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Invited Lectures from a Spatial Orientation Symposium in Honor of Frederick Guedry, Day 1

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United States Army Aeromedical Research Laboratory

Warfighter Health Division

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14. ABSTRACT

This report contains a transcript of the invited lectures comprising day 1 of a Spatial Orientation Symposium in honor of Dr. Frederick Guedry, held at the Institute of Human and Machine Cognition (IHMC) in Pensacola, FL on 19-20 November 2010. The conference was sponsored by the Coalition Warfare Program of the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. It was organized by Drs. Angus Rupert and Ben Lawson (USAARL) and Drs. Anil Raj and Ken Ford (IHMC). This report opens with the transcript of a speech by Dr. Rupert, who provides some little-known facts about Fred Guedry and gives an overview of the topics and speakers. The subsequent lectures by Drs. Laurence Young, Charles Oman, Jan Holly, Braden McGrath, Wallace Grant, and Ian Curthoys focus on the modeling and neuroscience of vestibular structure, function, reflexes, and orientation perceptions.

15. SUBJECT TERMS

vestibular, tactile, balance, falling, spatial orientation, spatial disorientation, motion sickness

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Introduction to the lectures

This report contains invited lectures from the first day of a two-day spatial orientation symposium in honor of the noted vestibular researcher Frederick Guedry, Jr., Ph.D. The symposium was held 19-20 November 2010 at the Institute of Human and Machine Cognition (IHMC) in Pensacola, FL. The conference was sponsored by the Coalition Warfare Program of the Office of the Under Secretary for Acquisition, Technology, and Logistics and organized by Drs. Angus Rupert and Ben Lawson of the U.S. Army Aeromedical Research Laboratory (USAARL) and Dr. Anil Raj of IHMC. The attendees included Dr. Guedry and many of his esteemed colleagues from around the world, including Drs. Alan Benson, Owen Black, Robert Cheung, Manning Correia, Jay Goldberg, Ken Money, and others.

This day one report opens with the transcript of a speech by Dr. Rupert, who provides some little-known facts about Fred Guedry and gives an overview of the topics and speakers for both days of the conference. Following this are transcribed lectures by Drs. Laurence Young (Massachusetts Institute of Technology), Charles Oman (Massachusetts Institute of Technology), Jan Holly (Colby College), Braden McGrath (then at QinetiQ), Wallace Grant (Virginia Technical University), and Ian Curthoys (University of Sydney). These lectures focus on the modeling and neuroscience of vestibular structures, functions, and reflexes, as well as self-orientation perceptions. The full conference agenda is shown in table 1.

Table 1.

Agenda

A Spatial Orientation Symposium Held in Honor of Frederick Guedry, Jr.

19-20 November 2010

Site Host: Institute of Human and Machine Cognition, Pensacola, Florida

Sponsoring Hosts: U.S. Army Aeromedical Research Laboratory, sponsored by Coalition Warfare Program, Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OSD AT&L)

Vestibular topics include modeling, psychophysics, plasticity, adaptation, motion sickness, clinical problems and tests, balance and vestibular rehabilitation

Day 1: 19 Nov

Continental breakfast – meet and greet: 8:30 AM

Modeling and Orientation: 9:00 AM
- Angus Rupert: Welcome to the Fred Fest, in Honor of Fred Guedry, a National Treasure
- Larry Young : Mathematical models of the Vestibular System
- Ken Ford: Welcome from IHMC Director
- Charles Oman: Models for Coriolis and Psuedo-Coriolis Response
- 15 min break
- Jan Holly: The Shape of Self-Motion Perception
- Braden McGrath: Visualization of Spatial Disorientation Mishaps in the US Navy: Case Study
- Discussion of research directions to expand model

Before lunch: Group photo (page 8)

Lunch – IHMC: 12:30 PM

- Anil Raj: IHMC Tour

Annual Update: 2:00 PM
- Wallace Grant: Experimental Measurement of Otolith Dynamic Displacement
- Wallace Grant: Computational Fluid Dynamics Model of Endolymph Flow around Hair Cell Bundle
- Ian Curthoys: Update from Sydney
- Discussion

Tactile Rehabilitation Brief and Demonstration Session 1
- Karen Atkins and Bruce Mortimer
- Bruce Mortimer

Table 1 (continued).

Day 2: 20 Nov

Adaptation and Maladaptation: 8:30 AM

- Scott Wood: Slow Rotation Room and Spaceflight: Similarities in Time Course of Adaptation and Readaptation
- Ben Lawson: The Understanding of Coriolis Cross-Coupling (Ccc)
- 15 min break
- Robert Kennedy: Maladaptation
- Angus Rupert: Motion Sickness Aeitology: Alternative to Treisman's Evolutionary Theory
- Discussion and future directions

Lunch – IHMC: 12:30 PM

Vestibular Injury and Treatment: 1:30 PM

- Owen Black: Vestibular Injury and Treatments: Clinical Applications
- Karen Atkins: Vibrotactile Postural Control in Patients with Sit-to-Stand Balance Deficit and Fall
- Kim Gottshall: Vestibular Physical Therapy
- Anil Raj: Anthro-Centric Multisensory Interfaces
- Måns Magnusson: Experimental Acute and Bilateral Vestibular Loss

Tactile Rehabilitation Brief and Demonstration Session 2

- Karen Atkins: Multimodal Biofeedback Demo
- Bruce Mortimer: Multimodal Biofeedback Demo

Banquet on the deck of World War II (WWII) aircraft carrier USS Cabot: 5:30 PM

Some words of explanation are necessary for the reader to fully appreciate certain important features of this report. First, it should be noted that the transcribed lectures and the audience discussion following them are preserved close to their original form rather than being rewritten as polished prose proceedings papers lacking any record of audience questions and comments. This has been done to faithfully preserve the spirit and immediacy of the presentations, and to capture the valuable verbal exchanges which occurred during and after many of the lectures. When the reader considers the people in attendance (See table 1 and page 8), he/she will readily understand that much interest can be derived from reading the audience exchange that occurred outside the context of the planned lectures, *per se*. In fact, it could be said that many advances in the young field of vestibular science start as in-person discussions among researchers.

Table 2.
Conference attendees.

Attendee	Affiliation
James Atkins, M.D.	Director, Florida Ear and Balance Center
Karen Atkins, Ph.D., P.T.	Director, BalanceSense LLC
Kara Beaton, M.S.	Johns Hopkins University
Alan Benson, Ph.D.	Royal Air Force Medical Institute, retired
Jamie Bishop, M.S.	Research Scientist, Environmental Tectonics Corporation
Owen Black, M.D.	Senior Scientist, Director of Neurotology Research, Legacy Research Institute
Kristin Blackwell, B.A.	Senior Consultant, Ventera Corporation, Former Primary Research Assistant to Dr. Guedry (accompanied by her spouse, David Blackwell, Delta Airlines pilot)
Robert Cheung, Ph.D.	Senior Defence Scientist, Defence Research and Development Canada (DRDC), Toronto
Manning Correia, Ph.D.	Department of Otolaryngology, University of Texas Medical Branch Galveston, retired
Ian Curthoys, Ph.D.	Professor, University of Sydney
Linda Elliot, Ph.D.	Research Scientist, Army Research Laboratory/Human Research and Engineering Directorate
Jay Goldberg, Ph.D.	Professor, University of Chicago
Mark Goto, M.D.	Director of ENT, Naval Hospital Pensacola
Kim Gottshall, Ph.D., P.T.	Director, Vestibular Assessment and Rehabilitation, Naval Medical Center San Diego
Wallace Grant, Ph.D.	Engineering Science and Mechanics Director, Virginia Technical Institute
James Grisset, Ph.D.	Chief Scientist (retired), Naval Aerospace Medical Research Laboratory

Table 2 (continued).

Attendee	Affiliation
Frederick Guedry, Ph.D.	Professor Emeritus, University of West Florida and former Chief Scientist, Naval Aerospace Medical Research Laboratory
Casey Harris	Research Technician, US Army Aeromedical Research Laboratory
Jan Holly, Ph.D.	Associate Professor, Colby College
Robert Hoyt, M.D.	Faculty Associate, School of Allied Health and Life Sciences, University of West Florida
Anthony Hughes, M.D.	Otolaryngologist, Nemours Children's Clinic
Ben Lawson, Ph.D.	Research Scientist, US Army Aeromedical Research Laboratory
Måns Magnusson, M.D.	Professor and Head, Department of Otolaryngology, Lund University, Sweden
Albert Mateczun, M.D.	Former Commanding Officer, Naval Aerospace Medical Research Laboratory
Braden McGrath, Ph.D.	Chief Technology Officer, QinetiQ (at the time of this meeting); Currently Professor at University of Canberra, Australia.
Kenneth Money, Ph.D.	Senior Defence Scientist (retired), Defence Research and Development Canada (DRDC), Toronto
Bruce Mortimer, Ph.D.	Director of Research and Development, Engineering Acoustics, Inc.
Michael Newman, S.M.	Research Scientist, Environmental Tectonics Corporation
Charles Oman, Sc.D.	Director, Man-Vehicle Laboratory, Massachusetts Institute of Technology
Henry Porter, M.D.	Head of Neurology, Naval Operational Medicine Institute
Anil Raj, M.D.	Research Scientist, Institute for Human and Machine Cognition

Table 2 (continued).

Attendee	Affiliation
Angus Rupert, M.D., Ph.D.	Research Scientist US Army Aeromedical Research Laboratory
Mark Shelhamer, Sc.D.	Associate Professor, Otolaryngology, Johns Hopkins School of Medicine
Daniel Thomas, M.D., M.P.H.	President, Snell Memorial Foundation
Scott Wood, Ph.D.	Senior Scientist, Universities Space Research Association
Laurence Young, Sc.D.	Professor, Massachusetts Institute of Technology

This symposium was held late in 2010, slightly more than two months before the falling-related death of Dr. Guedry occurred. However, it took considerable time to make these lectures available in print, because the original plan for automated software speech-to-text conversion of the recorded speeches did not produce a usable result. Therefore, it was necessary for a team of people to transcribe and edit all of the speeches and discussions manually based only on the video records. It is hoped that the discussions among vestibular experts will prove as interesting to vestibular specialists as the audience discussions that were preserved following the lectures from the classic first four symposia held on the Role of the Vestibular Organs in Space from 1965-1968, and available in the Journal of Vestibular Research repository at www.jvr-web.org/Links.html. These earlier symposia serve as an important historical example of the usefulness of preserving free-flowing scholarly discussion. It is in the spirit of those fascinating early discussions among vestibular researchers[1] that we have attempted to capture the spontaneous dialogue of the esteemed participants at our 2010 meeting. Our goal was to strike a balance between a literal transcription (which can be very difficult to read) and a volume of conference proceedings papers (which would not faithfully represent the actual lectures and discussions).

While reading this document, the reader should keep in mind two writing conventions that have been employed to aid understanding concerning missing sections of the transcript and insertions made by the authors:

a. The majority of the speakers did not utilize the individual microphones that were available during the rapidly-shifting question-and-answer sessions; therefore, some of the comments were not intelligible. Wherever this occurs in the transcript, it is noted with the word “unintelligible” inserted at the appropriate place. Brief, fragmentary unintelligible comments or trivial side-

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[1] Highlights from which appear in Lawson, B. D. 2012. How I learned to stop worrying about space and start loving the vestibular organs. Journal of Vestibular Research Online Repository, www.jvr-web.org/Links.html.

comments were usually excluded from this report; however, any important discussions were included, even if they were partially unintelligible.

b. The goal of editing was to preserve the integrity of the content of the original lecture while removing the most distracting word repetitions, half-finished thoughts, speech fillers (such as "um"), malapropisms, or grammatical errors that are common in spoken but not written expression. Therefore, square brackets -- "[ ]" -- are included in this report to denote our insertion of any significant words that were not spoken by the lecturers but were inserted to help the reader's understanding. Examples of this include the insertion of the last names of people the lecturer mentioned by first name only, insertions of the name of any person speaking during the question-and-answer session, or insertions of information that was implied during the speech (by tone of voice and body language) but difficult to convey in text (e.g., jokes that may not be immediately obvious to readers are denoted by following them with "[laughter]" to indicate the audience response at that point in the speech).

For those who may require an introduction to the honoree Fred Guedry, a few biographical comments are offered. Fred Guedry (Nov 1921 to Feb 2011) was a native of New Orleans, LA. After military service in combat during WWII, Dr. Guedry earned his master's and doctorate degrees from Tulane University in 1948 and 1954. He joined the Army Medical Research Laboratory at Fort Knox, KY in 1954 and served as Director of the Psychology Department starting in 1958. He moved to Pensacola, FL in 1961 to work at the School of Aviation Medicine, later renamed the Naval Aerospace Medical Research Laboratory (NAMRL). At NAMRL, he served as Chief of the Perception and Behavioral Sciences Department, Head of the Sensory Sciences Department, and finally, the Chief Scientist of the laboratory.

Dr. Guedry retired from NAMRL in 1990, but continued his research under the shared auspices of NAMRL and the University of West Florida, continuing to consult and carry out research from his home until the time of his death in 2011. Dr. Guedry was a pioneer in the field of vestibular science, and authored hundreds of research articles, including studies now considered classics in the fields of spatial orientation, visual-vestibular integration, gaze control, sensorimotor coordination, and motion sickness. His work is the foundation for much of today's vestibular research.

Figure. Attendees of the Fred Fest. Not pictured: Correia, Money, Mortimer, and K. Blackwell.

Welcome to the Fred Fest, in Honor of Fred Guedry, a National Treasure – Angus Rupert

[Slide 1, page 12] When you [i.e., the meeting participants, starting with Ian Curthoys] sent emails back with "Fred Fest" [in the subject header], I said, "That sounds nice, we'll entitle it Fred Fest," but I have subtitled it "A National Treasure" and I'll thank Jay Goldberg for that. When Jay was giving a retirement presentation in Iceland, just a couple of months ago, he mentioned three people that had a very strong influence on his career when he first started: one of course being Larry Young, another being Geoffrey Melvill Jones, and the third Fred [Guedry]. When he came to Fred he stopped, and what he said was "I consider Fred a national treasure." So that gave us the subtitle. Thank you very much. I have a few thank yous:

- Obviously to Ian [Curthoys] and Jay [Goldberg] [slide 2, page 12][2]. This came together rather quickly because it was only in October that we found out that we actually had some funds that we could apply to make this happen.
- We are being hosted by the Institute for Human and Machine Cognition [IHMC]. At the back is Anil Raj, I think most of you know Anil or have met him over the years. Anil works at the Institute for Human and Machine Cognition. He previously worked with Fred at the Naval Aerospace Medical Research Lab. The head of it [IHMC] is Ken Ford and he'll come by around ten o'clock after Larry [Young] has given a presentation [the first one] and [Ken will] give us a little bit of background on what the institute is all about.
- Ben [Lawson] and I thank you all for coming because the real stars are all of you folks who have come here for Fred.

[Slide 3, page 13] The bus pick up we really don't need; turns out everyone has enough vehicles from all the folks staying at the two hotels, so we will cancel the bus side of things. Saturday night I will, however, arrange to have a bus that will come to the two Marriotts; part of the reason for that is you can feel free to drink at the bar at the museum and get home without being apprehended.

[Lawson] Can I drive the bus after [drinking]?

[Rupert, laughing with reply] You're the DD [designated driver].

So we will try and leave from the hotels around 4:45 PM; that will get us to the museum about a quarter after five. The bagpiper is scheduled to take Fred to our place in the museum at 5:30 PM. So be there by 5:30 PM at the very latest for those of you that are driving. I'll have to charge you for it because we can't exactly pay for that with government funds.

Well who is Fred Guedry [slide 4, page 13]? Sometimes, when we look at ourselves in the mirror we still see ourselves as we looked 20 years ago. I imagine this is how Fred sees himself in the mirror each morning [referring to slide 4]. This is the picture of Fred Guedry [referring to slide 4] about 30 or 40 or maybe 50 years ago. We won't ask for the date Fred, but I'm sure you can give us an approximate time.

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[2] Also, Curthoys traveled farthest to be at the meeting; Goldberg overcame significant physical challenges to attend.

I want to go back just a little bit [further] [slide 5, page 14]. This is Fred Guedry pitching baseball. Now, Fred has had some shoulder surgery and there's a reason for that. It's because Fred was a very talented pitcher. Many of you who worked with him many years ago know he was also an outstanding tennis player. This is Fred at age 15; he has graduated from high school. Think about that, 15, graduated from high school, and ready to start Tulane [University] pitching in the under-sixteen category. Fred told me that this particular game was a no run, no hit game. So, I think you [addressing Fred] probably got a few accolades then, I'll give you another couple now.

Fred went on and was a great pitcher at Tulane University. I asked him "Well what was your best game?" He said, "When we beat LSU [Louisiana State University] seven to six," and I said, "Well… that doesn't sound like such a great game. It doesn't sound like you trounced them or anything." He said, "I was the relief pitcher," and I said, "That doesn't sound like a great accomplishment, so why was it such as great game for you?" He said, "Well… I came in as the relief pitcher in the first inning. The bases were loaded and the score was five to nothing" [laughter]. Now that's not just a great accomplishment by itself, but LSU was a powerhouse team at that time, and just a few weeks before that LSU had beaten a professional baseball team by the name of the New York Yankees in an exhibition game. So that gives you an idea of Fred's capability as a pitcher and we should be very grateful that Fred never decided to go professional.

This is nine years later [slide 6, page 14]. That means he has finished four years of Tulane University, he's graduated, and he has had several years aboard the ship called the LST-273. That ship was on every invasion crossing the Pacific, one after the other. Fred's there in the middle; and you can see the [same hardcopy] picture we've hung up over on the side [of the room]. Fred was the Commanding Officer when he departed this boat after World War II.

