues for several years. More recently, as president of Charles River Analytics, he has joined with the Laboratory in a research project concerning pilot performance in terrain avoidance flying, which involves use of our graphics computer.

In an extension of Zacharias' work, Jen-Kuang Huang, in his Master's thesis, demonstrated the visual field influence on motion sensation in yaw and provided persuasive evidence that the lower thresholds and increased sensitivity to motion

with a fixed wide field visual surround, relative motion in the dark, was attributable to the oculogyral illusion. He also used the Link Trainer to extend the nulling method to visual-vestibular interaction for roll axis motion and was able to separate the influence of primarily otolith cues from those associated primarily with stimulation of the vertical semicircular canals. He then extended the capabilities of the MIT sled by building a projector system which reflected moving stripes off a mirror running the length of the sled room, onto a rear projection screen in front of the subject's seat on the moving cart. The subject was therefore able to judge his relative motion, with respect to the laboratory, either by using gravito-inertial cues from sled motion or optokinetic cues which were not always veridical. A model for lateral translation visual-vestibular interaction was developed. (Following his Ph.D. research in 1983, Jen returned to his native Taiwan to teach. He found the lure of the USA too strong, however, and is now carrying out a very successful career in control systems teaching and research as an faculty member of the ME Department at Old Dominion University in Norfolk, Virginia.)

Ren Curry became enamored of the research and meteorological climate at NASA Ames and returned there to take up a research position in 1976, where he became the country's leading authority on cockpit automation and pilot workload. Now a private consultant in Palo Alto, Curry remains active in the human factors field and is a continuing friend and supporter of the Laboratory. The year that he left, we were pleased to welcome Henk Stessen, of the Mechanical Engineering Department of Delft University, who worked with Tom Sheridan and with our lab and took over some of the man-machine systems teaching responsibilities.

We were very fortunate to have as a Visiting Professor, Rafi Sivan, formerly Dean of the Electrical Engineering Faculty of the Technion in Haifa and an international authority on optimal control systems. Sivan interested himself in the question of vestibular models and listened and read extensively in the field for his first several months at MIT. One morning in the winter, he declared, "Now I've read enough and I'm ready to go to work." He proceeded to work with us and the students in formalizing the optimal control implementation of the vestibular afferent error signal minimization for flight simulation. With Huang and Jehuda Ish-Shalom, he worked out the algorithm for the coordinated turn on a three-degree-of-freedom simulator, and set the groundwork for solution of the general six-degree-of-freedom simulator case. Following his return to Israel we shared a grant, and he pursued the clarification of several fundamental issues in motion drive logic. He was also of enormous value in clarifying issues in modern control theory and organized the teaching of the optimal control model in our Man-Machine Systems course. Oman, too, was influenced by Rafi's presence, to prepare his influential monograph on models for motion sickness based upon a formal sensory-motor conflict theory. Ish-Shalom eventually ran several experiments with varying weights of the vestibular error cost function for the motion drive optimization. In his Ph.D. thesis in 1982, Ish-Shalom determined pilot susceptibility to otolith and canal errors in simple three-axis motion control of our Link Trainer, and set the stage for later extension to six degrees of freedom and experiments on bigger simulators at Ames. (Ish-Shalom, a native of Israel, also remained in the US and changed fields somewhat to work on robotics with IBM.)

Not only vestibular motion detection but also visual motion detection continued as an important theme in the study of pilot performance during this period for the laboratory. We built upon earlier traffic situation display activity under Curry's supervision. T. Govindaraj performed a study of the ability of human

observers to detect system failures, in this context. Wally Acree then investigated the ability of pilots to distinguish between errors of glide path deviation and attitude during landing approaches. To accomplish this, he resurrected an old video Schmitt projector system we obtained from NASA Langley, and used it, along with video tapes generated in the Langley terrain model simulator, for back projection on a screen placed in front of the Boeing 707 cockpit. This first attempt of ours to generate wide-field-of-view-out-the-window realistic pictures proved to be successful but too difficult to expand to usable computer graphics with the Adage computer. In fact, this was the end of a long line of human factors experiments we performed using the Boeing simulator, which was later dismantled. The Adage computer was discarded several years later.

Through the Biomedical Engineering Center we continued in the development of the vestibular test battery during this period. We reduced to microprocessor control some of the stimulus and eye movement analysis programs which were deemed useful for the otoneurological examination. Craig Burch, along with John Tole, contributed to development of new electro-oculogram amplifiers which were self-checking, tested impedance and met the low drift and safety standards required. Dan Michaels used a new digital filter to generate a further advance on our series of computer programs for nystagmus analysis by elimination of the fast phases and saccades. The posture platform underwent further refinements and was also placed under microprocessor control, thanks to the Bachelor's thesis work of Jay Gould. Bill Morrison, who seemed to master every skill from digital electronics to histology, served the vital role of engineer to keep the vestibular project moving along. Demetrios Mena worked with Shelly Simon at Children's Hospital on a model of the swing phase of gait in another clinical offshoot of our clinical research.

Several important additions to the MVL staff occurred in the late 1970's and influenced the direction of our research. Bob Kenyon was recruited for a faculty position from Berkeley, where he had been working on eye movements with Larry Stark. We wanted to link the previously independent fields of eye movement measurements and flight simulation and arranged for Kenyon to spend a summer as a faculty fellow at the Air Force Human Resources Laboratory at Williams AFB, AZ, to delve into the problems of flight simulator technology. The issues that evolved fell into three groups, eye movement measurements to determine where the pilot is looking and to understand pilot workload, eye scanning strategies to improve the acquisition and tracking ability of pilots, and eye movement measurement technology applied to area of interest computer graphics for flight simulators. Over the seven years that Kenyon spent on the MIT faculty he developed various ingenious devices for eye movement measurement and flight simulation, and took over the task of computer czar from Oman with enthusiasm. Shortly thereafter, Josh Zeevi, from the Electrical Engineering Faculty of the Technion, joined us for a period of two years to work on related eye movement problems. With this strength, and Air Force funding, we expanded our basic as well as applied research on eye movements and made use of a borrowed TV oculometer as well as our EOG and photoelectric devices.

Zeevi's discovery of direction preference in saccadic eye movements generated considerable interest in the community associated with eye movement disorders and dyslexia. Howard Hermann returned to more active work in the Laboratory along with Nancy Sonnabend, a specialist in dyslexia, to work with Zeevi and with Paul Wetzell, a graduate student. Alan Natapoff and Bob Kenyon also became interested in the project. After Zeevi returned to Israel and with Kenyon's departure for the University of Illinois in 1986, the dyslexia project was deemed too remote

from our central interests in aerospace applications and left to the original investigators to pursue.

Another vital addition to our staff in the late 1970's was Bob Renshaw, who transferred from the Laboratory for Space Experiments in the Center for Space Research. Renshaw was a technician with ample experience in electronics and a strong feeling for design, construction and repair of a wide variety of instruments. He grew with the laboratory, particularly during our activities on Spacelab. Renshaw earned his engineering degree in the early 1980's and stayed with us for increased responsibility on the Spacelab program where he eventually took charge of coordinating astronaut training and maintenance of the crew procedures, the replenishment of Spacelab supplies, verification of the functioning of our space equipment, and logistics of setup and operation of our Baseline Data Collection Facilities at the Kennedy Space Center and at the Dryden Flight Research Center in California. He picked up the pieces of our equipment integration and checkout during many weeks in Germany, and demonstrated an extraordinary ability to communicate with bartenders in the absence of any common language. He became known affectionately to the crew of the D-1 mission as Coach Renshaw and earned much of the credit for the success of our SL-1 and D-1 missions. Meanwhile, Renshaw's versatility and strength with students became recognized by the Department of Aeronautics and Astronautics who claimed him half time and for a period in the early 1980's, he worked as a Technical Instructor on the Faculty.

We were also privileged to be joined by Otmar Bock, a young physician from Germany who believed in the power of systems analysis applied to physiology. Bock's post-doc period of nearly two years were spent mostly with Oman. Together they explored the mysterious world of reversing prisms, which led them to a discovery concerningvection adaptation and to the use of prisms for preflight testing of astronaut motion sickness symptoms. Bock returned to Berlin, to work in neurophysiology and then to Dusseldorf where he established a cybernetics lab.

The Spacelab Era - 1976-1987

By far the most significant change in research direction during this period was our decision to propose a spaceflight experiment on the shuttle, and the major change in our operation occurred after that proposal was successful in passing Peer Review and NASA selection for Spacelab 1. With the background of the laboratory in motion sickness and our aerospace orientation it seemed natural to apply for one of the experiments to be flown on the Space Shuttle. The actual decision to form a cooperative effort with Canadian investigators stemmed from some conversations between Ken Money, of DCIEM in Toronto, and myself during the Winter Conference on Brain Research in 1976. Money was a Canadian Air Force aviator as well as a vestibular researcher and was most interested in going into space himself. Thus, he was willing to have me handle the experiment integration and administration. (I never felt unwilling to go into space, but placed it secondary to other professional activities, which is why I will probably never go.) Money was selected as a Canadian Payload Specialist in 1983 and is awaiting his turn to fly. In a joint activity with our Canadian colleagues (Money, Richard Malcolm, Doug Watt and Geoffrey Melvill Jones), Oman and I proposed an integrated series of space experiments to uncover the underlying etiology of space motion sickness and study the nervous system's adaptation to weightlessness. We were fortunate to be able to add three distinguished senior citizens of the vestibular community, Walter Johnson, Ashton Graybiel and Fred Guedry, as advisors. The proposed program

was of both operational and basic interest since the unique exposure to several days of weightlessness posed a special problem to the nervous system in terms of its interpretation of the gravito-inertial signals from the otolith organs. The integrating theme for our Spacelab proposal was adaptation to weightlessness and we explored several different stimulus modalities and behavioral responses. Each sub-experiment was under the direction of a lead investigator. We planned to test perceptual responses to linear accelerations, eye movements -compensatory and ocular torsion - and motion sickness susceptibility. Originally, Money had responsibility for the motion sickness testing, Malcolm was overseeing the perception of linear acceleration, Oman dealt with compensatory lateral eye movements, and I was concerned with ocular torsion. As time went on, Malcolm left the program for private enterprise and I took over the linear perception experiment, ably assisted by Anthony Arrott. By the time the sled actually flew on the D-1 mission in 1985 (it had been "descoped" for mass saving from the 1983 mission), Anthony took over the lead investigator role for the sled testing. Watt, with the collaboration of Melvill Jones, laid out the otolith-spinal reflex (hop and drop) experiment. Oman defined our inflight head movement and symptom monitoring experiment and collaborated with Money on the preflight predictors. We all combined efforts on the post-flight experiments, which consisted of repetitions of the inflight tests and some emphasis on postflight postural stability.

From the moment the proposal was accepted as one of the 14 American experiments selected from over 300 candidates, the scope of the proposed research began to be reduced. The pressures of crew time, cost and mass forced us to make a series of compromises in the kinds of instrumentation, the numbers of repetitions of the experiment, and the data available. We then entered protracted negotiations with the Johnson Space Center, which were directed towards reducing the scope of our experiment, the budget and the amount of crew time required. (Our original experiment called for complete testing of crew responses to acceleration along x, y, and z axes taken at least three times during the mission.) In the end, our position was whittled down to a reduced number of axes and repetitions, permitting the flight of a valuable pilot experiment but with too few data points from a single flight to produce results likely to be of statistical significance. Financial problems, aggravated by Shuttle delays, were somewhat alleviated by the generosity and farsightedness of Walter Rosenblith, then Provost of MIT, who made available from the MIT Sloan Fund sufficient money to cover two research assistants through much of the preflight period. NASA, unused to dealing with university groups in this field, was unwilling to fund graduate students at that time.

Byron Lichtenberg, a graduate student and Air Force/National Guard pilot who shared a desire to fly the Space Shuttle, worked from the outset on the redefinition of the experiment to fit the realities of working within a large complex scientific/managerial system called Spacelab. The centerpiece of the experimental plan was the use of the European Space Agency "Space Sled" for linear acceleration of crew members at various times during the space mission, monitoring eye position and subjective response. The Space Sled was "descoped" from Spacelab 1 to save mass. Our experiments as actually flown in 1983 were, to a great extent, replanned on the basis of this withdrawal and finally flown in close to the original version in 1985 on D-1. Nevertheless, our activities during the late 1970's in support of Spacelab 1 brought us through the realities of building equipment which would satisfy the safety and reliability constraints of space, and dealing with large engineering organizations in NASA and ESA.