I'll tell the story here as I will tell it again tomorrow, because I know some of you are going to be leaving tomorrow and won't make it to the museum [banquet]. Fred took this boat from Guadalcanal, on one engine, back to the United States to Long Beach, California. When he got there, there was no one to sign his discharge papers… so Fred signed them. So what I present to you here today is still technically (probably on active duty) Lieutenant Fred Guedry, who was the Captain of a ship as a Lieutenant Junior Grade. That is just unbelievable. He was probably the youngest, or certainly one of the youngest, in all of World War II. There he is, front and center [slide 7, page 15]. Now, I was debating on whether or not I was going to get Fred upset, because he's never been happy about this picture, since the Executive Officer didn't tell him about it ahead of time, and he didn't get a chance to shave. He was worried that people would see that he wasn't properly shaven in this picture. If there is one thing about Fred, he is always clean shaven; I've never seen him with a beard. But about three weeks ago, I invited the Navy historian down and Dr. Jane Herman did an oral history on Fred. So I heard things about Fred that I had never heard before, and a professional historian can ask questions the rest of us really can't ask. He got into the details of many of the invasions including one of the later ones where there were a lot of Kamikaze pilots coming at them. Fred had mentioned that he had not shaved for fourteen days and I said, "Well, why?" He said, "Because every two hours they would have a call to General Quarters and we would have to get up and man the battle stations." I'll tell some other stories tomorrow night, but Fred truly had a remarkable history by the time he had departed the Navy, just nine years after he was that graduating kid from high school, pitching a no run, no hit game.

This is Fred Guedry, the artist [slide 8, page 15]. Fred always likes to doodle and this is a particularly good doodling, and Anil [Raj] has asked, “You know, I have never found a good non copy-righted picture for the vestibular system that displays all the things I’m looking for.” So when I gave him this yesterday he said, “There it is.” So Fred, thank you for your artistry.

We will come back to ‘re-present’ Fred Guedry here and tomorrow night I’ll get a chance to go over all the things that he did with the Army. Most people don’t know that he had a career with the Army before he joined the Navy, and that he ran a facility bigger than NAMRL. His one little division of psychology was even bigger than NAMRL before he left there to come down here [to Pensacola] to [work for] the Navy [slide 9, page 16].

Our first session this morning is going to deal with some of the psychophysics that Fred has carried out for over forty, fifty years and it was titled “Modeling Vestibular Perception.” We have four people lined up [slide 10, page 16]. Larry [Young] is going to give us the historical background. Chuck [Oman] is going to bring us some updates in the models that Lionel [Zupan] had worked on and that Dan Merfeld had worked on. Then Jan Holly will give us a presentation of some of the work she has been doing as of late. Then I’ve asked Brad [McGrath] to give us some samples of aviation mishaps that use these models which Fred had worked on with us, even as recently as a year or two ago. Then the production I’m hoping for, while we have this illustrious group, is some suggestions for a path forward. What research should be carried out that will help expand the model? I will take the comments from this group and then I will beg for dollars and cents from the Army, Navy, and Air Force and see if we can keep that work moving along.

Before I turn it over to Larry [Young]… Fred has always been interested in practical applications as well, and where these models go [slide 11, page 17]. Brad [McGrath] is going to talk about the aerospace mishaps side of it, but simulator training is another side and there are new simulators coming out. I was going to show a video clip of Desdemona [an advanced acceleration device in the Netherlands], but I will simply say there is a Desdemona equivalent being built in the United States very soon[3], and this device has a track about 37 feet long, with a capsule that moves in unlimited roll, pitch, and yaw, moves up and down in heave, and moves back and forth along the track while it rotates. So it has multiple degrees of freedom. Well, along with that comes simulator sickness. Bob Kennedy is supposed to show up a bit later in the day,[4] but we have a lot of experts on motion sickness here. So we will look for some ideas coming back from this group as well. Patient diagnostics is another application for the modeling. With that I will turn it over to Larry.

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[3] Rupert refers to a device being built by the Environmental Tectonics Corporation, for the Naval Aeromedical Research Unit Dayton, at Wright Patterson Air Force Base. Rupert, Lawson, Tom Allen, and others at NAMRL were heavily involved in the technical requirements and selection process which led to this device.

[4] Dr. Kennedy was unable to attend due to a sudden business demand.

WELCOME !!

FRED Fest

“A National Treasure”

Slide 1

Thank Yous

- Name & Concept:

  Ian Curthoys & Jay Goldberg
- Hosts

  Ken Ford & Anil Raj – IHMC

  Ben Lawson & Angus Rupert – United States Army Aeromedical Research Lab

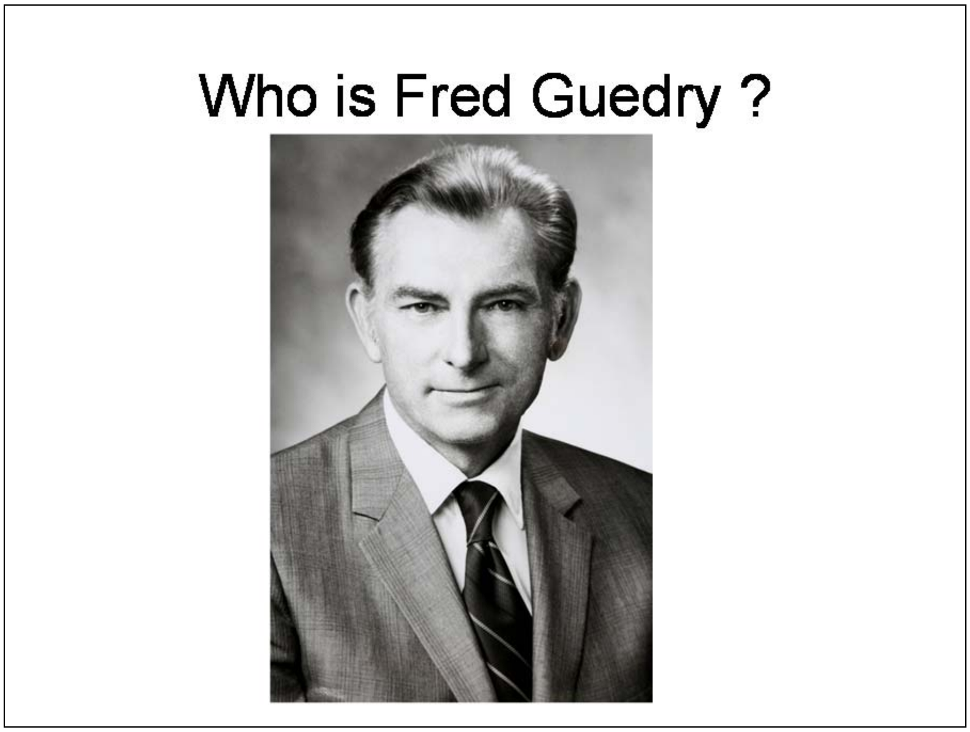
Slide 2

Transportation

- Bus pickup Sat AM 08:10 Courtyard
  08:20 Residence
  Return 15:40 (3:40 PM)
- Saturday Museum 30 passenger bus
  Bus pickup Marriott(s) 16:45 (4:45 PM)
  Return from Museum 19:45 (7:45 PM)

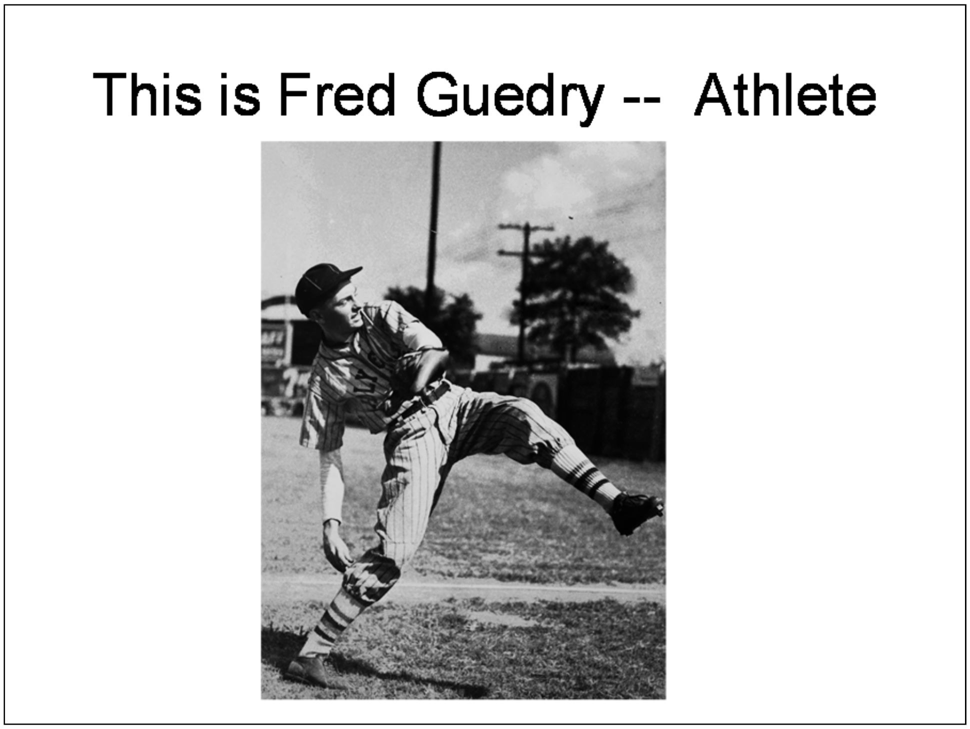
FredFest – 5:30 PMDinner & Museum $30

Slide 3



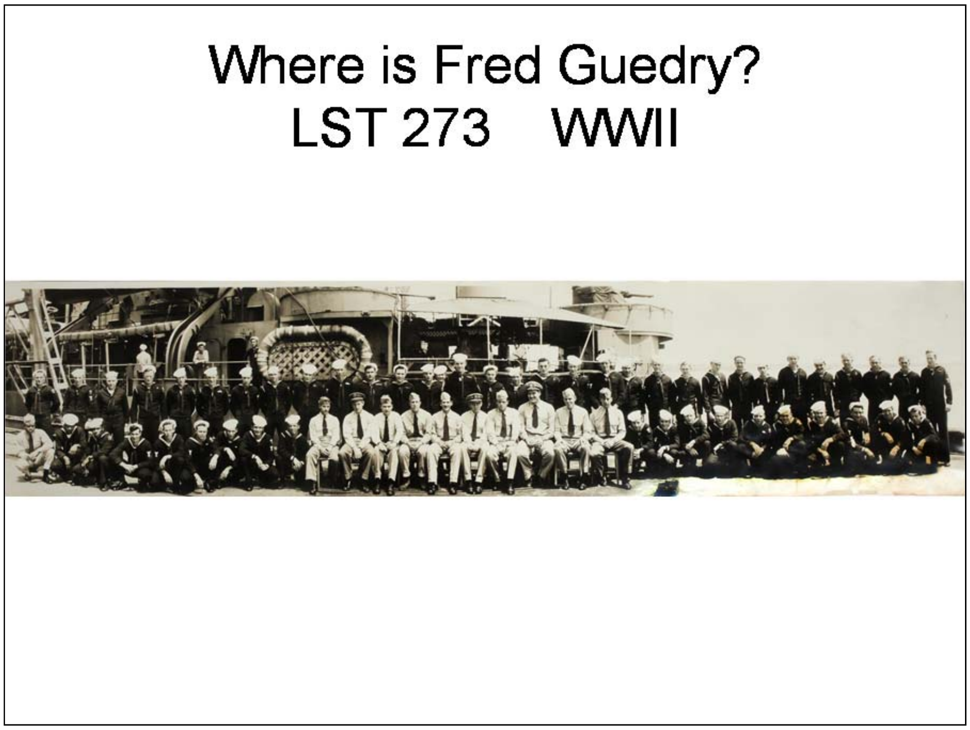
Who is Fred Guedry ?

Slide 4



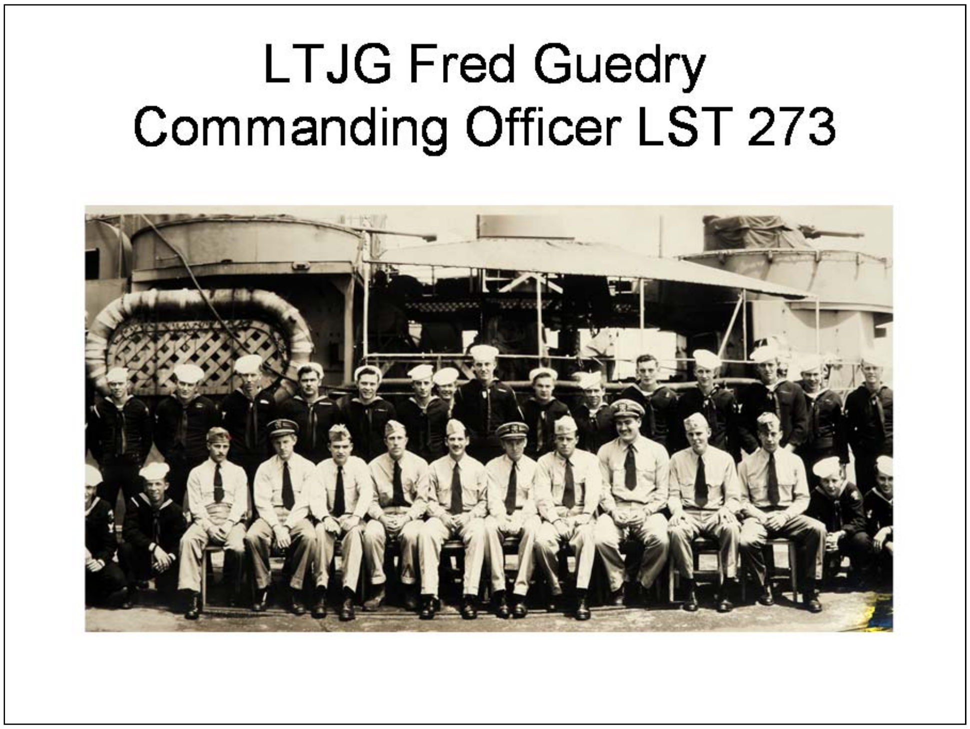
This is Fred Guedry -- Athlete

Slide 5



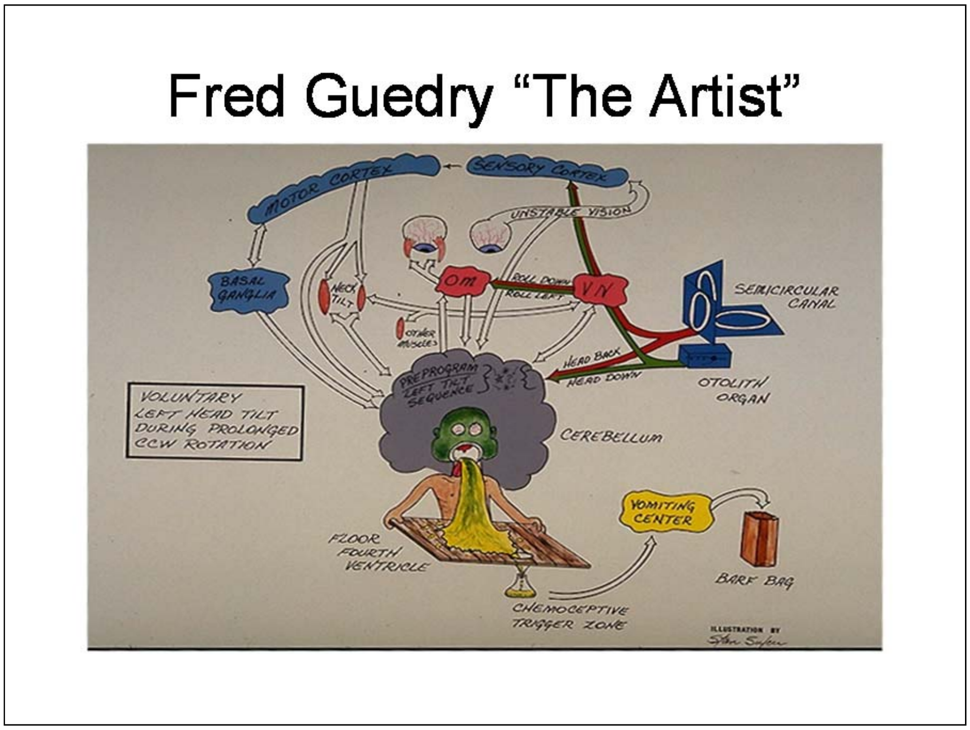
Where is Fred Guedry?
LST 273 WWII

Slide 6



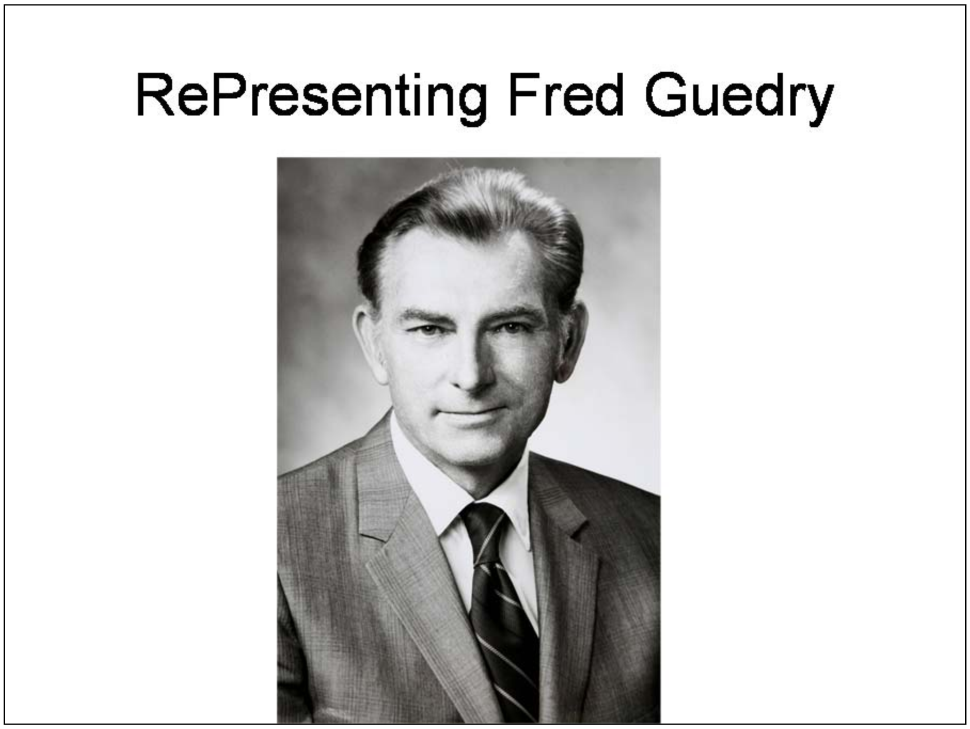
LTJG Fred Guedry
Commanding Officer LST 273

Slide 7



Fred Guedry "The Artist"

Slide 8



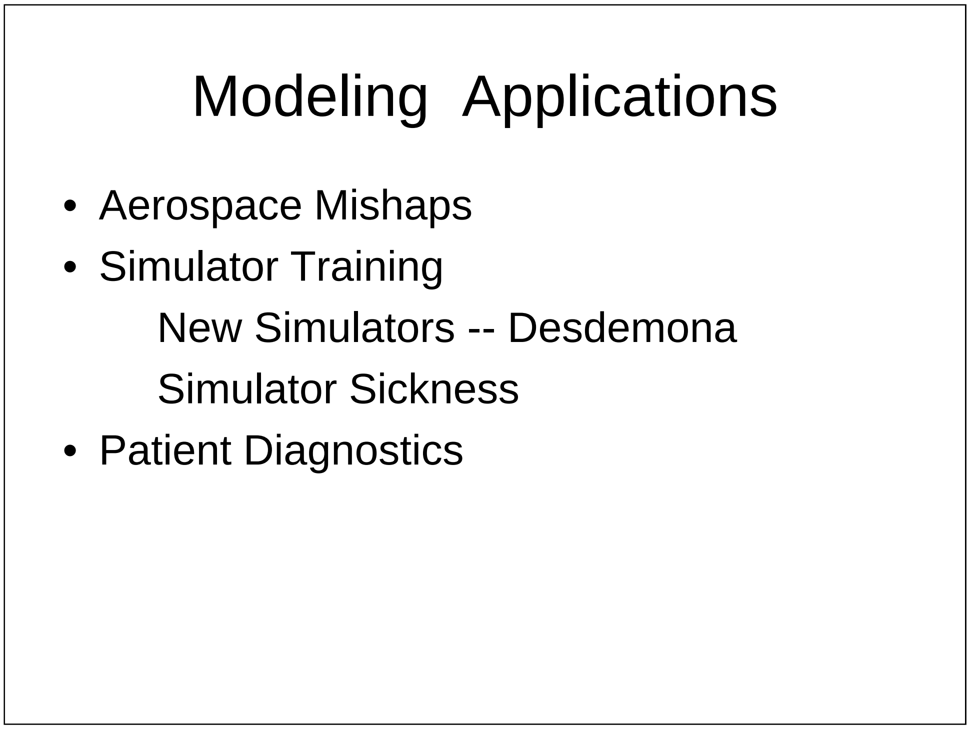
RePresenting Fred Guedry

Slide 9

Modeling Vestibular Perception

- Larry Young – 50 plus years of modeling
- Chuck Oman
- Jan Holly
- Brad McGrath – Aviation Mishaps
- PANEL: The path forward

Slide 10



Modeling Applications

- Aerospace Mishaps
- Simulator Training
    - New Simulators -- Desdemona
    - Simulator Sickness
- Patient Diagnostics

Slide 11

<u>Question and answer session</u>

[No questions recorded.]

Mathematical Models of the Vestibular System – Laurence Young

When I discussed with Angus [Rupert] the possibility of coming here and he mentioned the topic, I said, “Tell me when and where and I’ll be there.” I think many of the rest of us feel the same way. It’s a great privilege to be able to honor our friend Fred Guedry, who did so much for so many years in our field. We agreed that I would talk about the history of modeling. So this is the beginning, but there was a “Before the beginning,” before the Big Bang. For me, the “Before the beginning” was a report that Fred authored with Ashton Graybiel, when Fred was still [with] the Army [Guedry and Graybiel, 1961]. The title [slide 1, page 26], doesn’t really represent the strength of it. It looked at vestibular system, motion sickness, disorientation training -- all the things that many of us have been involved with for [our] careers. It was a spectacular report. [Slide 2, page 26] When you look at some of the people who were on it -- and this is really the reason I wanted to show it to you -- you realize that before the beginning there were a lot of extraordinarily capable people who were contributing to this field. We look down the list and see:

- Klaus Cappel. Klaus, I give credit for inventing the six post flight simulator.
- Bob Galambos.
- Dr. Graybiel, of course.
- Rufus Hessberg, who was responsible for really putting a life sciences component into the man-in-space program that was just beginning in the United States.
- Henning von Gierke, by this time at Wright-Patterson.
- Earl Wood, who had been doing those incredible centrifuge tests at the Mayo Clinic. All of them contributed to that.

I want to talk a little bit about mathematical models [slides 3-4, page 27]. [The] question is: “Can anything as complicated as the vestibular system be reasonably reduced to equations?” I think a number of us here would say, “Can you really deal with anything that complicated without reducing it to equations, without having quantitative approaches?”

This was a sense that I had as a young man and I was fortunate enough to be introduced to Dr. Graybiel who said, “Oh, you’re from MIT [Massachusetts Institute of Technology], you can solve all of our problems,” and I said, “Like what?” He said, “Well for instance, why don’t you start off with determining what the fluid flow is in the semicircular canal during what (we now call) Coriolis cross-coupling [Ccc].” I said, “Alright.” Well that took a couple of decades [laughter]. [Slides 5-6, page 28] We referred to some of the things that had been done earlier and launched ourselves into the issue of trying to apply the techniques of mathematical modeling to understanding spatial disorientation. I’ll give you an overview of that this morning.

I want to jump ahead from 1962 to 1978, by which time we at MIT had begun our serious work in the space program. A lot of it grew out of a fortunate conversation that Ken Money and I had in Aspen, in which we decided I would be the PI [principal investigator] and he would be the astronaut, and we would go and understand how the vestibular apparatus was working in space. We got our friends to work with us on this program [slide 7, page 29]. This was a cover page of the proposal, and [shows] just some of the names to remind you who was there. Not only Ken and myself, [also] Dick Malcolm, Geoffrey Melvill Jones, Chuck Oman, Doug Watt, Walter Johnson ([who] was then at the University of Toronto), Dr. Graybiel (down here), Byron

Lichtenberg (who became the first American payload specialist), and then very importantly, the contributions of Fred Guedry, who was interested in any psychophysical experiments in unusual environments that would drive us to a better understanding of the vestibular system. So thank you, Fred.

We began as any systems engineers would, by trying to parse the problem and determine what we needed to understand [slide 8, page 29]. So this was kind of a map which steered us for many years, (a lot of you have drawn similar ones). The map is as follows [identifying model components]: You start with angular acceleration and a specific force, gravity minus acceleration. You can measure the control commands (if you're steering an airplane or spacecraft), perceived orientation, nystagmus, [and] postural reflexes. In order to get there, you have to fill in these boxes [concerning] the orientation [model] of the labyrinth. It's interesting how the orientation of the labyrinth has changed over the last 50 years. Evolution is a lot faster than we thought, [laughter].

[As for] models of the semicircular canal -- you know what we had for models in 1960? The torsion pendulum model -- that was it [Van Egmond, Groen, and Jonkees, 1949] -- no adaptation. There was no understanding that the output that we see measured by nystagmus would be any different than one would theoretically get by deflection of the semicircular canal. This was pre-Fernandez and Goldberg [1971], at least pre-this aspect of their wonderful work. We did models of the otolith organs and there were almost none. It was De Vries [1950, 1956] who had done some measurements that can be interpreted as representing the effective stiffness in the otolith organs but otherwise, those were absent. Very little said about how signals from the canals and otoliths might be integrated. I had been working along with some others on manual control compensation, and Dwayne McRuer had developed some models out here [McRuer and Krendel, 1962]. A little bit on postural reflexes; that was basically the road map of things that would have to be filled in and that's what I'm going to tell you about (at least a piece of) now.

Following Dr. Graybiel's lead, looking at the fluid mechanics, our early students Bob Steer, [Jacob] Meiry and others worked on the following issue: What's going on with caloric stimulation [slide 9, slide 30]? Can we really understand what this phenomenon is, for which Robert Bárány won his Nobel prize? In fact, this required a fair amount of fancy footwork to develop the instrumentation to measure the thermal coefficient of expansion of human endolymph, to measure the viscosity of endolymph, and finally to develop a model which showed how to compare the temperature differences at the tympanic membrane, [i.e., the] temperature difference from the body temperature -- how that temperature drive could be compared with the stimulus that you would get from angular acceleration to produce a certain torque on the ring of endolymph and result in a cupular displacement and nystagmus. And it actually worked out really well and I think gave a rather rational explanation for what was really the dominant aspect of caloric stimulation. We begin looking at those boxes and said, "Well, we have a model for the semicircular canals [slide 10, page 30], let's begin with a model for the otoliths." This was largely the thesis of Jacob Meiry [1965] where in our laboratory we built our first linear acceleration sled. Then we began measuring perceptual thresholds and nystagmus measurements in response to linear motion along the horizontal axis. We came up with models for the otolith organs relating specific force to what we believed would be displacement of the otolith. Of course we were unable to measure it at that time, but what we could measure was perceived acceleration and tilt. It required a neural processing term, and most importantly it established our idea of a mechanical threshold which was not that far from what had been suggested by Ernst Mach [1875] (somewhere in the 5 to 10 milli-G region). So we had something for an otolith model.

We began puzzling over the issue of three-dimensional use of linear acceleration information [slide 11, page 31]. In particular, the question of what is the sacula and how does it differ from the utricle in terms of its processing of information. There had been the speculation that the sacculus was really a hearing organ, that it was associated with low frequency infrasound, that it might not play any role in orientation. With Charles Ormsby [Ormsby and Young, 1975], we did a number of measurements on orientation, looked at the work on different G levels, and came up with a model in which basically information that's processed by the sacculus was fundamentally different (in terms of its having a non-lineararity) than information that's coming from the utricle. I'm not going to go into any details on these models; these are just sort of placeholders you might take note of. But, what we could do with this was predict the direction of what we called the estimate of down --which way the person would point to was down (what we would now call the subjective visual vertical), [i.e.,] what you would get by orienting a lighted line until it appeared to be in vertical.

Now, compare that with some of the existing literature. For example, the literature that came out of Seeweisen [Germany -- the speaker cites Ormsby and Young, 1975, and is referring to the work of Schöne]; [the work] that came out of here in Pensacola [the speaker cites Ormsby and Young, 1975, and is referring to the work of Miller and Graybiel] in which you looked at the relationship between perceived tilt angle and actual tilt angle, the Aubert effect and the Müller effect, overestimating tilt at small angles of tilt, and underestimating at large angles of tilt, and doing it not only in 1G but also in a centrifuge. Here's the 2G data looking at this on a centrifuge [slide 12, page 31]. That inevitably involves the need to consider what signals are coming in the z-axis and are detected by the sacculus. The model was reasonably effective in matching the data having to do with static orientation and the role of the sacculus. These models by the way were presented at the Pensacola meetings, the meetings on the vestibular system in space exploration, and are available in the NASA [National Aeronatuics and Space Administration] special publications from those meetings[5]. They were generally not published in the open literature and I think that's one of the reasons that many of them have been largely forgotten [slide 13, page 32].

So, we did a little bit on otolith modeling, canal modeling, and then we got to the question of linear and angular acceleration and how they interact. How does the position of the head and its reaction to the specific force stimulus influence the normal canal responses, where you have an input angular acceleration going through the semicircular canals, resulting in nystagmus or [affecting the] magnitude of perception of rotation? This was a field that was very hot in the late '60s, primarily the work of Fred [Guedry], of Alan Benson, and then of Geoffrey Melvill Jones, showing the strong influence of head orientation on semicircular canal responses, and wonderful sets of experiments, rich data sets, and a number of speculations about how gravity was affecting canal responses. There were (Alan [Benson], you may remember the slosh theory), ideas about how we modeled the effect of gravity on the semicircular canals by an analog to the roller-pump action that you would get by moving the pitch part of the canal around, and so forth. The explanations are not what I'm after here -- I just want to emphasize that we became interested in

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[5] Proceedings of the Symposium on the Role of the Vestibular Organs in Space Exploration, Journal of Vestibular Research Online Repository. www.jvr-web.org/Links.html.

how specific force was affecting the responses to angular acceleration. Probably more important than that was that we began emphasizing the direct effect of specific force, of gravity and acceleration on nystagmus, that you could generate nystagmus by pure linear motion. This is only 1969 -- it's not the Middle Ages, but up until that point, vestibular nystagmus was considered to be almost exclusively, or exclusively an angular acceleration issue, and the idea that you could stimulate it by linear acceleration was novel. We'd worked on it for some time, we'd coined the term L nystagmus (L for linear). That again has been largely forgotten. People now discuss widely the importance of LVOR (linear vestibular-ocular reflex), but the beginning of it was our attempt to take the material that came out of Fred's lab with his work with Alan Benson and Geoffrey Melvill Jones, as well as the centrifuge experiments that had been conducted by Landolt, and make sense of them.

We pulled it all together as engineers will -- in a model that looks very complicated and actually was. Chuck Oman [1968] ([who] had come to work with us by that time as a graduate student) produced, as a master's thesis, the first papers on adaptation in the vestibular system, trying to rationalize some of the inconsistencies in the torsion pendulum model. We came up with a biocybernetic model in which the inputs are the usual, angular acceleration and specific force and the outputs are nystagmus and subjective velocity, and it included adaptation operators both for subjective [orientation] and for nystagmus. It included thresholds in the angular and the linear pathways. It recognized the difference in the dynamics between the horizontal canals and the vertical canals, and it represented what we didn't know at that time about the function of the sacculus [slide 14, page 32]. This I would say was the first attempt in our laboratory to get an overall model relating the vestibular inputs to the prime perception outputs.

We were interested in vestibular processing, not just for perception but for control of posture [Young and Oman, 1969; Oman, 1982; Oman, 1991] [slide 15, page 33]. One of our graduate students, Lewis Nashner (for his thesis) developed a little platform which could move both in translation and pitch [Nashner, 1970]. Subjects would stand on it, be disturbed, and we could try to tease out the relative influences of the semicircular canals on posture, [and] of the otolith organs and proprioceptive feedback through the muscles as well [slide 16, page 33]. We had an inverted pendulum model of the body as a simple single (rather than compound) pendulum. It worked quite nicely, not only to get Lew his Ph.D. thesis, but allowed him to succeed very well with the commercialization of it[6], and I'll show you that at the end.

So by 1970, the field of Control Theory had become dominated by the notion of optimal control, optimal estimation in a Bayesian sense (a maximum likelihood sense) [slide 17, page 34]. It says if you're going to try to combine information from different sources, how do you do it to minimize the expected error? There was a well-developed theory at least for linear stationary systems which was an outgrowth of Kalman filters and Kalman controls, called a Kalman estimator. I became convinced that this was the way we should be approaching the spatial orientation perception issues. We should look at not only the dynamics of the canals and the otoliths, (and this is for vestibular only), but also the expected signals that they would be receiving [unintelligible], what their spectrum was, and the noise -- how noisy they are. Now if you're trying to make an estimate based upon two different measurement sources you will tend to put more weight on a reliable source, and tend to ignore the noisy one, and that's exactly what

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[6] He founded the company Neurocom®.

the Kalman estimator does. We wanted to see to what extent human spatial orientation could be represented as a Kalman filter, in which we have signals coming from both canals and otoliths which would be used to represent not only angular velocity but also orientation [perceptions]. That led to the Kalman filter model in which the characteristics of the major sensory outputs are allowed to be computed in a steady state Kalman filter to give you a model [slides 18-19, pages 34-35]. We then combined it with the visual effects. This is an ongoing topic in which the canal signals and their contribution to your perception of rotation are combined with signals from the visual field. You know all about the vection experiments where the whole visual field is moving one way and after a while you feel you are moving the other way. We dealt [with] the problems in visual field rotation similarly for the linear part of the system, comparing otolith outputs with translation of the visual field and tilt of the visual room. So those all got put into an optimal estimator -- and I'm not really showing you data except for two slides [slide 20, page 35]. We applied that to a problem of step in angular velocity about a vertical axis, the simplest task that you could do, the kind of thing that could be done on a Bárány chair, under different conditions. So we looked at the situation in which this is the stimulus, this is the angular velocity [referring to slide 20] -- it jumps up and stays constant. If you are rotating around in a lighted room, the perception of angular velocity is almost as fast as the actual angular velocity, and over time (this is 10, 20, and 30 seconds) it decreases only slightly, that's rotation in the light. If you're rotating in the dark (and this audience doesn't need any reminder of this), of course the perception of angular velocity decays almost as a first order exponential with a time constant of about 16 seconds, and then disappears and will reappear as an after sensation somewhere in the 1minute time frame if you're lucky, so this would be the perception of rotation.