The first major decision in our project was to build the flight equipment within MIT's Center for Space Research, using the remaining capabilities of the Laboratory for Space Experiments, which was being decimated by the lack of astronomy experiments. Ed Boughan was our first project engineer and worked diligently with Pete Tappan, Bob Goeke, and Will Yelle to produce an experiment control and data system (ECDS) for running our sled, dome and drop experiments, and preparing data for transmission to the ground. (Yelle was later recruited by MATSCO and moved to Houston.) Bill Mayer later took over project management of all of our vestibular Spacelab programs and steered a course through the rapids of ESA and NASA bureaucracy with extraordinary skill. Larry Beckley was in charge of the administrative activities for the Center for many years, and started us in the right direction. Joe Binsack was faced with the problem of keeping the project solvent without excessive sacrifice of scientific return. The process of building the experimental hardware in our own building had the advantage of flexibility and informality, allowing changes to be made more easily than otherwise as experiment protocols became defined and as the wishes of the crew became known. It also had the disadvantage, however, of lack of clearly defined contractual obligations such as might be expected for both sides in dealing with an outside contractor.

The next major decision to be made in our Spacelab hardware was to run our experiment independent of the main Spacelab computer, which was used by most of the non-life science European experiments. This turned out to be the correct choice, since the Spacelab computer was based upon a design which left much to be desired in terms of bus architecture, limited memory and low sampling rate of the remote acquisition units. We also had our share of fighting the never-ending political struggle to maintain the integrity of our experiment against the competing wishes of others. For example, the Materials Science experiments were constantly challenging the vestibular experiments for reasons associated with both crew time and the interference of vibrations of the Spacelab caused by our test. When we attended the first Investigator's Working Group meeting of Spacelab-1, we found that ESA had a similar vestibular experiment, led by Dr. R. Von Baumgarten of the University of Mainz, with participation of many of our friends and colleagues. The detailed "functional objectives" of the European experiment bore an extraordinary resemblance to our own, which is probably not surprising in view of the similar backgrounds of the investigators. A single unified experimental protocol was ruled out as impractical by the European investigator at our first meeting. As a result the ensuing years consisted of occasional collaboration but frequent competition for Spacelab resources, especially crew time. Once the fundamental facility, the Space Sled, was threatened and finally removed from the mission, both our teams found it in our clear common interest to cooperate fully in restructuring the vestibular experiments on the mission and fighting the various common competition. The European vestibular investigators eventually included our ~~former~~ colleagues and Alain Berthoz, Johannes Dichgans, Thomas Brandt and Alan Benson. Later we made the acquaintance of many of the younger members of the ESA team and gained considerable understanding and respect from the intensive joint activity.

We were particularly pleased when the Payload Specialist selection process eventually selected Lichtenberg as one of the two American PS's to train for the mission. Preflight investigations on our part included extensive testing of the Spacelab crew for factors which might be related to a prediction of space motion sickness susceptibility, and working closely with the crew in the development of the detailed protocols for the experiment. It was an exciting although often

nervous introduction for all the MVL staff into the realities of spaceflight in the Space Shuttle era.

Many of the students in the Lab, including a large number of undergraduates, worked closely with us on development of protocols and astronaut training. Lichtenberg built an MIT ground-based version functionally equivalent to the space sled and used it for his Ph.D. thesis on the development of ocular counter-torsion during lateral sinusoidal linear acceleration. Troy Crites worked on the issue of visual-vestibular interaction, which was one of my primary personal concerns and analyzed much of our preliminary preflight data. (Troy had been one of the high school science students who had an experiment flown on Skylab. He is now working on space utilization at Aerospace Corp., and took pleasure in greeting me at our post-flight party at Dryden with a smiling "Congratulations on being the second member of the MVL to have an experiment in space!") Jim Gidney and Kevin Johnson built our rotating chair for the BDCF, which admirably spun many astronauts for pre and postflight testing. A large team of undergraduates was involved in development of protocols for the MIT sled tests, conducting normal studies and running the astronauts through the procedures at MIT and, as a special treat, at Dryden. (We were informed, when the landing site was switched from Florida to Dryden that we would have no ocean but a much larger beach in the desert.) Brenda Kitchen investigated the eye movements induced by linear motion on the sled, and spent much of 1983 working with the NASA sled at Dryden. Mohammad Massoumnia refined a new technique for removing saccades from nystagmus data from Spacelab records. Joy Weiss worked out the knotty problem of electrooculography electrode motion artifacts. Bob Abramson devoted himself to the ocular torsion measurement issue and Linda Robeck, along with Darryl Palmer, pursued the experiment concerning perception thresholds for linear acceleration. Dale Hiltner perfected a closed loop manual position control task on the sled which was incorporated into the post-flight protocol and proved most illuminating. David Loo who had started working with me on ski injury projects as an undergraduate, designed a hybrid controller for the sled as his Master's thesis, and then went off to work for Ormsby at TASC. Bob Grimes was hired to install our new multi-user computer system for data analysis. Lichtenberg finished his Ph.D. thesis in 1979, based upon the demonstration that ocular counterrolling could be generated by lateral linear acceleration as well as tilt. He was followed in this area by Anthony Arrott who extended this work to demonstrate the range of linearity of ocular counterrolling for his Master's thesis and then followed it with his Ph.D. thesis demonstrating the basic reflex nature of ocular torsion in response to lateral acceleration, independent of rotation of the gravito-inertial vector. Arrott made a major contribution to the Spacelab programs, however, as the leader of a team of undergraduate students on the Spacelab-1 pre and postflight sled test development and data analysis. For D-1, Arrott was given the role of lead investigator on the important sled experiments, and spent considerable time in Germany doing protocol development and training, as well as in Houston for simulations and flight. Arrott finally completed his Ph.D. thesis in 1985, several months prior to the flight of the D-1 mission. Following his outstanding performance as a Payload Specialist on Spacelab-1, Lichtenberg, along with Arrott, established a consulting firm, Payload Systems Inc., in Wellesley and changed his MVL ~~tie~~, to that of Research Affiliate. Bob Grimes joined them after his graduation, making it more of an MVL spinoff. We are currently working with PSI on several activities.

Dan Merfeld joined the lab as a graduate student prior to the D-1 flight and spent much of one year at KSC running sled tests on the crew and others. Because of the delay in future missions he will have to turn to a non-flight vestibular problem

for his thesis work. Several students were brought into the Spacelab project well after the mission was completed, to assist in the important and enormous task of data recovery and analysis. Bob McCoy made sense of the human head movement recordings from SL-1, and was followed in this effort by Ilya Shubentsov. Mark Kulbaski and Oman found changes in the postflight angular VOR responses. Andrew Alston took over the job of automatic ocular torsion analysis from Merfeld. Bin An began work on a new protocol for assessing post-flight changes in spatial orientation.

One of the major changes in style of the Laboratory during the Spacelab era was the overwhelming amount of travel and short deadline paperwork required by NASA. Investigator Working Group meetings of the NASA and ESA researchers were held two or three times a year in the US and in Europe. The investigators were nominally in charge of the payload, but, in fact, we did little more than serve as a sounding board for the important decisions made by management. Except for the decision of ESA to remove the Space Sled to save weight, rather than any individual experiment, our concerns largely had to do with delays and the limitation of running the mission with a single relay satellite which restricted real time coverage. (Because of our dependance upon real-time data we pressed for a brief delay in the launch date to allow the launching of a second relay satellite. Had our position been upheld, we would still be awaiting out first flight!)

Training for Spacelab-1 began in 1979 at MIT, with the introductory academic sessions on vestibular function and the purpose of the experiments and a variety of tests of vestibular reactions. The tour continued to Montreal in an exceptionally cold period, even for Montreal, which nearly froze Gloria Salinas, our hard-working and resourceful crew training coordinator from Houston. Then on to Toronto for heavy water and linear acceleration tests, and the famous provocative head-over-heels rotations in Money's "precision angular mover" (PAM). Other training sessions were largely at MIT and later at the Spacelab ground trainer in Huntsville, Alabama. Some of us learned to enjoy bourbon and to order grits without a smile.

Of particular value were the several opportunities to try out experimental protocols with the crew during parabolic flight and to use their reactions both to refine the experiments and to serve as a baseline against which they could compare their perceptions during the flight itself. We tested our protocols and equipment 20 to 25 seconds at a time during parabolic zero gravity flights on NASA's KC-135 airplane over the Gulf of Mexico. The experiment lead investigators and a number of our students and staff flew on the KC-135 a number of times and thoroughly enjoyed the experience and the understanding of working under weightlessness that it afforded. Mark McQuain analyzed the ocular torsion measurements during parabolic flights for his undergraduate thesis. We all treasure the memories and the photographs and movies of working and playing Superman during the parabolas, and we all learned to tolerate or live with the motion sickness monster.

As the years wore on and the flight was delayed because of a delay in the initial launch of the shuttle, we became very close to the SL-1 crew. To a great extent the flight and backup crew were an integral part of our experiment team. I had the advantage of knowing both Mission Specialists prior to their assignment. Owen Garriott, a senior science astronaut who had flown on the very successful Skylab mission, participated with Oman and me in a National Research Council on Life Sciences in the Shuttle era in the late 70's. His colleague, Bob Parker, who had been the Science Coordinator during Skylab and an Apollo backup, but was awaiting

his first flight, was an old friend from the 50's when we were fraternity brothers at Amherst College. My friendship with Parker and understanding of his often biting sarcasm made for a fine relationship. When the press asked about his terse and apparently sardonic remarks to me over air-to-ground during the Spacelab mission, I explained that it was the way scientists talk to each other during an experiment, especially Bob! Mike Lampton, an astronomer from Berkeley, who ended up as Lichtenberg's alternate, is a delightful and extraordinarily intelligent scientist, who made several vital suggestions which improved the instrumentation of our experiment. Mike is awaiting his first flight on the Atlas mission in the 1990's. Lichtenberg, of course, as one of my graduate students, could be counted upon to react to situations in training and simulation as I would hope that I might. It was my delight to learn that he was looked upon with the same admiration for his abilities and personality by all of the people on the mission. Ulf Merbold, the German physicist who flew as the first ESA Payload Specialist showed a strong desire to perform all procedures without error and worked hard to get things right. We shared, among other things, a love of skiing fast. Two of our training sessions were adjacent to weekends where we managed to extend the lecture time onto the ski slopes of New Hampshire and Utah. Wubbo Ockels, the alternate Payload Specialist, who went on to fly as the ESA PS on D-1, is an extraordinarily imaginative and delightful nuclear physicist from the Netherlands who also became a close friend during all these years together. The "Flying Dutchman" concentrated on the underlying experimental hypotheses, and, except for his never ending attempts to restructure the experiment, was a continual source of motivation, inspiration, and good humor. He laughed at our jokes and got many of us at MIT started on board-sailing with his enthusiasm, equipment and instruction.

The visits of the crew, along with their ESA and NASA entourage, created a high point for the laboratory and especially for the graduate and undergraduate students involved in their testing. Prior to each visit, extensive pretest simulations and runs on a normal subject population were conducted to assure a smooth operation. NASA officials frequently remarked on the impressive ability of the MIT students to participate in the experiments at a professional level, and pictures of our students (including Sherry) working on the sled were widely distributed.

The Baseline Data Collection Facility (BDCF) was established by NASA for all of the SL-1 life-science teams at the Dryden Flight Research Facility adjacent to the shuttle landing site in California. Renshaw, Modestino, most of the faculty, and several students decamped to the high desert for one to two weeks per month during the half year prior to the flight in order to establish the pre-flight data base. Arrott took the lead in running the ground sled tests and Mark Shelhamer took over the ground rotating dome studies. Kenyon ran the posture platform tests and Oman spun the crew on a rotating chair to measure compensatory eye movements and the effects of gravity on nystagmus. Modestino conducted rod and frame tests of visual orientation and never discussed what took place with the crew in the small dark room. She also bought the crew standard shoes for the rails balancing test and raised some eyebrows when she ordered six pairs of men's shoes in various sizes. Money, Watt and I ran ground versions of our flight protocols. With similar extensive ground test devices from ESA and from Mil Reschke and his team from JSC and Michigan, the BDCF represented the most complete human vestibular test laboratory ever existing. The isolation in the desert added to the sense of adventure and helped to create lasting friendships despite the close working quarters. The opportunity to concentrate on well-defined research tasks and to be

free of paperwork, committees and interruptions was a pleasure, and made the shock of academic reentry sometimes difficult.

The flight of Spacelab-1 finally took place at the end of 1983. The extensive amount of time spent in preflight simulations in Huntsville and Houston paid off during the hectic but exhilarating nine days of 24 hour per day operation. After a day, the shuttle operations people learned that they could (probably) trust the payload investigators to act responsibly, and allowed us rather free use of communications and near-real-time replanning. Most of the equipment worked and protocols went as planned. The major exceptions were the failure of the 35 mm camera flash and our failure to obtain any usable ocular counterrolling data from the European eye movement recording system. A considerable amount of press coverage accompanied the mission and taught us all a bit about how to respond to TV or print interviewers. (In general, the most responsible were the periodicals - The New Yorker, Psychology Today and New Scientist. The least responsible were the general assignment reporters from the daily papers and the TV news.)

The results were summarized fully in a series of papers all the teams published in a special issue of Experimental Brain Research in October 1986. We learned a great deal about vestibular adaptation to weightlessness. However, it is clear that the limitations on numbers of subjects and numbers of repetitions and controls forced a style of scientific analysis which is far inferior to that which we would apply to experiments in the lab. Of the decade which passed between generation of the proposal and the publication of the papers, only two intensive periods, at the beginning and at the end, were heavily devoted to scientific activity on our part. These were the phase of generation of the experiment for the proposal and of performing the experiment and analyzing the data postflight. Most of the interim period was spent in technical/administrative tasks associated with integration of the experiment, defense of its integrity, training of the crew, revising requirements for scarce resources such as video or real-time data coverage, and verification of equipment function. The experience was fascinating even though frustrating at times. I feel that the administrative and technical overhead is unreasonably high, particularly for investigators who may not have any interest or background in the engineering issues. We had been overconfident in terms of the ease of doing space experiments in the space shuttle era. However, hope remained that the delays and confusion associated with planning for the Spacelab-1 mission were attributable to the fact that it was a first and that subsequent missions would be easier.

Indeed, the D-1 mission which followed went through a more rapid cycle, but with its own set of additional problems, chiefly related to the fact that we were administratively a guest of a guest on that mission (we were a guest of ESA which in turn was a guest of Germany). All of the interactions regarding equipment specifications, safety, integration requirements, protocols, crew time and training were new and made considerably more difficult by the physical presence of the equipment in Europe and by the need to go through several intermediate steps and agencies rather than dealing directly with our counterparts at JSC. Nevertheless, the D-1 experience was also fruitful and educational for us all. The D-1 crew was also outstanding, although we never developed the same rapport as with SL-1, possibly because of the briefer association. Guy Bluford and Bonnie Dunbar, the Mission Specialists, were thoroughly professional in their approach to performing the experiments as specified. Ernst Messerschmid, the German Payload Specialist who worked most closely with our experiment, took a keen interest in understanding not only the detailed operation of the equipment, but also the theory behind the

hypotheses. Not only did he win a bottle of champagne for blind assembly and loading of the 35 mm camera, he won another bottle for learning to place two marked contact lenses in his eye within less than a minute. Ockels and Reinhard Furrer, the other German Payload Specialists, rounded out the payload crew and kept sessions lively by their questioning and innovation. Renshaw took on increasing responsibilities as field engineer caring for our equipment as well as in crew training and assistance during simulations in Germany and at JSC. During the flight, Lichtenberg represented the team at the German Space Operations Center and the rest of us controlled the experiment and monitored data from the Science Monitoring Area in Houston. Unfortunately the main BDCF was moved to KSC in anticipation of a landing there. When it became clear several months prior to the flight that the landing would be in California again, we arranged to have most of our smaller equipment set up at Dryden for a few hectic hours and then flown to KSC for the rest of the post-flight testing week. By the end of the D-1 mission, in late 1985, we had a much better notion of vestibular adaptation to weightlessness and the etiology of space sickness. Space sickness definitely did appear to be a form of motion sickness, provoked primarily by conflict situations such as pitch or roll head movements or, for some people, ambiguous or otherwise unexpected visual orientation cues. Otolith organ signals appeared to be reinterpreted to represent linear acceleration rather than tilt, and the strength of otolith information as reflected in eye movements, postural reactions or counter-rolling was reduced. Visual-vestibular interaction demonstrated an increased reliance upon moving visual fields for spatial orientation, and a dependence upon tactile cues, when the no-longer appropriate otolith information was ignored during adaptation to weightlessness. Postflight postural instability, especially with eyes closed was thoroughly documented. The dynamics of the angular VOR appeared changed postflight. The space sled worked beautifully when it finally flew, and seemed to demonstrate no major shift in linear acceleration sensitivity or thresholds during linear motion. Much of the D-1 flight data is still being analyzed in 1987.

The MIT-Canadian team was also fortunate enough to be chosen as one of the 21 life sciences experiments for the dedicated Life Sciences Spacelab, originally designated as Spacelab-4. This proposal was written in 1978, for a flight expected to take place only a few years later. However because of oversubscription of this flight, problems with accommodation of animals, delays in the shuttle schedule, and finally the major delays imposed by the Challenger accident, this experiment is now expected to be flown as part of two missions in approximately 1990 and 1992. Despite all the delays and frustrations, Oman and I were pleased when we were selected as two of the Principal Investigators whose 1984 proposals were accepted, in 1987, for further definition and potential future flights.

My general conclusion from a decade of working on Spacelab is one of guarded optimism. The results obtained thus far, though of significant interest, are generally based upon too small a sample size to form definitive significantly sound conclusions. The hope that experiments would be repeated frequently and that new questions could be posed to follow up interesting leads from previous flights is dashed. The return on investment to date is positive, but if we judged the results purely on the basis of the contributions to knowledge which appear in our publications, we must be forced to the conclusion that we would have been more productive if we had stayed with our previous line of ground laboratory experiments. The reason for optimism is based upon my conviction that NASA as well as the scientific community have learned a great deal about how to do space experi-

ments more effectively and efficiently. We paid the price paid by all pioneers and hopefully we will be in a position to reap the rewards.

During the relatively quiet period imposed by the Challenger accident, student activity regarding space experiments has remained high, but it has shifted toward areas of data analysis techniques and modelling, rather than preparation for the next flight.

Earthly Research - 1980-1987

As the day-to-day pressures of keeping up with a changing Spacelab experiment grew, our ability to perform basic research unrelated to space diminished. The research activities of the Laboratory during the early 1980's, although predominantly associated with our Spacelab experiments, extended into a few associated directions. Our Spacelab work on post-flight postural instability led to my concern that some of the problems might be associated with muscle atrophy rather than sensory inadequacy. We began an association with Boston University's Neuromuscular Research Laboratory, headed by Carlo DeLuca. Bob Kenyon began an investigation of the fatigue characteristics of fast and slow muscle fibers of astronauts following weightlessness, working principally with Serge Roy of BU.

The most important major research spinoff of the Spacelab activities in the early 1980's was a thrust into the measurement and explanation of motion sickness. Although the original motivation was tied closely to the NASA problem of space motion sickness, Oman broadened the issue to all forms of motion sickness. Working on the ideas inspired by Sivan's visit, Oman wrote a monograph covering the theoretical basis of the sensory-motor conflict theory. His experimental work, beginning with the development of a skin temperature and skin pallor monitor which has flown on several space shuttles, extended into other alternate endpoint measurements. Walter Cook was heavily involved in the development of the pallor monitor and Brian Rague has continued to work on the electrogastrogram. Sensitive and objective measures of motion sickness end points which fall short of strong nausea and vomiting. John Smedtje, a physician who completed his training at the Harvard School of Public Health with an interest in aviation medicine, spent a year with Oman in which he tested the side effects of anti-motion sickness drugs on human visual-motor performance and cognitive function. Oman, along with others in the laboratory, resumed research on wide-field-of-view displays, to achieve a goal which we had first proposed in the 1960's. A wide-field-of-view "anti-vertigo" display could be used to eliminate or reduce motion sickness symptoms for sailors, astronauts or aviators not otherwise having a wide view of the horizon. This work is in its preliminary stages in the middle 1980's.

Some basic studies were pursued because they supported the scientific or technical objectives of our Spacelab investigations. One of the studies in this category was the Ph.D. thesis project of Roger Wicke, who investigated the postural responses of subjects who fell in front of a vertically moving wall. In addition to the problems of multi-channel EMG analysis, Wicke had to overcome our safety concerns. He eventually restricted his subject pool to those who had their own stiff hiking boots or could fit into the one standard MVL size 8 pair. Roger had a continuing interest in acupuncture, and after a period doing research at the Palo Alto VA Hospital, turned his career toward acupuncture entirely.

Oman had the opportunity in the 80s to expand his earlier work on the composition and fluid mechanics of endolymph in the semicircular canals. With Ed Marcus, an undergraduate and fellow sailor, Oman refined the mechanical model for angular acceleration transduction. More recently, in a collaboration that reached to Australia, Oman and Ian Curthoys tied together new anatomical measurements on vestibular dimensions and the mechanical models.

Our interests in non-space aspects of eye movements continued at a reduced pace - and indeed the field moved ahead as other groups took over the lead in modelling of eye movement control. The only research I supervised in this area during the late 1970's was that of Ed Jernigan, whose Ph.D. thesis concerned the use of eye movement analysis in the plotting of human visual fields. Antonio Medina explored visual information processing as influenced by alertness. Kenyon continued his earlier interests in oculomotor disorders and studied the eye movement patterns of patients with Korsakoff's syndrome and with alcoholics.

The ski-accident research continued steadily with a grant from Salomon, and supported Bachelor's theses by Gerry Melsky concerning the dynamic response of bindings and by Fred Wilson on the testing of releasable Nordic bindings.

The simulator research grew in importance during the 80s as it became apparent that several basic problems in matching the flight simulator to the pilot remained. Kenyon and Zeevi concluded their grant on eye movements related to target acquisition and tracking. The recognition of the importance of adequate out-the window visual displays for flight simulator research as well as training led us to a program with the Air Force Aerospace Medical Division. Kent Gillingham recognized our joint interests in vection and disorientation, and Kenyon and I were awarded contracts to place SGI Iris graphics computers on his disorientation trainer and the large centrifuge at Brooks Air Force Base. Ed Kneller and Steve Adkins worked under Kenyon to bring these programs to fruition. Kenyon and I began a graduate course in flight simulation which later was offered regularly as a special summer course, along with Antonio Elias.

As a complementary activity to our human vestibular experiments in space, Kenyon became interested in embryonic development in weightlessness. He initiated a study of chick embryo development and vestibular testing of newly hatched chicks, which was our latest, and noisiest, venture into animal research. He had a pilot experiment with chicks on board the final flight of the Challenger, and hopes to resume this line of study. As the coach of "Kenyon's Killers" he regularly defeated "Young's Yankees" in our annual MVL field day, despite the advantage I had of awarding sportsmanship points at will. The laboratory lost a strong contributor and good friend when Kenyon moved to the University of Illinois at Chicago in 1986.

We were fortunate to be able to hire Steve Bussolari as an Assistant Professor in 1983, following the completion of his Ph.D. research with Forbes Dewey in MIT's Mechanical Engineering Department on vascular fluid mechanics. Steve stepped in to assume responsibility for our ongoing work on optimal motion cue washout for flight simulation. His research interests extended to several aspects of space human factors, including remote manipulation and expert systems. I should have known from his activity as chief instructor for the MIT Soaring Club that his interests would be related to airplanes. He bought a classic Piper Cub with former MVL student Rick Sheppe, earned a commercial pilot's license, and became

one of the driving forces on the Department faculty behind the successful Daedalus man-powered flight project.

The search for the ideal simulator motion drive algorithm led Bussolari to NASA Ames, with Bryan Sullivan and later Kathy Misovec, for investigation of the efficacy of our vestibular model optimal washout system. These studies, on a helicopter simulator and on a commercial transport simulator, demonstrated the sensitivity of pilot control strategy, but not pilot opinion, to wide variations in motion cue utilization.

A human-in-space investigation independent of our vestibular system work was proposed by Lichtenberg and Bussolari and selected to fly on the Atlas Earth Observations in Spacelab Mission through which Byron will again be a Payload Specialist. (With redefined payloads this experiment has been shifted about and is currently anticipated for flight on the International Microgravity Laboratory Mission, on which Oman and Watt also have experiments, scheduled for the early nineties.) The purpose of this human factors experiment is to measure the effects of weightlessness on human workload and performance using a standard psychological test made up of the Sternberg and the Fitts tests of short-term memory and accurate movement. The practical application will be guidance for space users associated with the best ways of entering place data into a computer, comparing the pros and cons of keyboard, trackball and joystick entries. Dava Newman and Ted McDade followed Jess Fordyce as graduate students exploring the mysteries of the "Fittsberg Test".

Our basic work on experimentation and human modeling of visual-vestibular interaction was summarized in the late 1970's in a small book written by Bernard Cohen, Volker Henn and myself as a result of a Neurosciences Research Program workshop on the subject. It laid out the common threads among models and the areas where additional data was required. In keeping with this theme, we have continued to work on visual-vestibular interaction both in space and on the ground. My main interests in the mid-1980's are the interaction of optokinetic and vestibular stimuli for linear acceleration, both lateral and vertical. The reasons for this line of research are based upon observed asymmetries in vertical nystagmus and their possible relationship to the special role of the sacculus organ vis-a-vis the utricular macula in orientation to the vertical.