Interior to this model is our model of the semicircular canal, because fundamental to the idea of the Kalman estimator is that the brain has a model of its own sense organs. That is the notion of the internal model and it goes back to [earlier theories concerning] corollary discharge, efferent copy, and so on. The time constant of the canal afferent is much shorter than the time constant of your perception of rotation in the dark. A lot of people have made a big deal of this. The velocity storage concept was based on trying to give an explanation of that difference, and we would hold that it falls out naturally from the idea of an internal model in a Kalman filter. So here's the cupular [response] decaying rapidly [slide 20, page 35]; here's the perception of rotation in the dark decaying. Here's the perception of rotation in the light, which stays high, [and] here is circular vection. If you're stationary and the stage around you goes through a step change in angular velocity, you feel that you are turning faster and faster, until you feel that all of the rotation is self-rotation, saturated vection. Anyway, that's the only one I'll go into any detail on, talking about the kinds of successes that this early attempt at a Kalman filter model for spatial orientation had, and this was finally published in 1988 in the open literature, but in fact was written and presented [Borah, Young, and Curry, 1988, 1979] here in Pensacola, back in the '70s.

The one other piece of data I'll talk about here is a problem that's well known to everybody in naval aviation, and that's the sensation of pitch up on catapult launch from a carrier. If you are suddenly accelerated forward say at two-tenths of a G[7], you know that the perception will be at first that you are accelerated forward, and that dies down and is replaced by the sensation of

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[7] Dr. Young appears to be referring to experimental data on slide 21 and inferring from that to jet takeoff illusions. The actual G force of a catapult launch is approximately 2G to 6G.

being pitched upward, and of course the reaction to that can be a very wet afternoon as you go diving into the ocean [slide 21, page 36]. So, that same model that I just showed you would correctly predict the perception of its forward acceleration, decaying with time, and being replaced by the perception of pitch, as that would build up.

There are many other applications which I won't take the time to get into [slide 22, page 36]. We then had to turn to this knotty question of: Are there times in which you're not really weighing different sensory inputs and saying, "Well, the canals are noisy, maybe I should pay more attention to the otolith, or maybe I should stop paying attention to vision because this is an untrustworthy horizon." It's not just linear -- there are some times where you actually switch off a sensory organ, for example. We call this the conflict model of nonlinearity. It was building on some work done in our lab with Greg Zacharias [Zacharias, 1977]. Conflict nonlinearity would look at the differences between the perceptions of motion that you might get from your sense organs and the perceptions of motion that would be based upon the assumption that say the visual system was correct, and the brain would say, "No, that difference is so large and it has been large for long enough time as determined by this filter, that I'm going to change my switch, I'm going to reduce K," and what does reducing K mean? It says, "I'm going to pay less attention to the visual field motion. Or I may keep K very high, as you do when you're in an IMAX theater -- I'm completely immersed in this visual field and it will be sufficient for me to base all of my [self-motion] estimates on vision." So this was a nonlinearity which was introduced into the visual-vestibular interaction. I was very heavily influenced by Fred's work here on visual-vestibular interaction, and particularly visual inhibition of vestibular signals, which we used as a Space Lab pre-flight, post-flight test, and what a time -- we all got very sick [slide 23, page 37]. This notion of the Kalman filter was pushed further successfully by a number of people including Mark Shellhamer (who's here with us today) and Dan Merfeld [Merfeld, Young, Oman, and Shellhamer, 1993], another one of our graduate students, bringing it up the next step to Observer application, and they included quantitatively something I had had [included] only qualitatively, an internal model of control strategies. So your perception of motion would be based not only upon what you sensed, but also on the efferent copy idea of what you intended to be your motion [slide 24, page 37]. That developed into a full three-dimensional model. Brad [McGrath], I think, will talk about it and I know Chuck Oman will as well.

I'd like to close by going back to something that Angus [Rupert] mentioned in the introduction about Fred's interest in applications. We also had all this time (because we are engineers) [invested] in the application of these models and not merely doing [modeling] exercises to grant degrees. So I'll mention a few of these, we applied it to the problem of orientation in orbit, the emerging problem of space motion sickness, the question of developing a theory which we call the otolith tilt translation reinterpretation theory [Parker et al., 1985], together with our colleagues at the Johnson Space Center, this is the program that Fred helped us work out, where we became interested in the visual inhibition of vestibular responses [slides 25-26, page 38]. This is just an illustration of the rotating dome experiment that we did in space, but it's all a question of how does the brain go and move from basically a system whereby the otolith tells you where the vertical is and that's what you use them for, to one in which the otolith signals are interpreted as acceleration signals, so it was applied to 0G. It's been applied to artificial gravity, this is an interest that I've had in common with Pensacola people for almost 50 years and I continue to hope that we will test artificial gravity in weightlessness, and the issues there of course are Coriolis and cross-coupling as they affect orientation when you make a head movement in rotation [slide 27, page 39].

We've been interested in motion cues in flight simulators [slide 28, page 39]… what is the ideal way to drive a flight simulator so that the pilot in that flight simulator feels the same perception of motion, or as close to it as possible as he or she would feel in an airplane? We did that through the use of these vestibular models.

I mentioned Lew Nashner's thesis on a moving platform, eventually enough people wanted copies of that, that he developed a company, Neurocom,® which developed this platform I think all of you have seen, or used. It became a very successful international company in posturography [slide 29, page 40].

Spatial disorientation [SD] [slide 30, page 40] (and I believe Brad [McGrath] will talk about this a little later) -- application of the models to try and understand SD issues as they occur and result in accidents.

Well, it's been a whirlwind. I think that we can now go back to my first question, is the vestibular system too complicated to be amenable to description by equations? Probably not; I think that there have been some advances here. I'm very grateful to all my students and colleagues [slide 31, page 41], and especially to Fred [Guedry], who's at the top of the list, and is our guest of honor.

Thank you.

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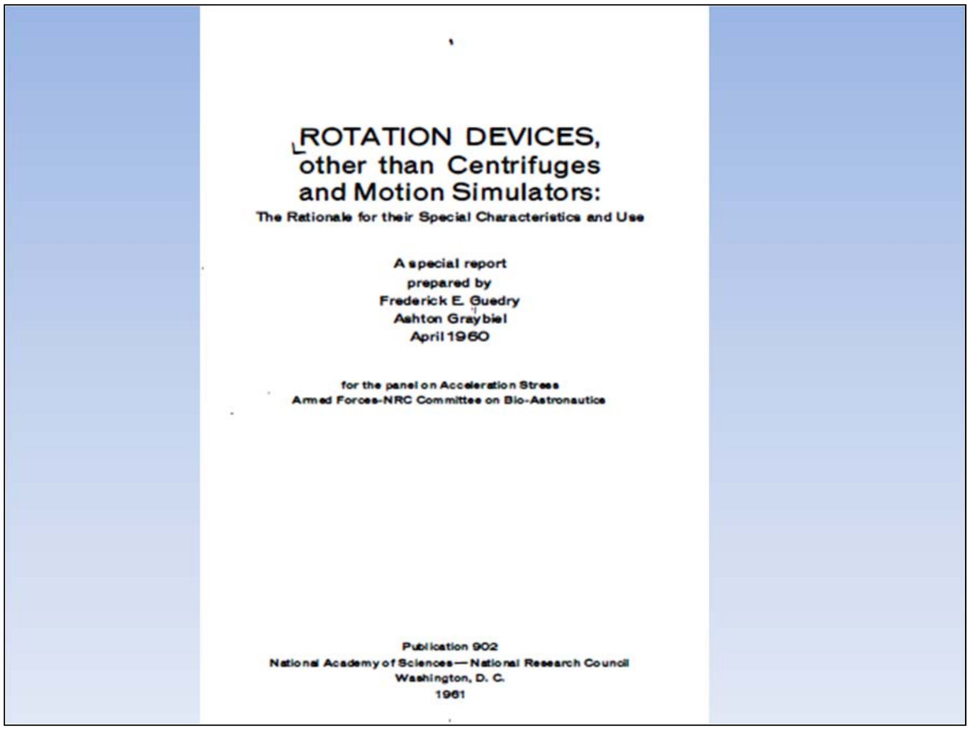


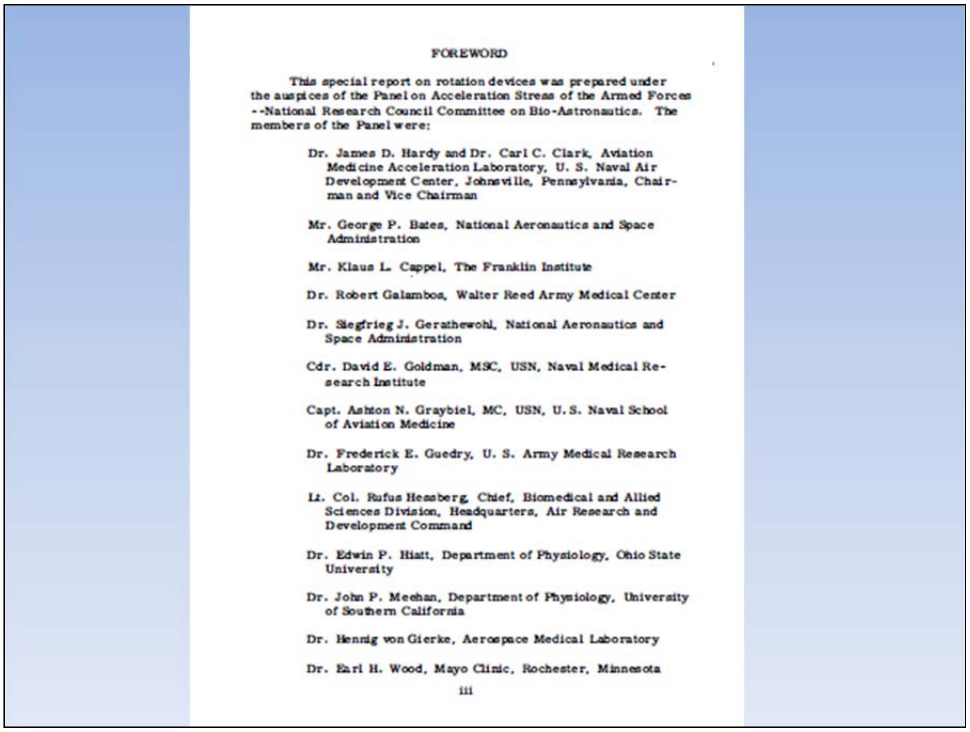
ROTATION DEVICES,
other than Centrifuges
and Motion Simulators:
The Rationale for their Special Characteristics and Use

A special report
prepared by
Frederick E. Guedry
Ashton Graybiel
April 1960

for the panel on Acceleration Stress
Armed Forces-NRC Committee on Bio-Astronautics

Publication 902
National Academy of Sciences—National Research Council
Washington, D. C.
1961

Slide 1



FOREWORD

This special report on rotation devices was prepared under the auspices of the Panel on Acceleration Stress of the Armed Forces --National Research Council Committee on Bio-Astronautics. The members of the Panel were:

Dr. James D. Hardy and Dr. Carl C. Clark, Aviation Medicine Acceleration Laboratory, U. S. Naval Air Development Center, Johnsville, Pennsylvania, Chairman and Vice Chairman

Mr. George P. Bates, National Aeronautics and Space Administration

Mr. Klaus L. Cappel, The Franklin Institute

Dr. Robert Galambos, Walter Reed Army Medical Center

Dr. Siegfrieg J. Gerathewohl, National Aeronautics and Space Administration

Cdr. David E. Goldman, MSC, USN, Naval Medical Research Institute

Capt. Ashton N. Graybiel, MC, USN, U. S. Naval School of Aviation Medicine

Dr. Frederick E. Guedry, U. S. Army Medical Research Laboratory

Lt. Col. Rufus Hessberg, Chief, Biomedical and Allied Sciences Division, Headquarters, Air Research and Development Command

Dr. Edwin P. Hiatt, Department of Physiology, Ohio State University

Dr. John P. Meehan, Department of Physiology, University of Southern California

Dr. Hennig von Gierke, Aerospace Medical Laboratory

Dr. Earl H. Wood, Mayo Clinic, Rochester, Minnesota

iii

Slide 2

Mathematical Models of the Vestibular System

Laurence R. Young

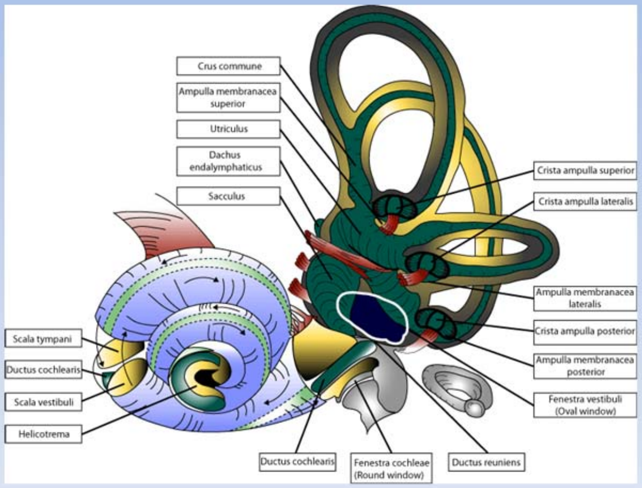
Fred Fest; Pensacola FL

November 19, 2010

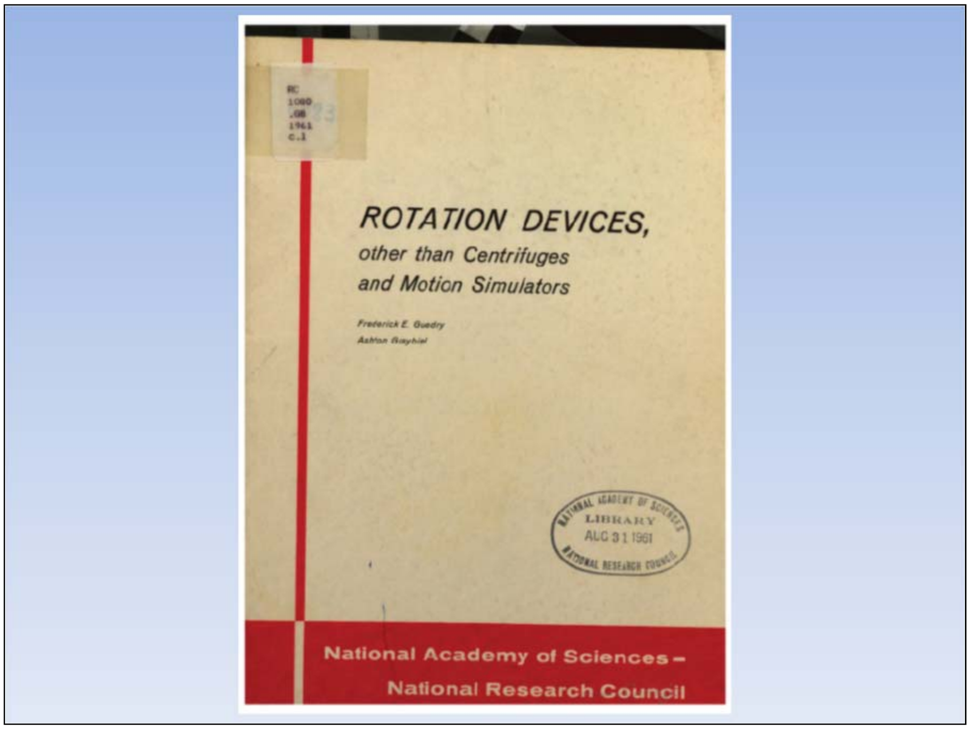
Supported by the NSBRI, Project NCC 98-11, SA 01604

Slide 3

Can this be reduced to equations?