Throughout its first 25 years, the Laboratory has been fortunate to attract many people who cheerfully devoted the extra work to make sure things got done. We have nearly always been overworked and underfunded, and the pace has never been boring. For most visitors the first contact and first impression is made by the secretary. Many of the secretaries have been outstanding - including the current one, Pat Preo, who mothers faculty and students alike while arranging for visitors to feel welcome and accomplish their goals. Several of the past secretaries are worth special mention. Margaret Armour brought her Scottish wit and accent in to save almost any potential debacle in the early 80s. And Kerry Campbell, who kept us going throughout the early Spacelab years, had the ability to dispel gloom and avoid disasters merely by a smile and some well directed hard work. Marilyn Cieuzo, Patty Rich and others kept the home fires burning during the busy, but rewarding, first twenty-five years.



MY SECOND QUARTER CENTURY

with the

MIT MAN-VEHICLE LAB

(1987-2012)

LAURENCE R. YOUNG

My second quarter century with the MIT Man-Vehicle Lab (1987-2012)

Laurence R. Young

This recital of some of my involvement in MIT's Man-Vehicle Laboratory was set down on the occasion of the 50th anniversary of the lab – in September 2012. It concentrates on the period 1987-2012, and follows a similar piece I wrote for the 25th anniversary, in 1987. (That memoir, “My Twenty-Five Years with the Man-Vehicle Laboratory” is available as paper 87.8 on the Man-Vehicle Laboratory Web Site, mvl.mit.edu)

My two memoirs, covering a half-century, reflect only my own interactions with my students and colleagues, and by no means the contributions of my faculty colleagues and their students over those years. The interested reader is referred to the lab web site where the list of over 900 publications and over 200 theses is available. Copies of most items may be obtained from the MVL.

Space and its Attraction for Students

By the beginning of the second quarter century of the MVL (1987) we were fully invested in space experiments. Our faculty and staff were becoming well known in space life sciences and we attracted students and visitors who wanted to become part of the space program. Some graduate students, especially from France and the Netherlands, came for their one-year research internship, and others began as undergraduates through UROP (Undergraduate Research Opportunities Program). All seemed to enjoy being part of the great human-in-space adventure and many stayed in the field. To illustrate, I mention only a few of the students whose careers were shaped by their brush with space research in the MVL.

Elazer Edelman (now an MIT Professor in the HST Program) for example, began as a freshman interested in eye movements and stayed through his SB and SM theses on measurements of ocular torsion.

Anthony Arrott carried much of the operational load during the long build up to SL-1, including time on console and crew training. He used the MVL

Lab Sled to investigate human ocular counterrolling for his PhD. (Following graduation he teamed with Byron Lichtenberg to form Payload Systems Inc. in Cambridge, and hired Bob Grimes, Bob Renshaw and other MVL alums to work on development of space experiments. PSI was later acquired by Aurora Flight Systems and remains in Cambridge.) Anthony eventually moved on to a career in network security. Dan Merfeld shared my desire to model the way in which the brain could tease out the component of gravity from the gravito-inertial force sensed by the otoliths, and followed his human experiments with ground-breaking monkey research at Ames in David Tomko's lab. (After his PhD Dan stayed in the MVL during my Payload Specialist years to serve as the Deputy PI for our SLS-2 experiments. Dan is pursuing a very successful career in neuroscience now at the Massachusetts Eye and Ear Infirmary (Harvard). Mark Shelhamer similarly applied his mathematical abilities to the analysis of compensatory eye movement during linear acceleration, one of a series of basic research projects carried out on the MVL Lab Sled, originally built by Lichtenberg for developing Space Sled protocols we used eventually during the D-1 mission. Mark also stayed in academia and is currently a professor at Johns Hopkins University, and remains active in space as well as vestibular research.

Models of Human Adaptive Control

My goal of modeling vestibular reactions to motion continued all during the Spacelab era of the 80s and 90s – despite the time consuming distractions of managing space experiments. I maintained an interest in Context Specific Dual Adaptation – which grew (slowly) out of the early influence of Doc Draper, Y.T. Li and Phil Whitaker regarding machine and human adaptation. The challenge was easily stated, but not easily resolved. We knew that human sensory-motor control laws changed according to the task, the environment and the controlled element. We could even model the process of developing the necessary adaptive control, building heavily on the concept of the “internal model” and the aerospace concept of a “Model Reference Adaptive Controller”. What remained a puzzle, however, was the question of how one decides to switch from one internal control law to another one, appropriate to the new situation, without having to “relearn” the law each time. I came up with the concept of “Context Specific Adaptive Control” (CDAC), which would pull up the appropriate new control law in each new situation – just as one drives a sports car differently than an SUV.

We applied the concept to the task of adapting eye and hand movements, and spatial orientation, to head movements during centrifugation – and then re-adapting when the centrifuge stopped. My colleague David Robinson, at Johns Hopkins was similarly interested in the “little garage mechanic in the brain who made the necessary adjustments” and frequently brought up the example of the differences in VOR gain required with and without magnifying spectacles. Indeed a whole cottage industry of neuroscientists worked over the problem of gain variation and direction reversal for a decade. Lionel Greene spent his post-doc year with me and with Emilio Bizzi, trying to determine if monkeys could adapt their VOR across axes. Mark Shelhamer went to work with Robinson at Hopkins, where he extended the experimental and theoretical basis for CDAC. During my sabbatical years with Alain Berthoz at the College de France in Paris I developed an experiment to test CDAC in drivers going from left hand drive to right hand drive as they emerge from the Chunnel. Results are not yet available.

The bulk of the spatial orientation modeling work after the mid-nineties was taken up by Chuck Oman and his students, leading to the “MIT Observer Model” for spatial orientation, and a sensory-motor conflict theory for motion sickness. The multi-sensory models we had begun promulgating in the 60’s came of age in the nineties in many labs including our own. The models of Dan Merfeld, of Brad McGrath, and more recently of Mike Newman, all led to quantitative prediction of the spatial orientation perception of an observer subject to certain angular and linear accelerations – and to a specified visual input. Applications abounded, from aircraft accident analysis to problems of landing on a planetary surface with a different gravity level, and understanding the origins of space sickness.

PI-in-a-Box

Challenger exploded before the eyes of the world in 1986 and human space research was forever altered. Gone was the secure sense that NASA, with its multiple levels of safety checks, would protect us from such catastrophic failures. The NASA poster on our MVL Lab Sled Door “We Deliver” (in many languages) was an ironic reminder that we were still in a very dangerous business. Bob Kenyon’s chick embryo experiment on Challenger was one of the victims. Our continuing human vestibular experiments for SLS-1 and SLS-2 were put on hold until the shuttle problems were fixed.

I was in doubt that the interruption in Shuttle launches would be as short as advertised, and took advantage of the “down time” to delve into a field that had first interested me as a student – that of Artificial Intelligence. It occurred to me that one might be able to use “Knowledge Engineering” techniques to capture the reasoning heuristics of a real scientist and allow for intelligent scheduling, operation and repair of an experiment – and a space experiment at that. I was very impressed by our experience in Spacelab 1, when the operation, quality assurance and even major repair of our “rotating dome” experiment was carried out just as though I, the PI, were in space looking over the astronaut’s shoulder. Of course this was because the astronaut doing the operation, Lichtenberg, was my own former graduate student and fully understood my scientific reasoning. This was in contrast to D-1, where the crew operated “by the book”, following the procedures carefully but unlikely to point out anomalies or interesting aspects of the data which might warrant further testing. I came up with the naïve idea of “Principal Investigator in a Box”, shortened to [PI], and benefitted from the advice of a real AI expert, Prof. Peter Szolovitz of MIT’s EECS Department. With encouragement from NASA Ames Research Center, primarily Dave Nagel and Peter Friedland, we examined the PI’s role in the following regimes: setup, calibration, data quality assurance, schedule, and “interesting data”.

The AI project took off when I got to Palo Alto for a sabbatical at Stanford in 1988, where I went to pursue AI space applications. My host was Prof. Peter Banks, with whom I had been working on Space Station planning. NASA Ames provided an IPA for my support. Stanford students, DEC engineers, and Ames co-workers brought a wealth of experience to [PI]. We narrowed down to use of one test application, the in-flight conduct of the “rotating dome” experiment, in which a moving visual field produced a sense of self rotation (vection) as well as eye torsion - all modified by the presence or absence of forces on the feet. My closest partner was Silvano Colombano, a computer scientist from Ames. Nancy Wogrin of DEC brought real-world tools to the project. Nick Groleau took on the tough problem of model-based scientific reasoning for his PhD thesis. Finally we got [PI] to work, used it for ground based testing of the rotating dome experiment on SLS-1, and used it in-flight to help guide the astronauts during dome experiments on SLS-2. It flew again on a sleep study of Harvard’s Chuck Czeisler on STS-95 (John Glenn’s second flight.) I was pleased that the technology worked, and by the awards we received, but

disappointed that it was not made available widely to other space scientists as an effective way of “putting themselves next to the astronaut”.

Daedalus and Telescience

When I left for the year at Stanford and Ames there was a lot of exciting work going on in the MVL. One project, with which I was not involved except as a fan, was the Daedalus, Human Powered Aircraft. Steve Bussolari was the Human Factors lead, responsible for supporting the pilot. We rejoiced in their prize-winning flight from Crete to Santorini.

Another unusual activity was our venture into “Telescience” or the remote conduct of experiments. I teamed with Prof. Jim Eliot of EAPS at MIT to win a NASA grant. Our goal was to determine how best to make use of a limited TV bandwidth to remotely coach an astronaut who was attempting to video the eyeball of a test subject (a portion of our “rotating dome” space experiment). With an astronaut surrogate and test subject at KSC, video transmitted over NASA select, and MVL operators at MIT, we adjusted the allocation of bits to color, gray scale, or refresh rate, in order to achieve scientifically acceptable images. (Large numbers of viewers of NASA Select TV around the world were left wondering about the endless series of eyeball pictures.) Telescience was clearly possible, as demonstrated by Barry Leiner and our other colleagues at SAIC at Ames – allowing the space scientist to get ever closer to real time operation and repair of an instrument in orbit. Overcoming the conservative NASA hierarchy operating the spacecraft was, however, not so easily accomplished.

Artificial Gravity

In its earlier designs, including the Space Station Freedom, the ISS was a US only destination for the Space Shuttle, and provided unbelievable opportunities for interactive science and technology in low-earth orbit. For the MVL and me it was intimately linked to the requirements and design for an on-board centrifuge. Back in 1979 our NASA Space and Life Sciences Advisory report (the Bricker Report) placed a centrifuge as number one in the priority for life sciences on the Station. Not only would it serve as a one-g control for microgravity experiments, but it would also provide an opportunity to study plant, animal and human physiology at levels between 0 and 1g. Finally, and most important from my point of view, it would allow for the determination of the effectiveness of artificial gravity (AG) as a

countermeasure against in-flight deconditioning. I worked first on a NASA Ames vestibular advisory group for the centrifuge, and then as a consultant to Lockheed Martin in Sunnyvale, which was in competition with TRW for the flight hardware. Large centrifuges were envisioned, capable of holding 4-8 animal habitats, each containing plants, fish or rodents. A separate “service arm” would permit the habitats to be removed for replenishment or sampling, without stopping the main rotor. In time the project was taken over by NASA Ames and solutions for many of the challenging problems, including momentum compensators, were devised to minimize vibration interference with other experiments on the Space Station. My Stanford PhD advisee, Robert Mah, was a major contributor. Then the Japanese Space Agency (now JAXA, then NASDA) took on the entire project as part of an ISS barter. They developed the Centrifuge Accommodation Module (CAM), a separate ISS module containing the centrifuge, animal holding facilities and other devices. It was nearly completed when, following the loss of Columbia and the anticipated end of the Shuttle era, the facility was abandoned. To my knowledge the module’s final resting place is in a parking lot at JAXA.

The MVL’s main interest in centrifugation has always been as a means of creating a footward centripetal acceleration to stimulate bone, muscle and cardiovascular function in weightlessness. The problems of Coriolis forces and cross-coupled acceleration, whenever an astronaut makes a head movement on a centrifuge, had been of major interest to the Ashton Graybiel’s Navy group in Pensacola, and we contributed an analysis in the 60s. By the 80s with the problem still unresolved, I was convinced by Peter Diamandis to let him build a simple human centrifuge for his SM thesis, spinning a bed around a vertical axis to force blood and other tissue down toward the feet. Peter’s concept was the “Artificial Gravity Sleeper” (AGS) in which astronauts could receive their AG conditioning while asleep. I was dubious, but introduced him to sleep researchers at Harvard and was amazed when he demonstrated that his friend could sleep soundly while spinning at 23 rpm. (This was hardly the last time that Peter amazed me by successfully pursuing seemingly impossible dreams, including the International Space University, Students for the Exploration of Space (SEDS), commercial parabolic flight through Zero-G Corp. with Byron Lichtenberg, the X-Prize, Singularity University, and now mining of asteroids!)

Once we had a short radius (2 m) human centrifuge in the lab we naturally began investigating the questions of adequate spin rate, g-level, exposure, exercise and training for effective AG in space. Two outstanding post-docs supervised student AG experiments in turn. Heiko Hecht, an experimental psychologist, now at the University of Mainz, came to us from Ames with his expertise in psychophysics and vision. Working with a generation of graduate students we demonstrated methods to adapt subjects to the unusual motion sensations associated with cross-coupled stimulation during head movements while spinning. Incremental exposure to increasing centrifuge speed and head movements allowed everyone to adapt to AG, and to maintain the “dual adaptation” for extended periods. But adaptation alone was not sufficient – we also needed to show the effectiveness of intermittent AG in reducing bone, muscle and cardiovascular deconditioning. In that quest we teamed with Bill Paloski of JSC (now at the University of Houston) to build a centrifuge at the University of Texas Medical Branch at Galveston and test experimental subjects who were deconditioned by extended bed rest. It became clear that some form of exercise on the centrifuge would be necessary to augment the centripetal acceleration. Thomas Jarchow, an extremely talented experimental psychologist from Zurich, oversaw the next generation of AG grad students. These included Jessica Edmonds and Kevin Duda, both of whom did exercise PhD studies on the MIT centrifuge - and later married. The impressive list of MVL graduate students whose thesis depended on centrifuge studies also included: Valerie Bilien, Carol Cheung, Lisette Lyne, Kathy Sienko, Shana Diez and Dana Forti (undergrads), Erika Brown Wagner, Paul Elias, Jeremie Pouly, Nate Newby, Sophie Adenot, Ian Garrick-Bethel, Sylvain Bruni, Bruce Webster, Scott Sheehan, Thaddeus Fulford-Jones, Jamie Mateus, and Justin Kaderka. The AG work is continuing as part of our newest collaboration, with Russia’s Institute for Biomedical Problems, under the umbrella of the MIT/Skolkovo Tech initiative.

Of course it has always been the ambition of the AG enthusiasts to develop and validate AG as a countermeasure demonstrated in space. Our latest efforts were as principal collaborators, with the PI, Satoshi Iwase, of Aichi Medical School in Nagoya, on an international experiment using a short radius centrifuge (SRC) with an exerciser on the ISS. Known as AGREE (Artificial Gravity with Ergometric Exercise), it is being delayed for financial and some technical reasons at this time. In travelling the world to inform ourselves about other SRCs, Justin Kaderka, Bill Paloski and I shared

our ideas and enthusiasm for AG with colleagues running SRC facilities in Nagoya, Beijing, Xi'An, Toulouse, Antwerp, Cologne, and Moscow.

Our resolve to understand and deal with disorientation during centrifugation led us to assemble a team of researchers from around the country to work under NSBRI sponsorship. With Bernie Cohen, Ted Raphan and Mingjia Dai at Mt. Sinai School of Medicine, Jim Lackner and Paul DiZio at Brandeis, Conrad Wall, Dan Merfeld and Lionel Zupan at MEEI, Mark Shelhamer and David Zee at Johns Hopkins, we attacked the key issues of the interactions and conflicts in vestibular sensations during AG, and their relationship to motion sickness.

The late 80s also brought Dava Newman to the MVL, for the first time. Her exuberance for human space research and policy issues presaged her incredible productivity when she was invited back to the MIT faculty in the early nineties – but that is her story and not mine.

Spacelabs Continue after Challenger:

Meanwhile Spacelab Life Sciences-1 (SLS-1), the first of a pair of missions devoted exclusively to life sciences, previously designated as Spacelab 4, got back on track with the resumption of Shuttle flights in the nineties. We extended the visual-vestibular interaction testing to explore the influence of tactile cues, and otolith-spinal reflex and pointing tests (Watt), and the otolith-canal interaction – or VOR “dumping” experiments (Oman) to build on our earlier results as well as our piggy-back experiments on IML-1 and IML-2. The biggest changes were in our ground based pre-and post-flight testing to determine how the adaptation to weightlessness carried over post-flight. By the nineties the prime shuttle landing site had been moved from Dryden to Kennedy. We gave up our lab in the high desert and set up two others – one at KSC for immediate pre-flight testing, and another extensive Baseline Data Collection Facility (BDCF) at JSC. Once again, an extensive MVL team of staff and students successfully achieved our goals of post-flight evaluation of astronaut vestibular function. In addition to the faculty, Bob Renshaw and Sherry Modestino along with students Dan Merfeld, Mark Shelhamer, Corrie Lathan, Gail Standish, Dave Balkwill, Chris Pouliot, Jock Christie, Nick Groleau, Keoki Jackson and Glenn Law all gained the respect of the astronauts and JSC engineers by their professionalism. The crew was flown from the landing site to Houston immediately post landing and we had our way with them for the better part of a week and periodically thereafter.

Our tests still included extensive runs on the linear sled to see how linear acceleration would be sensed and interpreted following. We also brought to JSC our small GAT-1 Link Trainer which enabled us to measure the effect of two weeks in space on the ability to maintain the attitude or balance of an airplane like device. (Merfeld developed this into a stand-alone post-flight test later approved but not implemented by NASA.) Steve Robinson came to the MVL from Langley to get more involved in human space flight and ran a part of the BDC experiments. (His involvement paid off as he was soon selected as a Mission Specialist and flew several successful Shuttle and ISS flights.) We extended our interests in human balance and especially the post-flight instability that made standing difficult. With Serge Roy and Carlo DeLuca of BU we developed pre-post flight measurement batteries of leg muscle strength and fatigue.

My Hiatus in Houston

Then a strange and wonderful present fell into my lap. I was selected as a Payload Specialist Candidate for the Spacelab Life Sciences-2 mission in 1992, along with Marty Fettman, and Jay Buckey. Originally there were to be two PSs on the mission, but when Shannon Lucid, a NASA Mission Specialist, took one of the slots it was left as a competition of three of us for one place on the shuttle. My original concerns about my age (I was 55 at the time – 20 years older than my competition) – or physical ability turned out to be misplaced. With various flight delays I spent two years at JSC training on payload operations and shuttle procedures – and learning to be part of the astronaut culture. The experience was unforgettable – one day after another of what Jay termed “FGE – Fun at Government Expense”. The unending support from my Payload Commander (Rhea Seddon) and STS-58 Mission Commander (John Blaha) made it a dream (almost) come true – from flying supersonic in the T-38 to parachuting into Pensacola Bay in a full flight suit. It was no surprise when my roommate, Marty, a skilled veterinarian, was chosen to fly as prime crew and perform the in-flight animal surgery. (Jay also got his chance to fly later, on Neurolab.) I had the excitement of being trained and ready to launch – and then the great satisfaction of being the payload communicator (to exchange messages and instructions with the crew) along with Jay, for the two weeks of the very successful mission. When I returned to MIT I had a much deeper appreciation of the reality of doing science in space, and the contributions and limitations of the crew as scientists in space.

Still other Spacelab and Shuttle flight opportunities were available. My PI-in-a-Box procedures and software flew as part of Chuck Czeisler's astronaut sleep and activity experiments on Neurolab, and on STS-95, a Spacehab flight with Sen. John Glenn as test subject. Chuck Oman was a PI on Neurolab, and Dava Newman was a PI on Shuttle-MIR, with their own adventures and accomplishment.

Other opportunities arose when I returned to MIT. Thanks to the generosity of Bob Seamans, the Apollo Program Chair in Astronautics was created, and Earll Murman honored me by selection as its first holder.

MVL People:

It was clear that Chuck Oman was effective and highly respected in his role as Director of the MVL, to which he was named when I went to JSC. He has continued to lead tirelessly to this day. We were very fortunate to have several superlative Administrative Assistants throughout the MVL history. Sherry Modestino was, for many years, the spirit and the sustenance of the MVL. She was the person to whom students turned for help, before confronting the faculty, and she was the one who made the MVL Kitchen a vibrant and nutritious daily lunch cooperative. In recognition of her devotion and care for the well-being of everyone in the lab we award an annual "Sherry Award" to the graduate student who does the most to enhance the MVL cooperative atmosphere. Over the years our secretaries, including Kerry Campbell, Barbara Glas, Marjorie Kulash, Roberta Wasserman, Sasha Natapoff, Marilyn Cieuzo Barbar, Pat Preo, and Kim Tseko all contributed to making the MVL a great place to work. Marsha Warren was one of the best writers to grace our administrative office. Marsha managed the early organization of the NSBRI, described below, and was my right hand when I was its director. And now we are blessed to have Liz Zotos as our highly talented and dedicated AA. Liz is always there to take care of big issues as well as small ones. She can be counted on to gently but firmly take care of anything from meeting rooms to budget under-runs, and to do it all with warmth and intelligence.

The National Space Biomedical Research Institute:

By the late 90s NASA was pressured to turn its human life science research away from in-house managed labs at JSC, and launched a competition for an NGO to take it over. Working with Bobby Alford of Baylor College of Medicine and Richard Johns of Johns Hopkins, with able support from Ron White, then at NASA HQ, we won the competition for the National Space Biomedical Research Institute and I was named its founding Director. With its headquarters at Baylor, in Houston, I was kept busy commuting between there and Cambridge for several year as the NSBRI took shape. We brought into the space life science arena many excellent researchers who had previously worked only on NIH grants. As the size and responsibilities grew, and I still maintained my prime allegiance to MIT, I had to step down and in 2002 was replaced by the current director, Jeff Sutton, who had been one of our NSBRI team leads when he was at Harvard and MGH. The NSBRI continues to fund our research, through competitive proposals, though 2012.

A continuing beneficial relationship with the NSBRI is in support for our Bioastronautics graduate education. Although not a direct MVL activity, the support gained through our decade long PhD training program in the Harvard-MIT Health Sciences and Technology Division allows all of the MVL students to participate in the annual NASA Human Research Program workshops and in related courses at MIT. We were successful in a 1996 national competition for the training program along with Texas A and M University, and have been training students in both the space flight and basic research aspects of Bioastronautics ever since.

Space Grant

Upon returning to MIT in 1994 I was asked to take over the direction of the Massachusetts Space Grant Consortium from Jack Kerrebrock. This educational activity, part of a national effort to increase training and awareness of space activities – was found to be in need of both geographical and socio-economic diversification in our state. Our ties to the MVL were chiefly through the willingness of the grad students to speak to school children and work with museums. In addition to several Associate Directors I had the good fortune to inherit the cheerful and highly competent Helen Halaris as Program Coordinator. She was able to weave her way through the tangled web of NASA's Education Office, and keeps fellowship funding

flowing to deserving students. When we recruited Jeff Hoffman to the Department he became co-Director and then Director, where he uses his finely honed diplomatic skills effectively to this day.

Return to the Moon

With the NASA Constellation Program and its projected return to the Moon, our attention turned to the particular issues of astronaut human factors during lunar exploration. Dave Newman was developing her “Biosuit”, Chuck Oman and Andy Liu had a project on robotics training. Kevin Duda and Chuck also had a project on operator interaction with cockpit automation, and Jeff Hoffman was involved with a Lunar Hopper. My own concentration was on two aspects of possible spatial disorientation during the landing phase. With Chris Oravetz we examined the misperceptions of the slope and distance of hills on the moon. The latest of my NSBRI research grants dealt with the issue of potential astronaut spatial disorientation and manual control disturbance during lunar landing. Both the reduced gravity level on the moon, and the loss of visual cues caused by lunar dust were of concern. Working with Draper Laboratory (Kevin Duda), JSC (Scott Wood), and the US Army Aerospace Medical Research Lab in Ft. Rucker (Art Estrada) we determined the specific danger phases of lunar entry. We were fortunate to have several of the Apollo astronauts who were old MIT students and friends, Ed Mitchell, Dave Scott, Buzz Aldrin, and Charlie Duke, as well as Tom Stafford, visit and critique our displays. Alex Stimpson and Torin Clark were the last of my graduate students to write theses on this topic. Begun during the “return to the Moon” planning of the Constellation Program, the lunar landing application is dying away without a mission to drive it.

The MEEI – A Continuing Clinical Relationship

Since the beginning of the MVL we relied on our colleagues from Harvard Medical School and the Mass Eye and Ear Infirmary to provide the bridge from our bioengineering efforts to clinical problems and human physiology. At first we were helped by David Cogan, head of the Eye Department, along with Carl Kupfer, mostly on issues of instrumentation. Beginning with the support and former vestibular patients of Harold Schuknecht, eminent head of the Ear Department, we had access to patients lacking vestibular function. Herb Silverstein supplied Bob Steer with endolymph for his PhD research. (Bob measured both the viscosity and the temperature coefficient of

expansion, putting the Barany theory of the caloric response on sound footing, although not identifying the direct (non-convective) thermal effect of later interest.) Al Weiss, a neuro-otologist with a longing to do engineering, not only worked closely with us on posture control, but brought along the EEG analysis specialist John Barlow from MGH. Together, using our space sled and a vertical hoist in the basement of the Center for Space Research, we characterized the differences between horizontal and vertical acceleration in different head axes. (Our description of linear-acceleration induced nystagmus, which we termed “L-Nystagmus” was generally ignored and only re-discovered some years later.)