Slide 4



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ROTATION DEVICES,
other than Centrifuges
and Motion Simulators

Frederick E. Guedry
Ashton Graybiel

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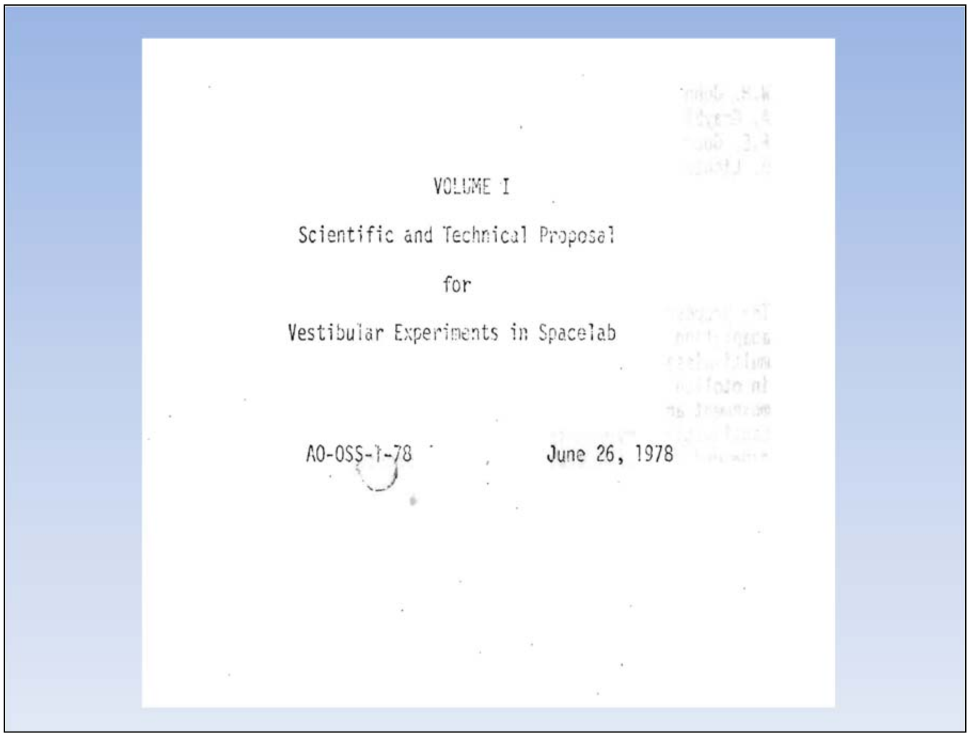
Slide 5



VOLUME I

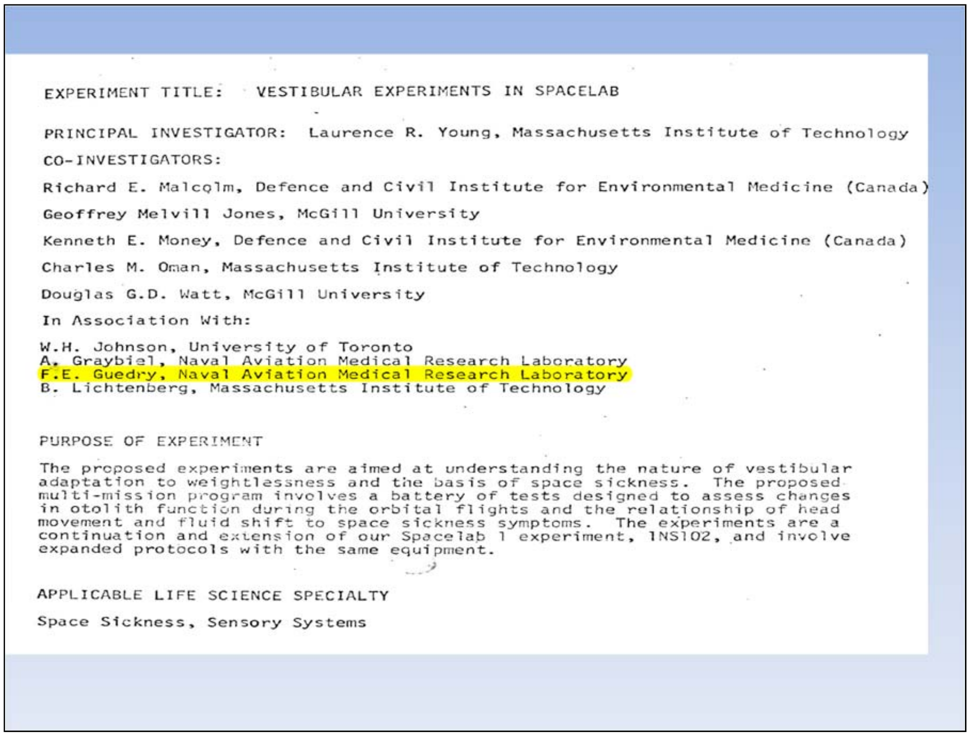
Scientific and Technical Proposal

for

Vestibular Experiments in Spacelab

AO-OSS-1-78 June 26, 1978

Slide 6



EXPERIMENT TITLE: VESTIBULAR EXPERIMENTS IN SPACELAB

PRINCIPAL INVESTIGATOR: Laurence R. Young, Massachusetts Institute of Technology

CO-INVESTIGATORS:

Richard E. Malcolm, Defence and Civil Institute for Environmental Medicine (Canada)

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In Association With:

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F.E. Guedry, Naval Aviation Medical Research Laboratory
B. Lichtenberg, Massachusetts Institute of Technology

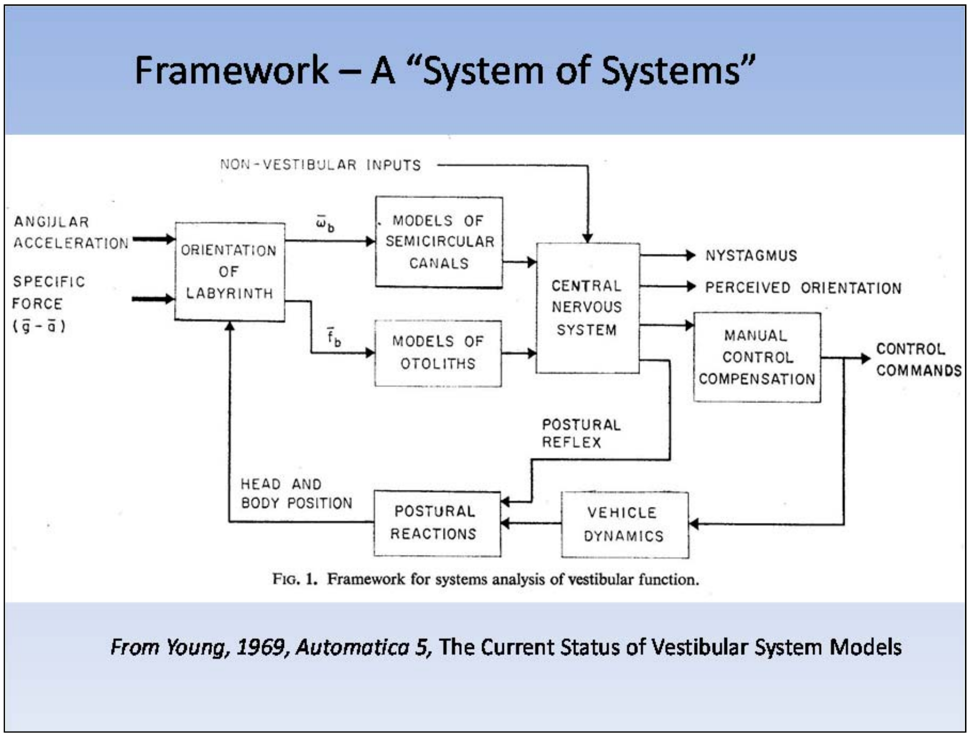
PURPOSE OF EXPERIMENT

The proposed experiments are aimed at understanding the nature of vestibular adaptation to weightlessness and the basis of space sickness. The proposed multi-mission program involves a battery of tests designed to assess changes in otolith function during the orbital flights and the relationship of head movement and fluid shift to space sickness symptoms. The experiments are a continuation and extension of our Spacelab 1 experiment, 1NS102, and involve expanded protocols with the same equipment.

APPLICABLE LIFE SCIENCE SPECIALTY

Space Sickness, Sensory Systems

Slide 7

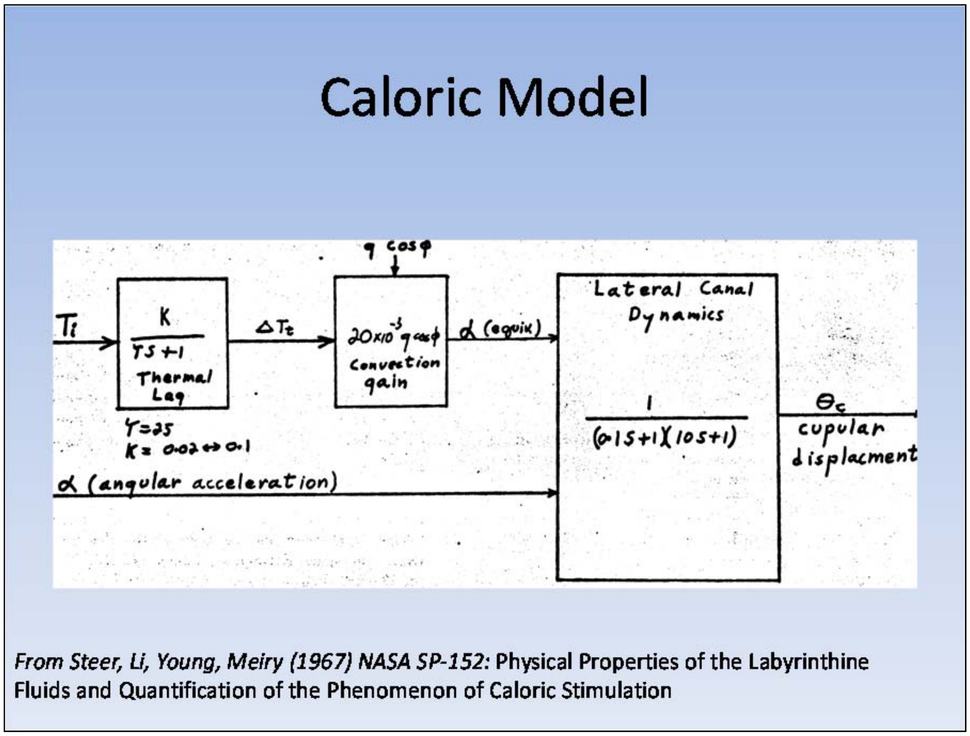


Framework – A "System of Systems"

FIG. 1. Framework for systems analysis of vestibular function.

From Young, 1969, Automatica 5, The Current Status of Vestibular System Models

Slide 8



Caloric Model

From Steer, Li, Young, Meiry (1967) NASA SP-152: Physical Properties of the Labyrinthine Fluids and Quantification of the Phenomenon of Caloric Stimulation

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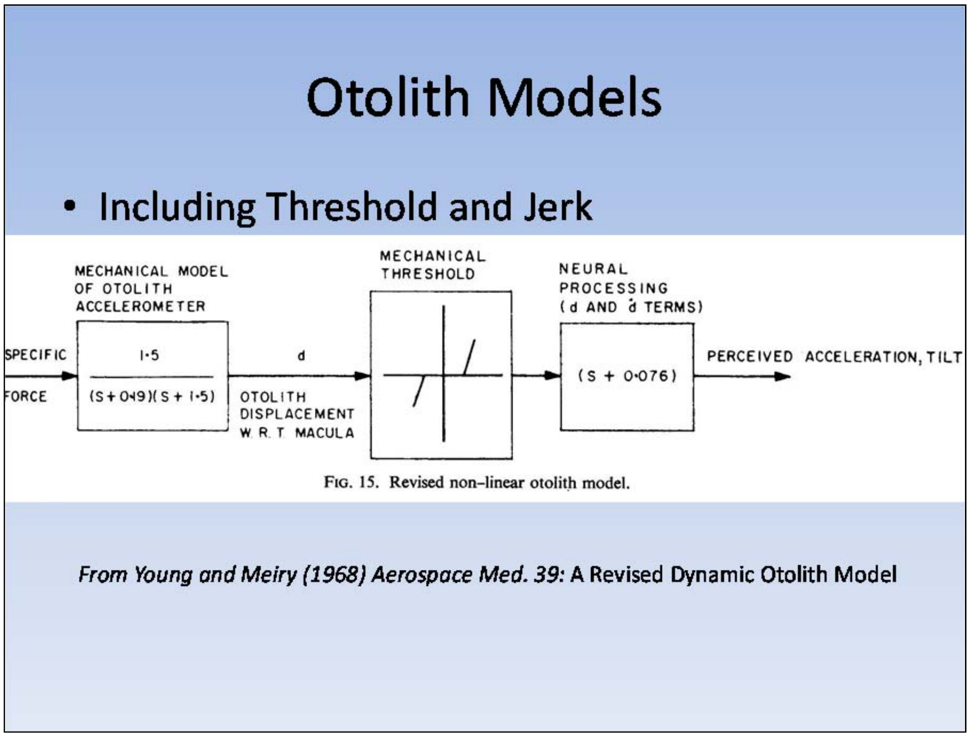


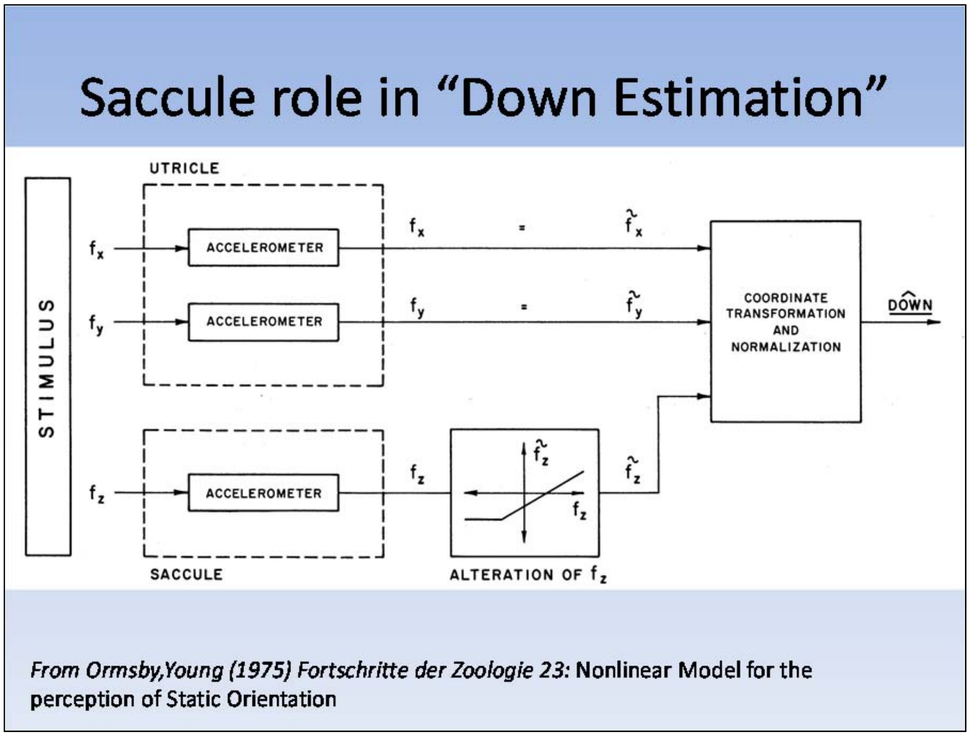
Otolith Models

- Including Threshold and Jerk

FIG. 15. Revised non-linear otolith model.

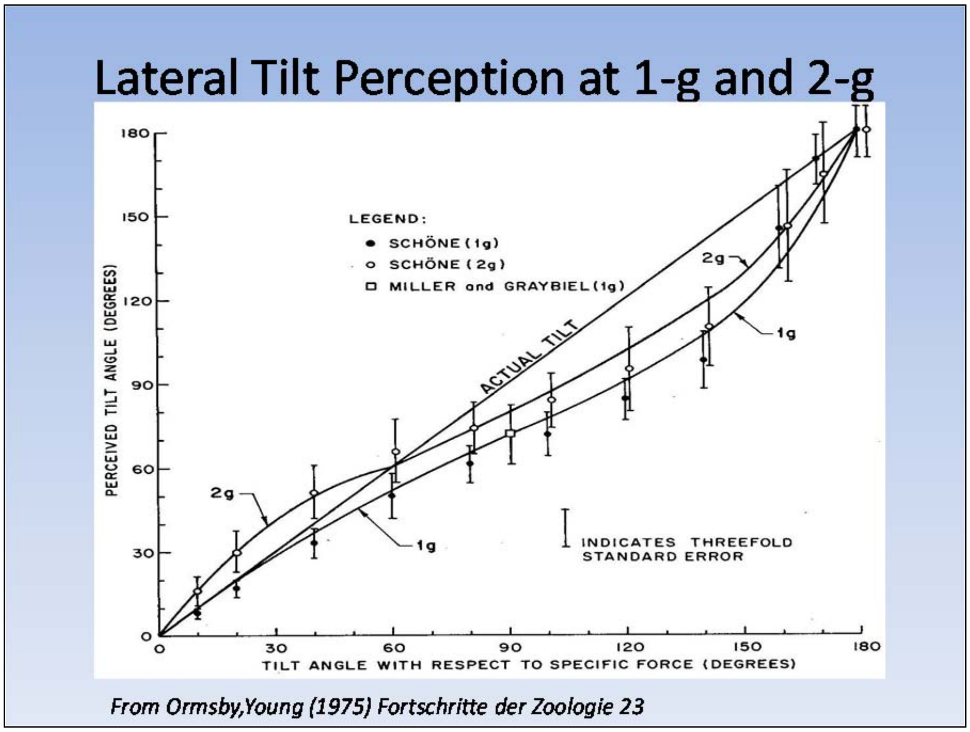
From Young and Meiry (1968) Aerospace Med. 39: A Revised Dynamic Otolith Model

Slide 10



Saccule role in "Down Estimation"

From Ormsby,Young (1975) Fortschritte der Zoologie 23: Nonlinear Model for the perception of Static Orientation



Lateral Tilt Perception at 1-g and 2-g

From Ormsby,Young (1975) Fortschritte der Zoologie 23

Interaction of Linear/Angular Acceleration

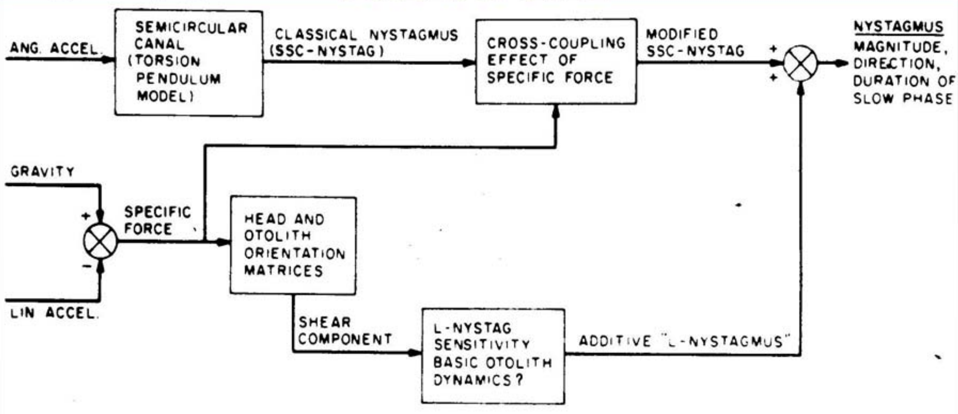
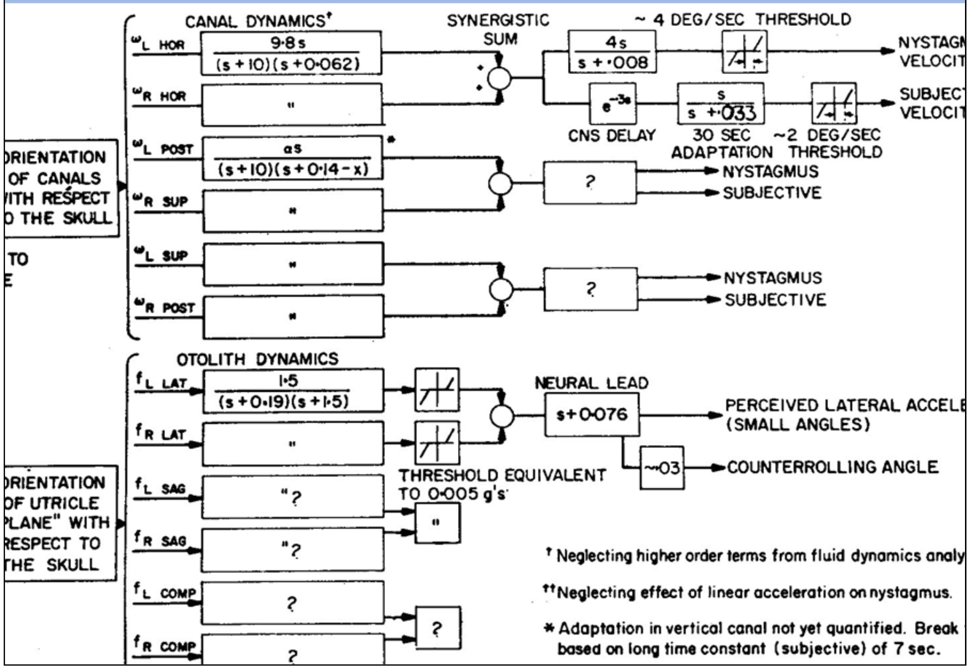


FIG. 17. Preliminary structure—model of influence of linear acceleration on nystagmus.

From Young (1969) Automatica 5

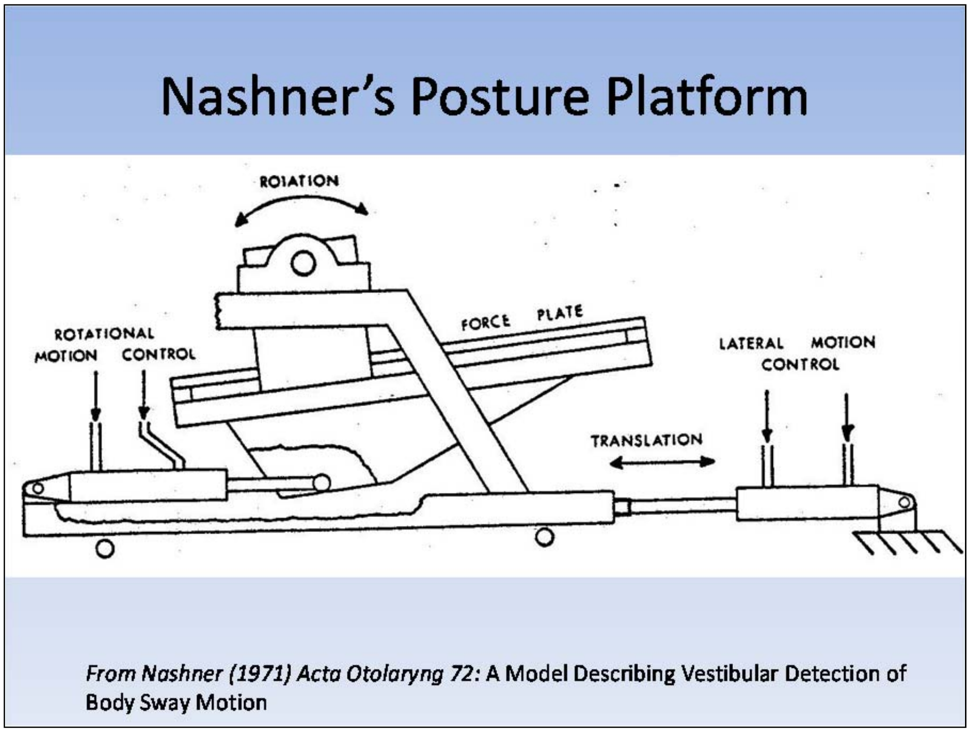
Biocybernetic Vestibular Model -1968



† Neglecting higher order terms from fluid dynamics analy

†† Neglecting effect of linear acceleration on nystagmus.

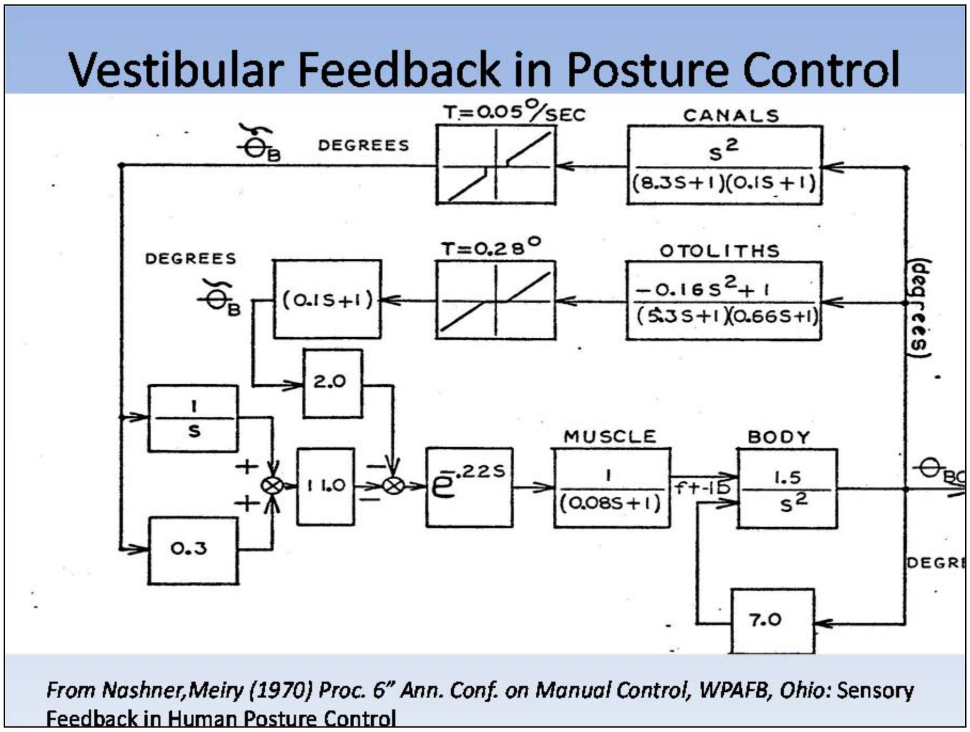
* Adaptation in vertical canal not yet quantified. Break based on long time constant (subjective) of 7 sec.



Nashner's Posture Platform

From Nashner (1971) Acta Otolaryng 72: A Model Describing Vestibular Detection of Body Sway Motion

Slide 15



Vestibular Feedback in Posture Control

From Nashner, Meiry (1970) Proc. 6" Ann. Conf. on Manual Control, WPAFB, Ohio: Sensory Feedback in Human Posture Control

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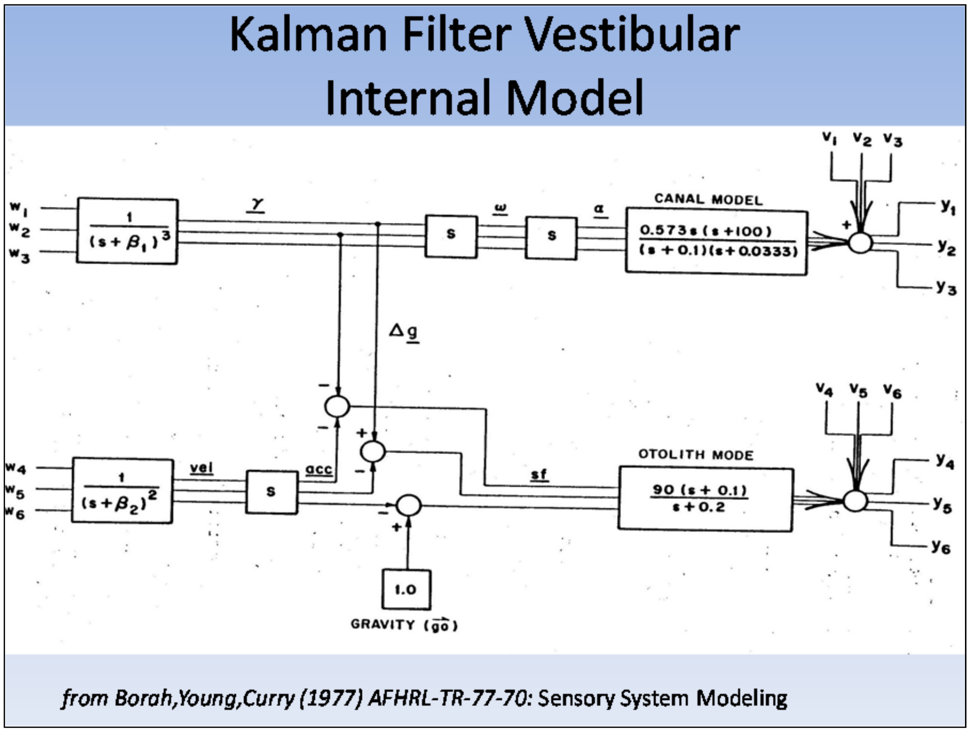
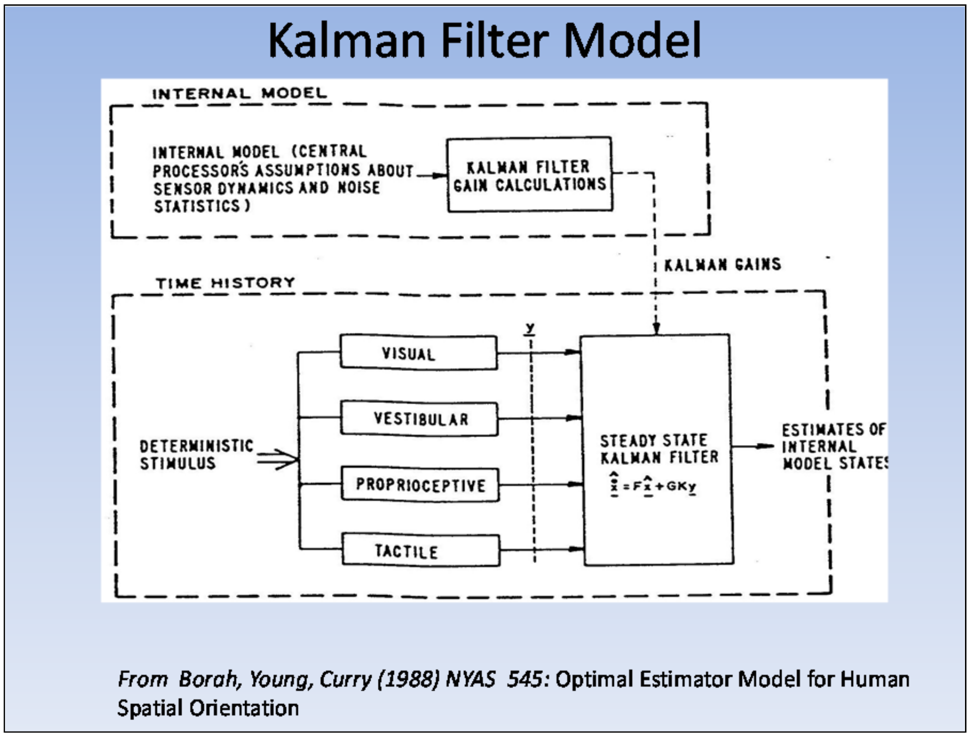


Kalman Filter Vestibular Internal Model

from Borah,Young,Curry (1977) AFHRL-TR-77-70: Sensory System Modeling

Slide 17

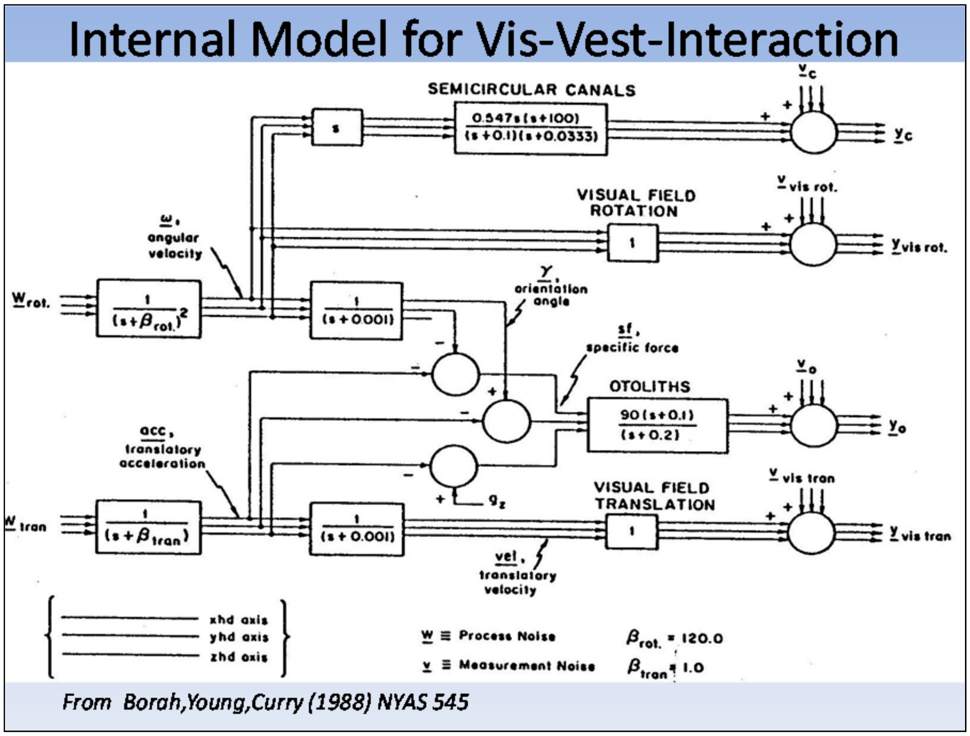


Kalman Filter Model

From Borah, Young, Curry (1988) NYAS 545: Optimal Estimator Model for Human Spatial Orientation

Slide 18

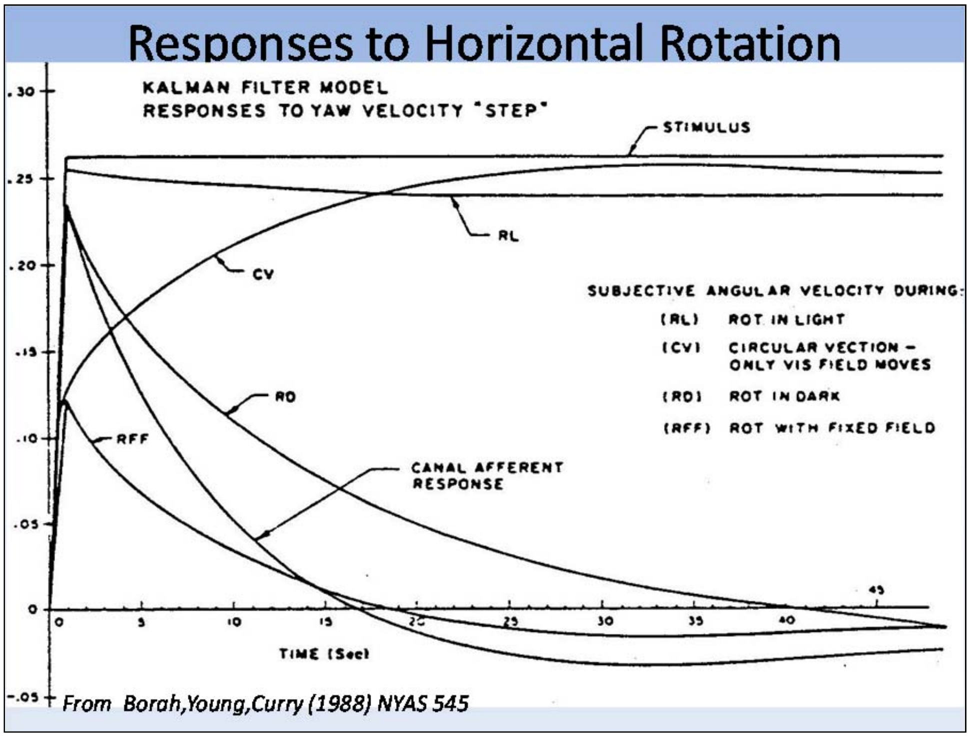
Internal Model for Vis-Vest-Interaction



From Borah,Young,Curry (1988) NYAS 545

Slide 19

Responses to Horizontal Rotation



From Borah,Young,Curry (1988) NYAS 545

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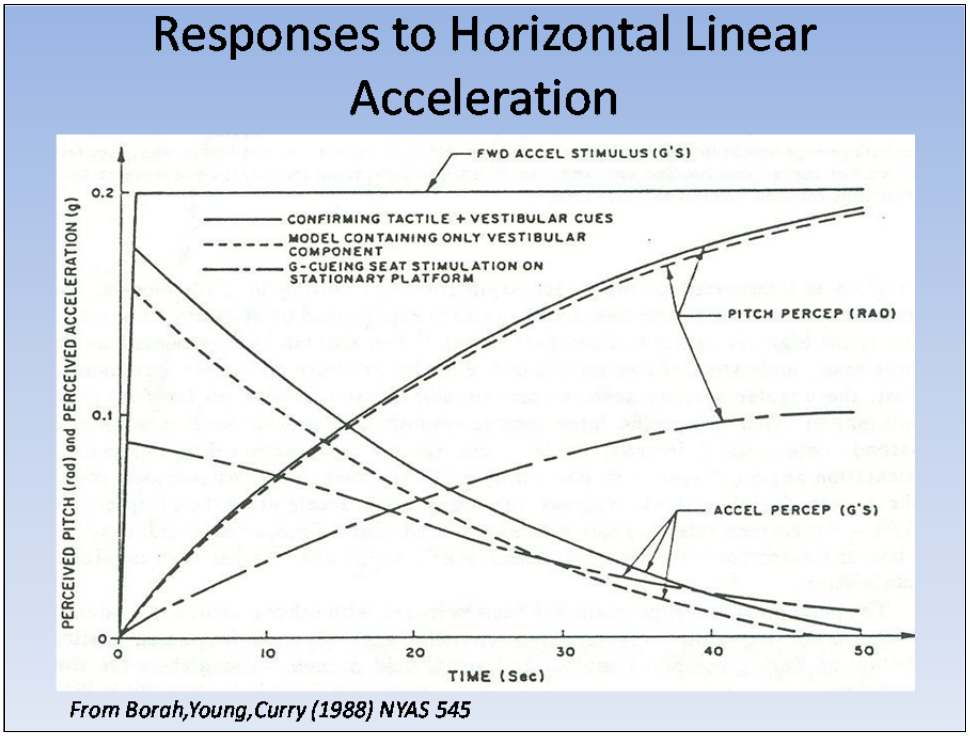