When Joe Nadol, later Chief of Otolaryngology at MEEI, decided to establish the Jenks Vestibular Diagnostic Laboratory I helped in the identification and recruitment of Conrad Wall, another aerospace engineer, from the University of Pittsburgh. Conrad has been affiliated with the MVL and contributes to student supervision. Dave Balkwill, who developed Spacelab nystagmus analysis methods for us, moved to the MEEI’s Jenks Vestibular laboratory as an engineer. Later Dan Merfeld was brought back from Portland Oregon to establish the Jenks Vestibular Physiology Laboratory performing monkey as well as human experiments. The exchange of students, faculty, and especially ideas has been a constant source of enrichment. Kathy Cullen, an outstanding neurophysiologist on sabbatical leave from McGill helps us in teaching and student supervision. Faisal Karmali now continues the MVL-MEEI connection in the area of vestibular psychophysics. By attending each other’s seminars and participating in teaching and thesis supervision we broaden our approach. (One current MEEI activity is development of an implanted vestibular prosthesis. The idea grew out of discussions at an MVL retreat, and reflected a dream expressed years earlier by Al Weiss.)

Helmets:

My involvement in helmet design started, like so many of my technical forays, at a ski resort – this time in Austria – in 2002. I noticed that only the North Americans there were wearing helmets, and was given the usual response – that Europeans don’t need them, they are too hot, they don’t do any good and, finally, that they mess up you hairdo. To try to improve the situation I invented a new helmet liner – foam with fluid filled channels, to distribute an impact spatially and to reduce the peak force transmitted to the skull. Back at MIT the Deshpande Fund supported initial student testing.

Glycerin/water mixtures filling channels within closed cell foam, reduced the pressure transmitted for an impact. When Ron Newbower of MGH's CIMIT saw our invention he encouraged me to consider the applicability to reduction of Traumatic Brain Injury from blasts – the signature injury of the wars in Iraq and Afghanistan. With support from CIMIT and the ONR we began a two pronged attack on this difficult problem – computer modeling and blast chamber testing of the helmet liners. Excellent modeling by the graduate students, George Christou and Andrew Vechart was accompanied by blast chamber testing at Purdue and the U of Nebraska by graduate students Rahul Goel and Allison Yost. To date the results are encouraging, but still a long way from a practical, light and comfortable helmet for soldiers to wear in dangerous areas. And the ski helmet remains a promising concept.

Other Clinical Forays

From its beginnings the MVL has been involved in the application of our control theoretic and instrumentation advances to clinical problems. Our emphasis on eye movements and vestibular-balance problems led to our role in the formation of the NIH sponsored Center for Biomedical Engineering at MIT working closely with Roger Mark and Stephen Burns. John Tole, who had contributed to numerous microprocessor controlled vestibular test devices, took our lead in the early development of “smart medical devices”. Josh Zeevi of the Technion, during his sabbatical years with us worked on human eye movement and their role in dyslexia. Together with Howard Hermann and Nancy Sonnabend he explored both the neurological basis of developmental dyslexia and means of quantifying the abnormalities in saccadic scanning.

Of the numerous spin-offs of the MVL, perhaps the most successful commercial activity was the NeuroCom posture platform developed by Lew Nashner. For his PhD thesis Lew built a computer controlled moveable posture platform to separate the roles of vestibular, visual and proprioceptive senses in human balance. After his move to Portland Oregon the demand for copies of the device led to the formation of NeuroCom, which became the leader in clinical and research posturography. Many other MVL alumni became leaders in biomedical devices, including Chas Burr at Hewlett Packard, Cori Lathan, who founded and manages Anthro-Tronix, and Andy Beall, who founded WorldViz, a VR software company.

Fear of Falling

Speaking of posture control – the regulation of balance may be looked upon as a problem in supervisory control. Higher cognitive function may be called upon to share attention with lower level balance tasks. Speech may slow when walking on a narrow beam, and walking may slow when concentrating on a conversation. The very nature of biped balance may shift from the ankle strategy to the hip strategy as earlier described by Nashner. The allocation may depend on the perceived consequences of balance loss – or “fear of falling”. I spent my 2009 sabbatical in Marseilles, in the CNRS lab of Liliane Borel and Michel Lacour, working also with Laurence Demanze, on the problem of balance strategy shifts in recovering vestibular patients when the threat of falling is increased by placing the posture platform well above the ground.

Mach

I had two heroes in science. Both were brilliant and imaginative scientists who dared to impose the principles of physics on a world of physiology that was not ready to accept an outsider so readily. One was Edwin Land, famed not only for the Polaroid Land camera but also for his two-wavelength (retinex) theory of color vision. The other was Ernst Mach, pioneer of fluid mechanics, after whom the unit for the speed of sound is named. In physiology he is known for his explanation of the physical principles behind vestibular function. His influential 1875 book “Grundlinien der Lehre von den Bewegungsempfindungen” (Fundamentals of the Theory of Movement Perception) had never received a proper translation into English until Volker Henn and I set out to do so in the 90s. Our research was pure scholarly joy – and supported the later modeling efforts of the MVL at many turns. After Volker’s early death in 1997 his last post-doc, Hansjoerg Scherberger stepped in and together we completed the translation, which was published by Kluwer in 2001.

Skolkovo

The latest in our international activities is with the MIT/SkTech (Skolkovo Institute of Technology) being established with the Russian Federation. In this bold concept, involving graduate schools of science and technology, research institutes and an industrial park, efforts are being directed toward

development of a technology based society. In an attempt to recreate Silicon Valley in Moscow, the research centers are to be feeders of Russian businesses, and work in close contact with the graduate schools. Our own role will be to develop space activities consistent with these goals. Jeff Hoffman and I, along with the rest of the MVL faculty and staff (Chuck Oman, Julie Shah, Dava Newman and Andy Liu) are actively pursuing collaborative research with our Russian colleagues. Fortunately for us the principle contacts at the Moscow Aviation Institute (Alexander “Sasha” Efremov) and at the Institute for Biomedical Problems (Inessa Kozovskaya) are old friends with whom we have worked in the past.

Teaching and Course Innovation

I was very fortunate to have started off my academic career under the wing of Y. T. Li, with whom I initially taught “Comparative Instrumentation”. Y. T. was insistent upon allowing the student to discover the fundamental “key parameters” of an engineering problem by himself. In the MVL, as in his later Innovation Center, Y.T. stressed the value of independent thinking. As the MVL grew I worked with my colleagues to introduce several new subjects. Each made use of the material we were developing in the MVL for research. In recognition of the growing flight simulator industry, and the needs of space, aviation and automobile users for training and research, we introduced “Flight Simulation”. Mark Connelly of LIDS, Walt Hollister and I taught it as a graduate course and a very popular summer course up until the early nineties. To meet the demand for physiology courses geared to the talents and interests of engineers, MIT developed a three semester sequence in Quantitative Physiology. I taught the sensory-motor subject, along with Larry Frishkopf, Chuck Oman and Bob Mann, and later with Neville Hogan, Dan Merfeld and Conrad Wall. Our labs and problem sets were far more technical than those in a medical school physiology course, as I have been told by several physician alumni. On the engineering psychology side of our discipline we recognized MIT’s absence of subjects in Human Factors. Tom Sheridan, of ME, and I teamed up to create an intense, mathematically oriented, graduate course, emphasizing models of human response. It later was extended to a senior Human Factors Engineering survey subject, which continues to this day, now taught by me with Missy Cummings and currently with Divya Chandra. The “learn by doing” component lies in the student presentation of real case studies of air or space accidents having a human factors cause. An unusual subject to come out of the MVL is the Biomedical Engineering Journal Club – a weekly session devoted to the

student presentation and critique of a published paper outside of our immediate field of expertise. It teaches graduate students to read critically, identify good and bad research practices, and develop communication skills. We are fortunate to have the regular participation of our statistician, Alan Natapoff, who helps guide us through the increasingly challenging problems of data analysis in modern biomedicine. For the faculty it is a refreshing dip in another pond each week. Closer to home academically, Chuck Oman, Dan Merfeld and I offer a specialty graduate course in Sensory-Motor Systems. Here again, student participation and critical thinking is developed by the practice of having small student teams present and summarize classical papers in the fields of vestibular physiology and related applications. Finally, led by David Mindell, and with the assistance of John Tylko, we offer a subject which could not be found other than at MIT – Engineering Apollo. Taking advantage of our close relations to many of the Apollo participants, in NASA, in industry, and in the Draper Laboratory, we offer a subject in which the students reexamine the technical choices that were made in getting astronauts to the moon and back. In every one of these subjects the research in the MVL informs the curriculum, and very often the best students in the class choose to write their graduate thesis on a subject of interest to us in the lab. I can't imagine a better arrangement.

Afterthoughts

Fifty years is a long time to be in the same lab, working on the same kind of problem. One is forced to ask if it was worth it. The answer is a resounding **yes**. The repeated cycle of learning of a problem of interest to the funding agencies, brainstorming an approach, recruiting a team to propose, writing the proposal, developing the hardware, training the students, doing the experiment, analyzing the data, writing the manuscript, responding to the critiques of the peer reviewers, and finally seeing the article in print - well - that's just a blast!

Not all of the ideas worked out. And some of the good ones were premature and were only realized when technology caught up - in someone else's lab. But enough of them stuck. The whole idea that quantitative methods could yield insights into vestibular, oculomotor and other areas of physiology is now so obvious as to no longer warrant discussion. The advances in manual control, though seemingly overtaken by automation and robotics in the current age, represent a giant step toward the efficiency and safety of modern aerospace systems. And the contributions of the MVL and its

hundreds of graduates to the space programs around the world speak to the effectiveness of our mission.

But most of all it is the people, of course. The other faculty – from Y.T. Li and Jacob Meiry at the beginning to our most recent addition, Julie Shah, were highly talented and great team players. The students have fantastic ability. They made it through the educational filter before I ever met them. They turn out to be, in general, really nice young people. That is what makes a half century of teaching and research so rewarding. To the extent that I have been able to pass along any of the dreams of Stark Draper about the value of physical analysis, of Larry Stark about the importance of quantitative modeling of physiological systems, and of Y. T Li about the need to think independently and get to the heart of a problem – then my half century with the MVL has been a success!



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MAN-VEHICLE LABORATORY

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Rader, Andrew Alan, **“Motion Perception with Conflicting or Congruent Visual and Vestibular Cues”**, Ph.D. in Aerospace Biomedical Engineering, August 2009

2010

Christou, George Alexander, **“Development of Helmet Liner for Protection Against Blast Induced Trauma”**, SM, AeroAstro, February 2010

Clark, Torin K. , **“Human Spatial Orientation Perceptions during Simulated Lunar Landing”**, SM, AeroAstro, June 2010

Holschuh, Bradley Thomas, **“Space Exploration Challenges: Characterization and Enhancement of Space Suit Mobility and Planetary Protection Policy Analysis”**, SM AeroAstro & Technology and Policy Program, June 2010

Johnson, Aaron W., **“An Integrated Traverse Planner and Analysis Tool for Future Lunar Surface Exploration”**, SM, AeroAstro, June 2010

Kaderka, Justin D., **“A Critical Benefit Analysis of Artificial Gravity as a Microgravity Countermeasure”**, SM AeroAstro, June 2010

Pontillo, Teresa M., **“Spatial Ability and Handedness as Potential Predictors of Space Teleoperation Performance”**, SM, AeroAstro, June 2010

Venkatesan, Raghav Harini, **“Multisensory Models for Human Spatial Orientation Including Threshold Effects”**, SM, AeroAstro, June 2010

Opperman, Roedolph A., **“Astronaut Extravehicular Activity – Safety, Injury & Countermeasures & Orbital Collisions & Space Debris – Incidence, Impact & International Policy”**, SM in AeroAstro and SM in TPP, September 2010

2011

Anderson, Allison P., **“Addressing Design Challenges in Mechanical Counterpressure Spacesuit Design and Space-Inspired Informal Education Policy”**, SM, AeroAstro, February 2011

Goel, Rahul, **“Study of an Advanced helmet Liner Concept to Reduce TBI: Experiments & Simulation using Sandwich Structures”**, SM, AeroAstro, February 2011

Hainley, Christopher, **“Lunar Landing: Dynamic Operator Interaction with Multi-Modal Automation Systems”**, SM, AeroAstro, February 2011

Stimpson, Alexander J., **“Design and Evaluation of an Achievability Contour Display for Piloted Lunar Landing”**, SM in AeroAstro, February 2011

Vechart, Andrew, "**Design of a Composite Combat helmet Liner for Prevention of Blast-Induced Traumatic Brain Injury**", SM, School of Engineering, Computation for Design and Optimization, February 2011

Arai, Tatsuya, "**Estimation of Cardiovascular Indices by Analysis of the Arterial Blood Pressure Signal**", PhD, AeroAstro, June 2011

Buckland, Daniel, "**Ultrasound Imaging of Cervical Spine Motion for Extreme Acceleration Environments**", PhD, AeroAstro, September 2011

Forman, Rachel Emily, "**Objective Performance Metrics for Improved Space Telerobotics Training**", SM, AA, September 2011

Wen, Hui Ying, "**Human-Automation Task Allocation in Lunar Landing: Simulation and Experiments**", SM, AA, September 2011

2012

Galvan, Raquel, "**Effects of Fatigue on Simulated Space Telerobotic Performance: A Preliminary Study Analysis**", SM, AA, September 2012

Gilkey, Andrea, "**Spacesuit simulator for extravehicular activity experimentation and training**", SM, AA, June 2012

Lowenthal, Caroline, "**Evaluation of Sleepiness in Space Robotics task Performance and Discussing Sleep with High School Students in a Museum**" SM AA & TPP, February 2012

Wang, Victor, "**Bimanual Cross-Coupling in Space Telerobotics**", SM ME, February 2012

Yost, Allison, "**Fluid-Filled Helmet Liner Concept for Protection Against Blast-Induced Traumatic Brain Injury**", SM ME, June 2012

**MAN-VEHICLE LABORATORY
PUBLICATIONS**

August 2012

Department of Aeronautics and Astronautics
Kavli Institute for Astrophysics and Space Research
Room 37-219
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139

NOTES

Publications are listed in reverse chronological order, and include journal articles, abstracts, and technical reports. MVL student theses are indexed in a separate list, "Man-Vehicle Laboratory Theses," which is available upon request. Copies of all publications are available in limited numbers upon request. When requesting publications, give the MVL publication number listed with each citation. Numbers are assigned when author makes publication available for distribution, usually when it is accepted for publication or is in press. Some publication numbers are missing from sequence because the manuscripts originally assigned to them were reassigned to the year of actual publication in the open literature.