Responses to Horizontal Linear Acceleration

From Borah,Young,Curry (1988) NYAS 545

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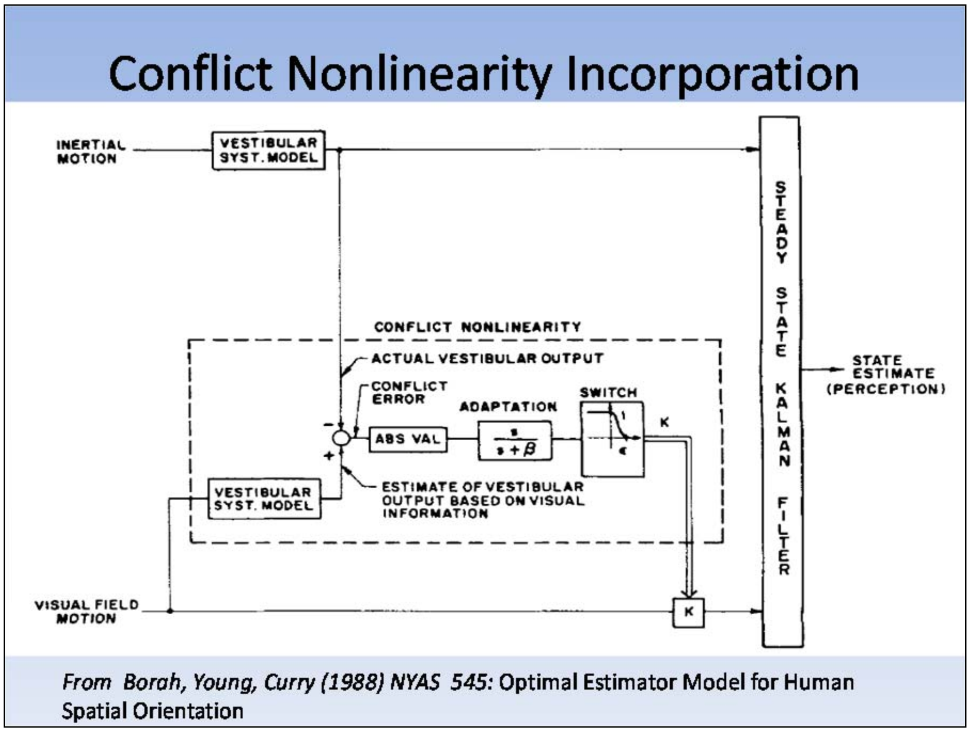
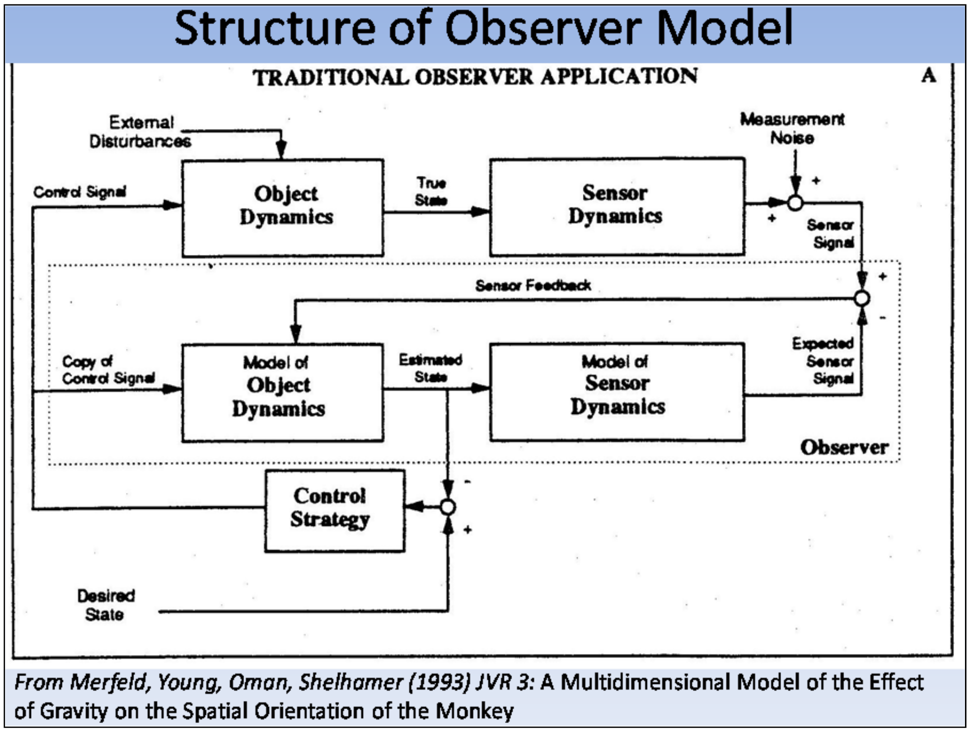


Conflict Nonlinearity Incorporation

From Borah, Young, Curry (1988) NYAS 545: Optimal Estimator Model for Human Spatial Orientation

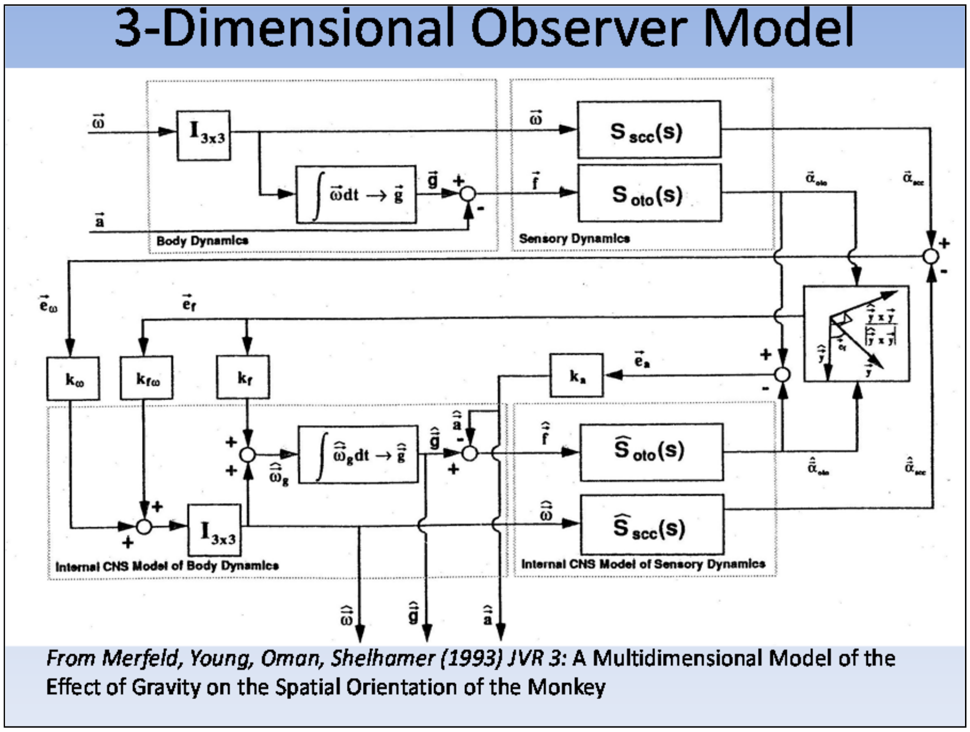
Slide 22



Structure of Observer Model

From Merfeld, Young, Oman, Shelhamer (1993) JVR 3: A Multidimensional Model of the Effect of Gravity on the Spatial Orientation of the Monkey

Slide 23



3-Dimensional Observer Model

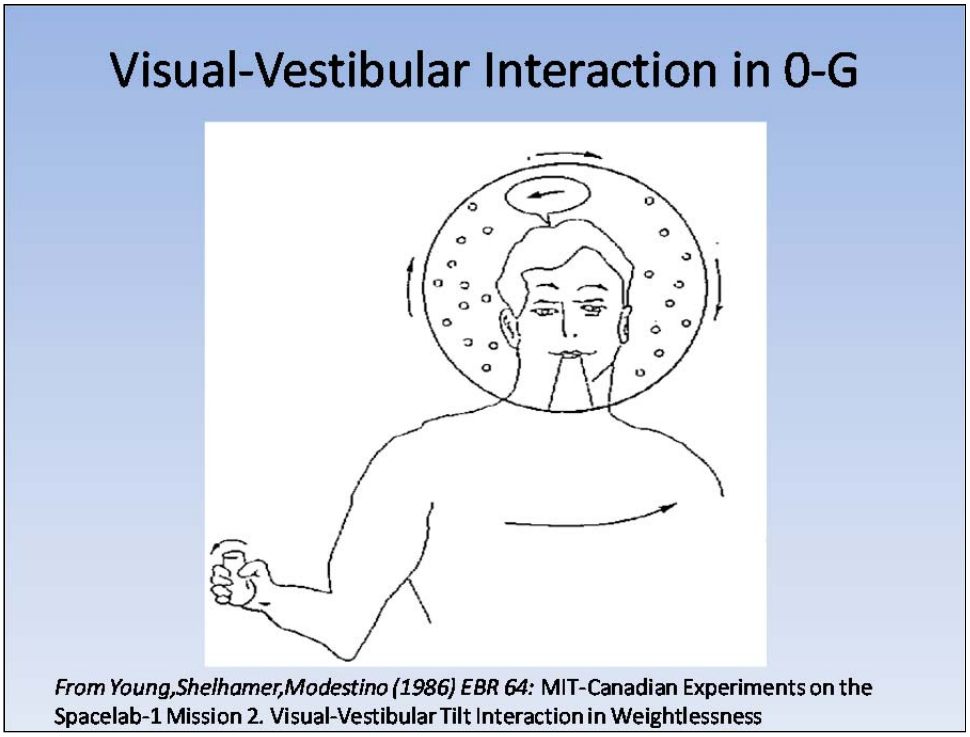
From Merfeld, Young, Oman, Shelhamer (1993) JVR 3: A Multidimensional Model of the Effect of Gravity on the Spatial Orientation of the Monkey

Slide 24

Applications of Models

Basic Psychophysical Experiment Planning
Neurophysiological underpinnings
Clinical Applications
Vestibular Rehabilitation
Flight Simulator Motion Drives
Space Motions Sickness and Disorientation
Aviation Accident Research

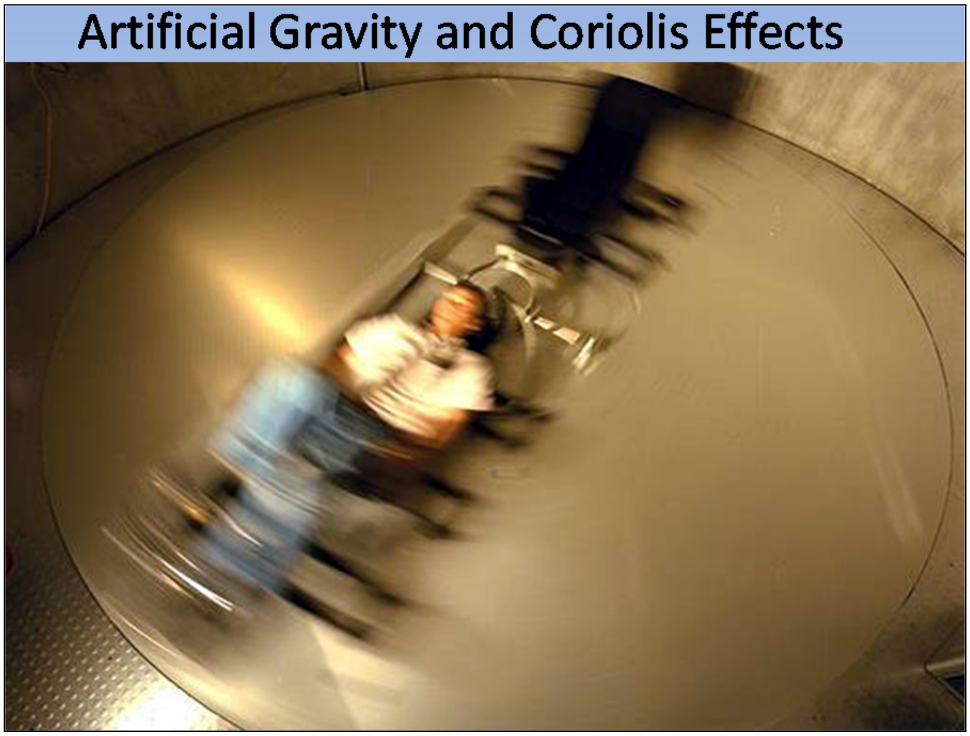
Slide 25



Visual-Vestibular Interaction in 0-G

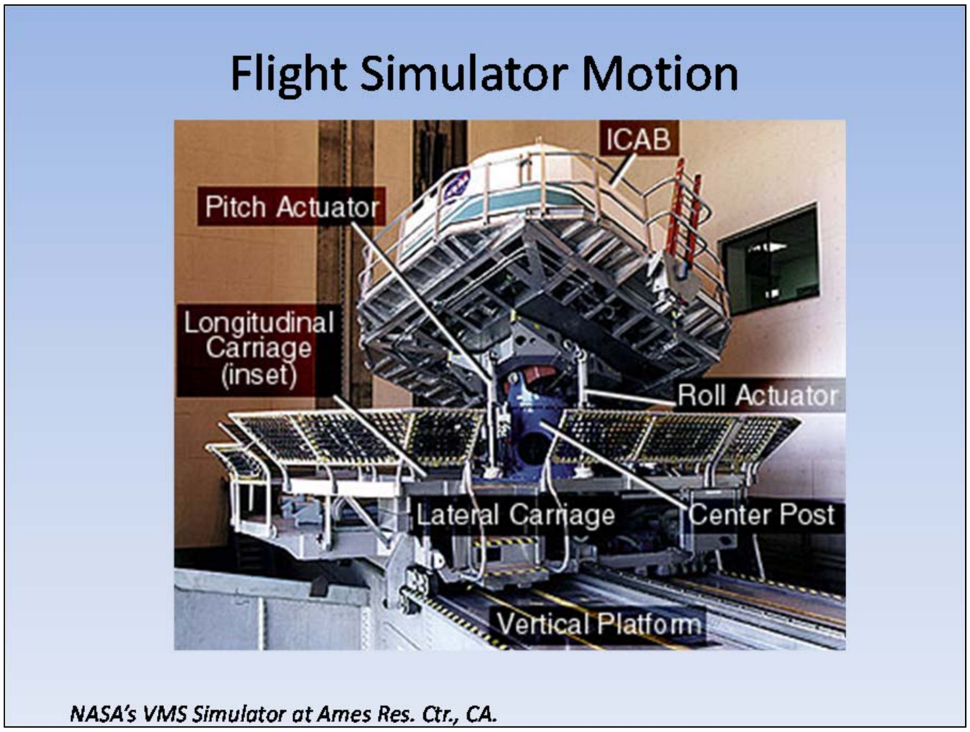
From Young,Shelhamer,Modestino (1986) EBR 64: MIT-Canadian Experiments on the Spacelab-1 Mission 2. Visual-Vestibular Tilt Interaction in Weightlessness