2012

- 12.01 Duda, K., Jarchow, T., Young, L., "Squat Exercise Biomechanics During Short-Radius Centrifugation", *Aviation, Space, and Environmental Medicine*, Vol. 83, No. 2, February 2012
- 12.02 Young, L.R., Natapoff, A., Greenberg, J., "The Harvard-MIT PhD Program in Bioastronautics", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.03 Liu, A.M., Wang, V., Forman, R.E., Galvan, R.C., Natapoff, A., Oman, C.M., "Advanced Displays for Efficient Training and Operation of Robotic Systems", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, Feb. 13-16, 2012
- 12.04 Young, L.R., Oman, C.M., Clark, T.K., Tritchler, S.E., Duda, K.R., Wood, S.J., Estrada, A., "Sensorimotor Interaction with Vehicle Displays and Controls to Enhance Human-Machine Cooperation during Precision Lunar Landing", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.05 Clark, T.K. and Newman, M.C., "Human Orientation Perception of Roll Tilt in Hyper-Gravity", poster, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.06 Kaderka, J.D., Duda, K.R., Oman, C.M., "Development and Simulation of a Pilot Failure Detection Model within a Closed-Loop Human-System Model", poster, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.07 Wen, H.Y., Johnson, A.W., Duda, K.R., Oman, C.M., and Natapoff, A., "Investigating Human-Automation task Allocation in Lunar Landing Through Simulation and Human Subject Experiments", poster, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.08 Liu, A.M., Lowenthal, C.S., Galvan, R.C., Forman, R.E., Rueger, M., Flynn-Evans, E.E., Natapoff, A., Lockley, S.W., Oman, C.M., "Validation of Assessment Tests and Countermeasures for Detecting and Mitigating Changes in Cognitive Function during Robotic Operations", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.09 Duda, K. R., T. Jarchow, L. R. Young (2012) "Squat Exercise Biomechanics During Short-Radius Centrifugation." *Aviation, Space, and Environmental Medicine*, 83(2):1-9.
DOI: 10.3357/ASEM.2334.2012
- 12.10 Van Loon, J.W.A., Baeyens, Berte, J., Blac, S., Bok, K., Bos, J., Royle, R., Braak, L., Bravenboer, N., Chouker A., Clement, G., Cras, P., Cross, E., Custaud, M-A., Angelis, M.De, de Dreu, C., Delavaux, T., Delfos, R., Denise, P., eekhoff, M., Felsenberg, D., Fong, K., Fuller, C., Goswami, N., Grillner, S., Groen, E., Harlaar, J., Heer, M., Heglund, N., Hinghofer-Szalkay, H., Hughes-Fulford, M., Iwase, S., Karemaker, J., Langdahl, B., Linnarsson, D., Luthen, C., Manzey, D., Monici, M., Narici, M., Norsk, P., Paloski, W., Poelma, C., Prisk, K., Rutten, M., Singer, P., Stegeman, D., Stephan, A., Stienen, G., Suedfeld, P., Tesch, P., Ullrich, O., van de Heyning, P., van den Berg, R., Veys, J., Vico, L., Woodward, E. Young, L., Wuyts, F., "A Large Human Centrifuge for Exploration and Exploratory Research", (abstract) 39th COSPAR Scientific Assembly 2012
- 12.11 Liu A.M., Wang V., Forman R.E., Galvan R.C., Natapoff A., Oman C.M., "Advanced Displays for Efficient Training and Operation of Robotic Systems", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.12 Clark T.K., Newman M.C., "Human Orientation Perception of Roll Tilt in Hyper-Gravity", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012

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- 12.13 Duda K.R., Kaderka J.D., Johnson A.W., Wen H.Y., Hainley C.J. Jr., Oman C.M., Natapoff A., Marquez J.J., "Human-Automation Interactions and Performance Analysis of Lunar Lander Supervisory Control", NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.14 Duda J.E., Opperman R.A., Gilkey A.L., De Vivero C., Newman D.J., Hoffman J., Gilkey K., "Space Suit Simulator for EVA Experimentation and Training" abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.15 Anderson A., Diaz A., Kracik M., Kobrick R., Trotti G., Hoffman J., Newman D.J., "Methodology Toward Developing a Spacesuit Trauma Countermeasure System for Extravehicular Activity", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.16 Anderson A., Newman D.J., "Modeling Astronaut-Spacesuit Interaction to Develop a Spacesuit Trauma Countermeasure System for Extravehicular Activity", abstract, NASA Human Research Program Investigators' Workshop, Houston, TX, February 13-16, 2012
- 12.17 Clark, T.K., Young, L. R., Duda, K.R., Oman, C.M., "Simulation of Astronaut Perception of Vehicle Orientation during Planetary Landing Trajectories", presented at the 2012 IEEE Conference, Bozeman, MT, March 3, 2012
- 12.18 Rood, A., D. Dietrich, K. Sparks, D. Dashevsky, D. Wajda, J. Mateus, A. Johnson and D. Newman (2012). *Pulse Oximetry and Ventilation Data during Exposure to 7620m (25,000 feet) Normobaric Hypoxia*. 83rd Annual Meeting of the Aerospace Medical Association Atlanta, GA.
- 12.19 George A. Christou, Laurence R. Young, Rahul Goel, Andrew P. Vechart, Antoine Jérusalem, Shock attenuation of PMMA sandwich panels filled with soda-lime glass beads: A fluid-structure interaction continuum model simulation", International Journal of Impact Engineering, Volume 47, September 2012, Pages 48-59
- 12.20 Small, R. L., C. M. Oman and T. D. Jones (2012). "Space Shuttle Flight Crew Spatial Orientation Survey Results." Aviation, Space, and Environmental Medicine **83**(4): 383-387
- 12.21 Young, L.R., Clark, T. K., Estrada, A., and Tritchler, S., "Lunar dust challenges to astronaut landing", abstract, Dust, Atmosphere and Plasma: Moon and Small Bodies Workshop, June 6-8, 2012, Boulder, CO
- 12.22 Oman, C. M. and K. E. Cullen (2012). "Brainstem processing of vestibular sensory reafference: implications for motion sickness etiology (Abstract 245)." Aviation Space and Environmental Medicine **83**(3): 279.
- 12.23 Lowenthal, C. S., A. Liu, A. Natapoff and C. M. Oman (2012). "Effect of sleepiness on performance and workload during space robotics tasks (abstract 227)." Aviation Space and Environmental Medicine **83**(3): 274.
- 12.24 Mateus, J. and A. R. Hargens (2012). "Photoplethysmography for non invasive *in vivo* measurement of bone hemodynamics." Physiological Measurement **33**(6): 1027-1042.
- 12.25 Liu, A.M., Oman, C.M., Galvan, R., Natapoff, A., "Predicting space telerobotic operator training performance from human spatial ability assessment", Acta Astronautica (2012), <http://dx.doi.org/10.1016/j.actaastro.2012.04.004>
- 12.26 Laurence R. Young^{a,*}, Laurence Bernard-Demanze^b, Michel Dumitrescu^b, Jacques Magnan^c, Liliane Borel^b, Michel Lacour^b Postural Performance of Vestibular Loss Patients Under Increased Postural Threat , JVR, Manuscript submitted, May 2012, Joint World Congress of ISPGR and Gait & Mental Function. Trondheim, Norway, June 24-28, 2012
- 12.27 Arai, T., Lee, K., Marini, R. P., and Cohen, R. J., "Estimation of Changes in Instantaneous Aortic Blood Flow by the Analysis of Arterial Blood Pressure", Journal of Applied Physiology, vol. 112, no. 11 (2012) PP. 1832-1838.

12.28 Schimizza, Benjamin, Son, Steven F., Goel, Rahul, Vechart, Andrew P., and Young, Laurence, "An experimental and numerical study of blast induced shock wave mitigation in sandwich structures", *Applied Acoustics* (2012)
<http://dx.doi.org/10.1016/j.apacoust.2012.05.011>

12.29 Anderson, A., D. Newman, "Developing a Spacesuit Injury Countermeasure System for Extravehicular Activity" International Conference on Environmental Systems 2012, San Diego. (Poster, 1st Place)

12.30 Anderson A., A. Diaz, M. Kracik, G. Trotti, J. Hoffman, and D. Newman, "Developing a Spacesuit Injury Countermeasure System for Extravehicular Activity: Modeling and Analysis" International Conference on Environmental Systems 2012, San Diego. (Paper + talk)

12.31 Anderson, A., D. Newman, "Modeling Astronaut-Spacesuit Interaction To Develop a Spacesuit Trauma Countermeasure System for Extravehicular Activity" NASA Human Research Program Investigator's Workshop 2012, Houston. (Poster)

12.32 Anderson A., A. Diaz, M. Kracik, R. Kobrick, G. Trotti, J. Hoffman, and D. Newman, "Methodology Toward Developing a Spacesuit Trauma Countermeasure System for Extravehicular Activity" NASA Human Research Program Investigator's Workshop 2012, Houston. (Poster)

12.33 Anderson, A., S. Wilcox, E. Gundersen, G. Trotti, D. Newman, "Using Space-Inspired Education Tools to Enhance STEM Learning in Rural Communities" American Society of Engineering Education Annual Conference 2011. Vancouver. (Paper+talk)

12.34 Anderson, A., M. Kracik, G. Trotti, D. Newman, "Preliminary Astronaut Injury Countermeasure and Protection Suit Design." IAA Humans Space Conference 2011, Houston. (Poster)

12.35 Domingues, A.R., Marreiros, S.P., Martins, J.M., Silva, M.T., Newman, D.J., "Analysis of ankle skin deformation for the development of soft orthotics", ESB 2012: 18th Congress of the European Society of Biomechanics, Lisbon, Portugal, Jul. 2012.

12.36 Kobrick, R.L., Carr, C.E., Meyen, F., Domingues, A.R. and Newman, D.J. (2012): "Using inertial measurement units for space vehicle safety, comfort, design, and performance optimization" (abstract). Next-Generation Suborbital Researchers Conference 2012. Session: Life Sciences. Palo Alto, California, USA.

12.37 Young, L.R., C.M. Oman, T.K. Clark, S.E. Tritchler, K.R. Duda, S.J. Wood, and A. Estrada (2012) "Sensorimotor interaction with vehicle displays and controls to enhance human-machine cooperation during precision lunar landing" [Abstract] NASA Human Research Program Investigators' Workshop. Houston, TX. 14-16 February.

12.38 Clark, T.K., L.R. Young, K.R. Duda, and C.M. Oman (2012) "Simulation of Astronaut Perception of Vehicle Orientation during Planetary Landing Trajectories" IEEE Aerospace Conference. Big Sky, MT. 3-10 March.

12.39 Duda, K. R., Johnson, M. C., and Fill, T. J., "Design and Analysis of Lunar Lander Manual Control Modes" *Submitted to AIAA Journal of Spacecraft and Rockets*.

12.40 Diaz, A., Anderson, A., Kracik, M., Trotti, G., Hoffman, J. and Newman, D. J. (2012): "Development of a comprehensive astronaut spacesuit injury database". 63rd International Astronautical Congress 2012. Naples, Italy.

12.41 Wen, H.Y., Johnson, A.W., Duda, K.R., Oman, C.M., Natapoff, A., "Decision-Making and Risk-Taking Behavior in Lunar Landing", 56th Annual Meeting of the Human Factors and Ergonomics Society, 22-26 Oct. 2012.

12.42 Alibay, F., Desaraju, V., Cowlagi, R., Duda, J.E., Johnson, A.W., Hoffman, J.A., "Multi-Vehicle Lunar Operations Simulation Using SEXTANT", AIAA SPACE 2012 Conference, Pasadena, CA, 11-13 Sept. 2012.

12.43 Johnson, A., Stimpson, A., Clark T., "Turning the Tide: Big Plays and Psychological Momentum in the NFL", *Football Outsiders Almanac 2012*, Ed. Aaron Schatz, Football Outsiders, 2012, 518-522.

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- 12.44 Johnson, A.W., Stimpson, A.J., Clark T.K., "Turning the Tide: Big Plays and Psychological Momentum in the NFL", poster presented at the 2012 MIT Sloan Sports Analytics Conference, Boston, MA, 2-3 Mar. 2012.
- 12.45 Clark, T.K., Johnson, A.W., Stimpson, A.J., "Why Devin Hester is a Better Returner when He Doesn't Touch the Ball: The Effectiveness of the Squib Kickoff in the NFL", paper submitted for the 2012 MIT Sloan Sports Analytics Conference, Boston, MA, 2-3 Mar. 2012.
- 12.46 Rood, A., D. Dietrich, K. Sparks, D. Dashevsky, D. Wajda, J. Mateus, A. Johnson and D. Newman (2012). *Pulse Oximetry and Ventilation Data during Exposure to 7620m (25,000 feet) Normobaric Hypoxia*. 83rd Annual Meeting of the Aerospace Medical Association Atlanta, GA.
- 12.47 Johnson, A.W., Newman, D.J., Waldie, J.M., Hoffman, J.A., "An EVA Mission Planning Tool based on Metabolic Cost Optimization", SAE 2009-01-2562, 39th International Conference on Environmental Systems (ICES), Savannah, GA, 12-16 July 2012.
- 12.48 Wilcox, Ronald; Nikolaidis, Stefanos, Shah, Julie, "Optimization of Temporal Dynamics for Adaptive Human-Robot Interaction in Assembly Manufacturing," In Proc. Robotics, Science and Systems (RSS); Sydney, Australia; July 2012.
- 12.49 Gombolay, Matthew, Shah, Julie, "A Uniprocessor Scheduling Policy for Non-Preemptive Task Sets with Precedence and Temporal Constraints", AIAA Infotech@Aerospace; Garden Grove, California; June 2012.
- 12.50 Nikolaidis, Stefanos, Shah, Julie, "Human-Robot Interactive Planning using Cross-Training: A Human Team Training Approach AIAA Infotech@Aerospace; Garden Grove, California; June 2012.
- 12.51 Wilcox, Ron, Shah, Julie, "Optimization of Multi-Agent Workflow for Human-Robot Collaboration in Assembly Manufacturing", AIAA Infotech@Aerospace; Garden Grove, California; June 2012.
- 12.52 Nikolaidis, Stefanos, Shah, Julie., "Human-Robot Teaming using Shared Mental Models", IEEE/ACM International Conference on Human-Robot Interaction, Workshop on Human-Agent-Robot Teamwork; Boston, MA; Mar 2012.
- 12.53 Holschuh, B., Obropta, E., Buechley, L., and Newman, D. "Materials and Textile Architecture Analyses for Mechanical Counter-Pressure Space Suits using Active Materials", AIAA Space 2012 Conference and Exposition, Pasadena, CA, September 11-13, 2012. (accepted)
- 12.54 Kobrick, R.L., Carr, C., Newman, D.J., Meyen, F., Domingues, A.R. and Jacobs, S. (2012): " Using inertial measurement units for measuring spacesuit mobility and work envelope capability for intravehicular and extravehicular activities" (abstract). 63rd International Astronautical Congress. Space Life Sciences Symposium, Life Support and EVA Systems Session. Naples, Italy. IAC-12,A1,6,6,x13275.
- 12.55 Newman, Michael, Clark, Torin, "Human Orientation Perception in Hyper Gravity" ETC Newsletter, June 29, 2012, <http://www.etcusa.com/etc-newsletter/?p=170>

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11.02 Stimpson, A.J., Young, L.R., Clark, T.K., Duda, K.R., and Oman, C.M., "Effects on an Achievability Display on Pilot Decision Making and Behavior in Simulated Lunar Landings", (abstract) 18th IAA Humans in Space Symposium, Houston, TX, 11-15 April 2011

11.03 Hainley, C.J., Duda, K.R., and Oman, C.M., "Graceful" Automation transitions in a Multi-Modal Lunar Landing Vehicle, (abstract) 18th IAA Humans in Space Symposium, Houston, TX, 11-15 April 2011

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- 11.04 Wen, H.Y., Duda, K.R., and Oman, C.M., "Modeling Effects of Human-Automation Task Allocation on Lunar Landing Performance", (abstract) 18th IAA Humans in Space Symposium, Houston, TX, 11-15 April 2011
- 11.05 Domingues, A.R., Marreiros, S.P., Martins, J.M., Silva, M.T., Newman, D.J., "Skin Strain Field Analysis of the Human Ankle Joint", 4^o Congresso Nacional de Biomecânica (CNB2011), Coimbra, Portugal, Feb. 2011.
- 11.06 Kobrick, R.L., Anderson, A., Wagner, E.B., Newman, D.J., "MIT's Man Vehicle Laboratory Capabilities for Suborbital Spaceflight", 2011 Next Generation Suborbital Researchers Conference, Orlando, FL, Mar. 2011 (submitted)
- 11.07 Rood, A., Dashevsky, D., Fast, B., Kobyljanec, A., Glickman, E., Newman, D.J., Dietrich, D., "A Novel Hypoxia Monitoring, Prediction and alert System, Aerospace Medical Association, Ankorage AK, May 2011 (submitted)
- 11.08 Meyen, F.E., Holschuh, B., Kobrick, R.L., Jacobs, S., and Newman, D.J., "Robotic Joint Torque Testing: A Critical Tool in the Development of Pressure Suit Mobility Elements" 41st International Conference on Environmental Systems 2011, Portland, OR, July 2011.
- 11.09 Gilkey, A., Kobrick, R.L., Johnson, A.W., Hoffman, J.A., Newman, D.J., "Evaluation of a Surface Exploration Traverse Analysis and Navigation Tool", 41st International Conference on Environmental Systems 2011, Portland, OR, July 2011 Session ICES400: AMSE Extravehicular Activity: Space Suits, Portland, Oregon, USA, AIAA Control ID: 1022016. (submitted)
- 11.10 Gilkey, A., Melo, P.L., Kobrick, R.L., Kuan, J.-Y., Young, D., Newman, D.J., "Using IMU Sensors for Real-Time Manipulation of Robot Spacesuit Tester to Determine Internal Joint Torque Measurements in Spacesuits", 41st International Conference on Environmental Systems 2011, Portland, OR, July 2011. (submitted)
- 11.11 Young, L. R., "Optimal Estimator Models for Spatial Orientation and Vestibular Nystagmus", *Experimental Brain Research* (2011) 210:465-476
11. 12 Mateus, J., Hargens, A.R. "Non-Invasive Bone Hemodynamics by Photoplethysmography", 18th IAA Humans in Space Symposium, Houston, TX, 11-15 April 2011.
- 11.13 Mateus, J., Hearn, A.N., Canizales, J., Young, L.R. " Cross-coupled stimulus during artificial gravity: Asymmetric tumbling sensation response", Poster Session 4, *Journal of Vestibular Research*, 21 (2011) 77-85, IOS Press, Special Issue, Abstracts from the Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX, April 8-10, 2011
- 11.14. Newman, M.C., McCarty, G.W., Comtois, P.W., Glaser, S.T., Bonato, F., "Adaptation to coriolis-inducing head movements in a sustained-G high performance flight simulator, Poster Session 4, *Journal of Vestibular Research*, 21 (2011) 78-79, IOS Press, Special Issue, Abstracts from the Eight Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX, April 8-10, 2011
- 11.15 Rosales-Velderrain, A., Cardno, M., Mateus, J., Schlabs, T., Kumar, R., Hargens, A.R., "Toe Blood Pressure and Leg Muscle Oxygenation with Body Posture", *Experimental Biology*, April 9-13, 2011, Washington D.C.
- 11.16 Bachman, L.L.Jr., Mateus, J., Hargens, A.R., "Hemodynamics of Bone and Muscle in the Lower Limb with Head-up and Head-down Tilt", 18th IAA Humans in Space Symposium, April 11-15, 2011, Houston, TX
- 11.17 Mateus J, Canizales J, Hearn AN, Young LR (2011) Asymmetry in vestibular responses to cross coupled stimulus. *Exp Brain Res* 209 (4):561-569. doi:10.1007/s00221-011-2588-0
- 11.18 Young, Laurence R., Vechart, Andrew P., "Head Impact Protection Through Filler Materials Embedded in a Helmet Liner", (abstract) 2011 ISSS symposium in Keystone, CO, May 1-7, 2011
- 11.19 Rader, Andrew, A., Oman, Charles, M., "Perceived tilt and translation during variable-radius swing motion with congruent or conflicting visual and vestibular cues", *Exp Brain Res* (2011) 210:173-184

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11.22 Kobrick, R.L., Street, Jr., K.W., and Klaus, D.M. (2011): "Custom Scratch Tips for Evaluation of Two-Body Abrasion on Lunar Spacecraft Materials" (abstract). 41st International Conference on Environmental Systems 2011, Session ICES510: AIAA Lunar and Martian Dust Properties and Mitigation Technologies, Portland, Oregon, USA. AIAA Control ID: 1021777.

11.23 Kobrick, R.L., Russ, R.B., and Bailey, T.J. (2011): "Yuri's Night: Linking the World Together with an International Space Celebration" (abstract). 41st International Conference on Environmental Systems 2011, Session ICES308: AIChE Education Outreach, Portland, Oregon, USA. AIAA Control ID: 1021104.

11.24 Oman, C.M., "Eight Symposium on the Role of the Vestibular Organs in Space Exploration", Introduction, *Journal of Vestibular Research*, 21 (2011) 63, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011

11.25 Oman, C.M., "Are evolutionary hypotheses for motion sickness "Just So" stories?", Oral Session 5: Motion Sickness and Pharmacology, *Journal of Vestibular Research*, Volume 21, Number 2, 2011, pp. 89, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX, April 8-10, 2011

11.26 Young, L.R., Bernard-Demanze, L., Borel, L., Lacour, M., "Fear of falling: Posture control as influenced by perceived fall height", Oral Session 6: Sensorimotor Integration, *Journal of Vestibular Research*, 21, (2011) 91, IOS Press, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011.

11.27 Selva, P., Oman, C.M., "Relationships between observer and Kalman filter models for human dynamic spatial orientation", (abstract), *Journal of Vestibular Research*, 21, (2011) 71, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011.

11.28 Small, R.L., Keller, J.W., Wickens, , Oman, C.M., Jones, T.D., "Modeling and mitigating spatial disorientation in low G environments: A progress report", (abstract), *Journal of Vestibular Research*, 21, (2011) 69, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011.

11.29 Newman, M.C., Oman, C.M., Clark, T.K., Mateus, J., Kaderka, J.D., "Pseudo-coriolis effect: A 3D angular velocity storage phenomenon described by a left-hand rule", (abstract) *Journal of Vestibular Research*, 21, (2011) 70-71, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011.

11.30 Sheehan, S., Oman, C., Duda, K., "Motion sickness etiology: A cholinomimetic agent hypothesis", *Journal of Vestibular Research*, 21, (2011) 84-85, Special Issue, Eighth Symposium on the Role of the Vestibular Organs in Space Exploration, Houston, TX April 8-10, 2011.

11.31 Young, L.R., "Head Impact Protection Through Filler Materials Embedded in a Helmet Liner", ppt slides presented at ISSS 2011, Keystone, Colorado, May 1-7, 2011

11.32 Clark, T. K., Young, L.R., Stimpson, A.J., Duda, K.R., Oman, C.M, "Numerical Simulation of Human Orientation Perception during Lunar Landing", manuscript, submitted to *Acta Astronautica*, Jan. 2011

11.33 MVL Presentations, MIT 150 Symposia, Earth, Air, Ocean and Space: The Future of Exploration, April 26-27, 2011, Kresge Auditorium, MIT, Moderators: Jeffrey Hoffman, Laurence Young, Panelists: Buzz Aldrin, Timothy Creamer, Terry Hart, Frederick Hauck, Byron Lichtenberg, Michael Massimino

11.34 Vechart, Andrew, "Making Army Helmets Tougher and Safer", SIMULIA Realistic Simulation News, May/June 2011, pp.4-5

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