Slide 26



Artificial Gravity and Coriolis Effects

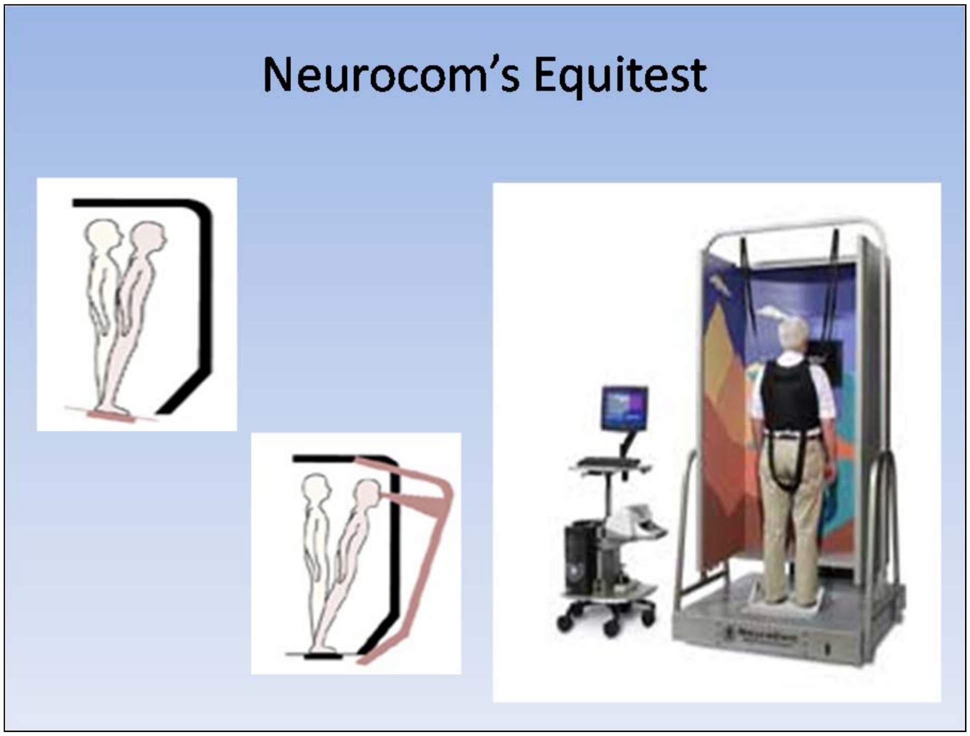
Slide 27



Flight Simulator Motion

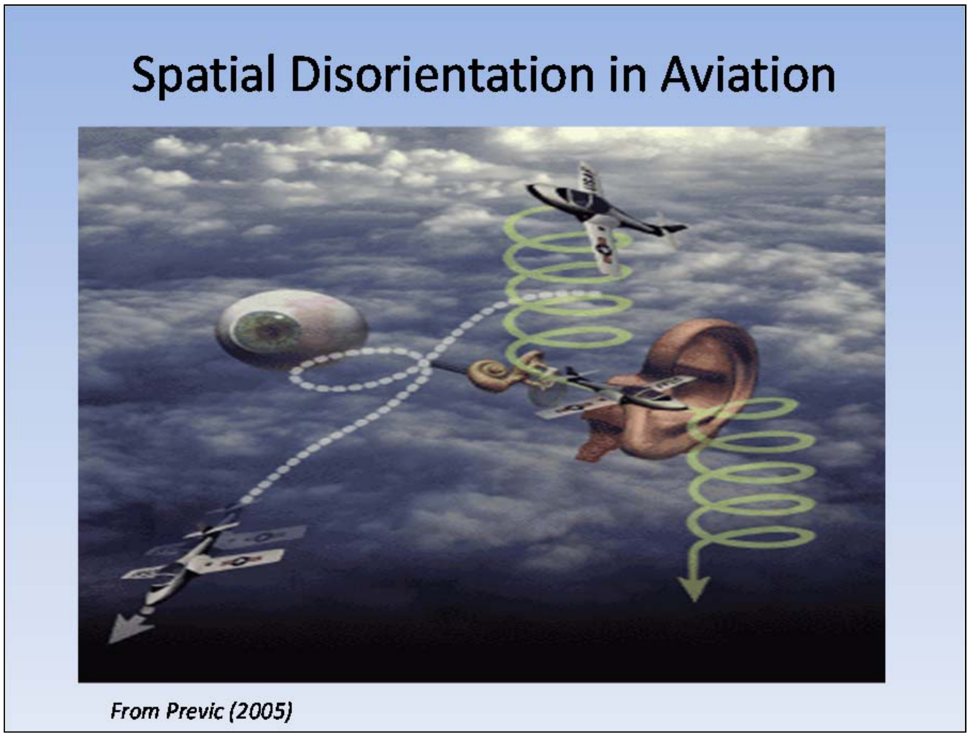
NASA's VMS Simulator at Ames Res. Ctr., CA.

Slide 28



Neurocom's Equitest

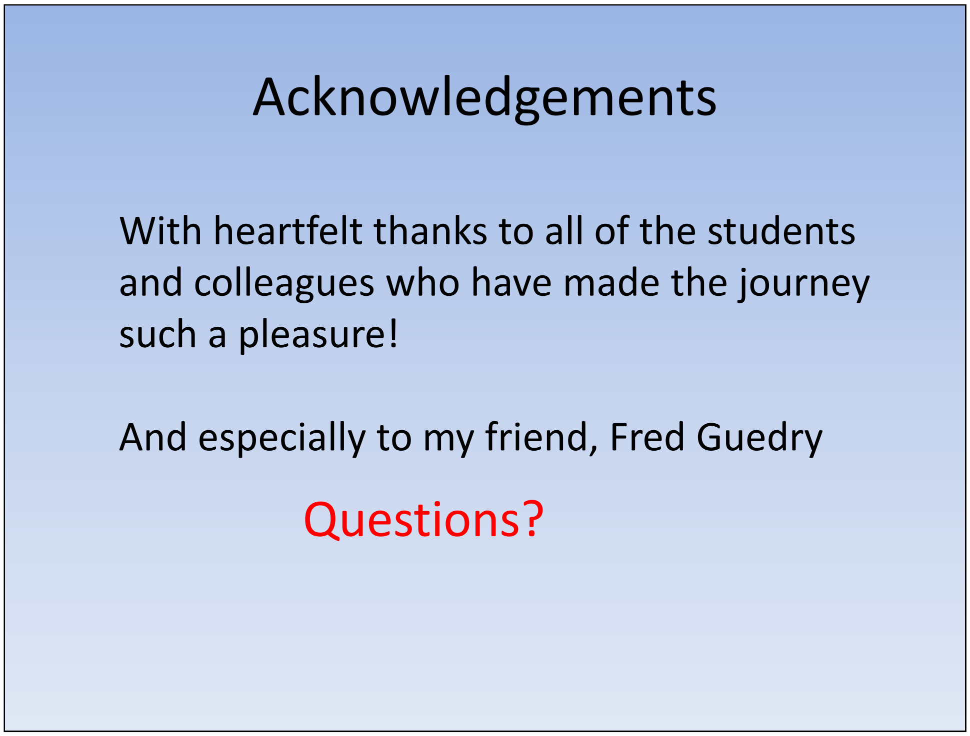
Slide 29



Spatial Disorientation in Aviation

From Previc (2005)

Slide 30



Acknowledgements

With heartfelt thanks to all of the students and colleagues who have made the journey such a pleasure!

And especially to my friend, Fred Guedry

Questions?

Slide 31

<ins>Question and answer session</ins>

[Money] In teaching undergraduates, is there a good answer now to the question of, 'What is the function of the saccule?'

[Laughter]

[Young] I would turn to Jay Goldberg and Ian Curthoys and see how they would answer it because it is too complicated for me.

[Goldberg] We agreed we weren't going to argue about that anymore [laughter]. Can I tell a story? It will only take about a minute. I was on a study section and was very busy at that time. It was the early '70s and I was doing about 18 reviews a session. This was a proposal I wasn't asked to review, so I didn't even read it [because] I was so busy. One of my colleagues was on the study section -- and I am old enough to mention names -- Rudy Tallman was savaging it, saying, "As everybody knows, the sacculus is a hearing organ." Even though I hadn't read it, after about 2 minutes of this unfair savaging, I raised my hand and said, "Rudy, I don't know how to tell you this, but you're wrong." At which point, somebody else, and I am old and forgetting names but it will come back to me, a very famous guy on the panel said, "Who discovered that?" I had to say, "I did" [laughter]. It's one of those triumphs in one's career that really doesn't count for a hill of beans, but it does give oneself some… [unintelligible].

I don’t think Fred [Guedry] is going to argue that it isn’t a vestibular organ. There has been some dispute as to how sensitive it is to relatively high level of sounds, but it is a hearing organ [also], and its directional properties, at least in the main part of the sacculus, are very much different from those of the main part of the utriculus, underlining “main”...because it’s hard to [isolate]. So, for those main parts, the utriculus gives you a two-dimensional signal relating to the orientation of linear forces in the horizontal plane, and the main part of the sacculus, I want to emphasize that again, gives you an estimation of vertical motion, of motion along the vertical axis. I don’t think there is any dispute about that. Okay, so the dispute is sort of on the margins, is the sacculus or utriculus under certain circumstances more sensitive to a relatively high level [sound]? By that I mean 90 to over 100 decibels or something like that...relatively large sounds. The notion is that, ‘Hey, in a fish, it is a hearing organ.’ But if I can go on just for one more second, audition or hearing has always been an advantageous kind of evolutionary [trait]. So there are different solutions in different groups of mammals, let alone in different groups of invertebrates. So, in fact, the sacculus is without question a hearing organ in fish, but you don’t go from fish to mammals without at least some experiments.

[Young] So Ken Money, the answer is, we are still learning about what the role of the sacculus is. I think for me, one of the things that became clearer to me is that it is wrong to think of the utricle as being a two-dimensional sensor and the sacculus as being a one-dimensional sensor, largely thanks to the findings of Ian Curthoys showing that there was (in fact) three-dimensional representation in both organs. You had a comment, Ian?

[Curthoys] Just a very general comment about your approach and what is going to be discussed this morning and how vital it is for aerospace work and space flight generally. I just want to comment that so much of the work that is currently being done, oriented toward the clinic, is going a different way. It is going toward very rapid tests which can be simply undertaken in the clinic, rather than looking at phenomena -- which are so important for you and almost everyone in this room -- about the effects of long duration angular accelerations. That’s just not the way the clinics work these days. It’s simply cost. You’ve got to be able to diagnose people really, really quickly. There is a real divergence now, I think, coming between the kind of material that you guys have been looking at for so long and clinical applications, developing clinical diagnostic tests for the real world.

Models for Coriolis and Pseudo-Coriolis Response − Charles Oman

[Slide 1, page 55] I first met Fred Guedry 42 years ago -- hard to believe. I was a young graduate student attending the fourth symposium on the Role of Vestibular Organs in Space Exploration, which was held here in Pensacola, and others in this room (you know who you are), were there. Over the last decade we have continued the Pensacola tradition, the sixth symposium was held in Portland [Oregon], (Owen Black organized it) it was a wonderful meeting, [and] I remember Fred [Guedry] attending. In 2006, we had another meeting which several of us arranged and hosted in Nordic, Holland, and we're going to have the eighth this coming spring at Sheraton Suites Galleria in Houston, Texas the weekend before the IAA [International Academy of Astronautics] Humans in Space meeting. We have obtained significant support from the NASA human research program, I'm putting in a little bit from National Space Biomedical Research Institute [NSBRI], and we also have a number of corporate sponsors who've contributed to the funding for the meeting, including, our lead sponsor which is ETC NASTAR [Environmental Tectonic Corporation's National Aerospace Training and Research center]. I would urge you [to participate] the due date for abstracts for this meeting is December 8 [2010] (so a week after the IAA meeting), so this is coming up in a couple of weeks. This is the one meeting where I think our aerospace vestibular community can really get together, and will have a chance to have platform presentations as well as posters. The IAA meeting is going to be wonderful, attracting a broad aerospace group, but that will be (unfortunately) posters only. So, this will be a two and a half day meeting, starting on Friday, Owen [Black] is chairing the program committee and a number of other people; Mark [Shellhamer], and Scott [Wood], and others are on the group. So please get your abstracts in, it's not all space and of course, I think it's a well-known joke (particularly to people in this room) that the real role of exploration discovery has been in the exploration of vestibular organs.

Ok, so Angus [Rupert] said I was going to give you an update on the Merfeld/Zupan model [Merfeld and Zupan, 2002]. I decided in thinking about it that I was going to give a more general talk for models for Coriolis acceleration because that's really something that's a common interest that Fred [Guedry] and I had, and where we really started working together in the late '80s. Dan Merfeld sends his regards to everybody. Sad to say, Lionel Zupan has (unfortunately for us) left the field, but the beneficiaries are all the students at Tufts University. He's Director of Information Services at Tufts now, so it's a loss for all of us.

I'm going to talk mostly about Coriolis and a little bit about pseudo-Coriolis -- most of you know what that is but I'll mention it when we get there. I'm going to be reviewing some work which Fred [Guedry], Angus [Rupert], and I began in 1988 when this really smart Australian graduate student showed up on my doorstep, Brad McGrath. That's what Brad looked like in the good old days [slide 2, page 55]; Fred and Angus really haven't changed much. We began with some Navy funding looking at disorientation in centrifuges [McGrath, 1993], and the application in those days was that the Navy and the Air Force had these high performance fighters, and I guess that's a Tomcat [F14], pulling high G's and the Navy and the Air Force were doing G-induced loss of consciousness training in centrifuges, and people were dimming out. I remember coming down here and having a ride and I was amazed. I used to fly a lot and did aerobatics and I thought I could hack it, but I think 3 or 4 minutes into a 5 minute run at 3Gs sitting upright, Angus [Rupert] tells me I 'fell asleep'… is that about right? Fortunately when your head falls down, the cerebral circulation is restored.

So what we did was a series of experiments where we studied perception, and I think we had -- what did we have Fred? -- 50 subjects, or something like that, and we studied the perceptions with the subjects being spun in the Coriolis Acceleration Platform centrifuge, which is in the background there. That's a centrifuge with a cab on the end and the seat inside is pendulous and it's on a large arm, the radius is a little over 20 feet, and we decided we would see what people were perceiving when they were accelerated in this thing, up to speeds that correspond to 3G, so the seat was swinging out quite a ways. In a subset of the experiment, Brad [McGrath] was very brave and had the courage to try measuring eye movement [with video-oculography], not with EOG [electrooculography], but this was 1988 and the small video cameras were just making their appearance, and we bought a system from ISCAN® (I'm going to count on you guys to help me out with the things I forget with Ricky Razdan). We put it on a pair of glasses and we discovered we needed to have a bite-board and we put it on the subjects and that was unfortunate, because they couldn't talk and give Fred and the rest of us any information about perception so we had to have a separate run. We recorded eye movements in these people and [asked], "What can we figure out?" Several tech reports and a couple papers came out of it, which were in the Journal of Vestibular Research [JVR], which by the way was in the Pergamon edition. One thing I think many in this room who published during the Pergamon era of JVR would wish [is] that somehow we [would] get intellectual property rights to that journal and get those things online. The IOS[8] versions of JVR are available readily through the libraries, but not the Pergamon, so I think we need to move on that. I can report that JVR has agreed to post (on the IOS website) the proceedings of all five preceding Pensacola symposia, so the papers which Larry [Young] mentioned are obscure will be publically available. Owen [Black] and Bill Polaski managed to get these things together back in 2002 and many of us have the CD sets.

This [slide 3, page 56] is an example of some of the eye movement data that Brad [McGrath] got. This is from his master's thesis. So, we spun them up slowly over 19 seconds to the 3G speed and tested them forward-facing the motion and back to the motion, and looked particularly at the horizontal and vertical line [eye] motion, we couldn't do torsion in those days. Fortunately, the torsion eye movements aren't too great. The two things we saw of course were that there were these significant transients which presumably were canal induced, largely, in the vertical eye movements, a little bit in the horizontal, especially at the beginning with the cab. Remember this is a pendulous centrifuge, so when the cab first starts out you're loaded in this position and the cab will swing out -- I'll show you the vectors in a minute. Then there was a significant up-beating nystagmus which came in, and the interesting thing about it is if you changed the subject's direction you'd always get the up-beating nystagmus because the acceleration was eyeballs down, but you could reverse the canal driven component, as it was. We weren't surprised by the sustained nystagmus, actually the amount varied a bit between the subjects, some people seemed to have considerably more than others, but the average came out to be exactly the L-nystagmus, which some of us call Larry's [Young] nystagmus by the way, he'd predicted 4 degrees per second on the basis of other experiments, and it was here. This is clearly interacting with the semicircular canal response, but our team said, "How much of this stuff can we explain? What's going on here? When we start the deceleration, why does the nystagmus transient reverse in direction?" That actually is something that the models did succeed in explaining, but you'll see in a minute that there was a lot that wasn't explained. Just to cement the idea of what's going on here; this is from Fred's paper [slide 4, page 56], this is Gz going this

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[8] IOS Press located at http://iospress.metapress.com/home/main.mpx.

way, time going this way during your start up. So you start at 1G and when the centrifuge starts spinning what this shows is the VOR [vestibulo-occular reflex], and I guess it was two dimensions, the component of it that we measured, during the spin up, and you can see basically that you start feeling a yaw, or the eye movements are primarily in yaw, and by the time you've reached speed the peak response is pretty much in pitch. Here is the spin down [slide 5, page 57], and you can see the G level is dropping off, now the thing that you notice when you are a subject in here is although there are difference in spin-up and spin-down vectors, the subjective experience doesn't correspond to the eye movement. When you've spun down to a stop during this phase here you get a tumbling [sensation], what's the record Angus [Rupert]? 8 spins -- 10 spins, tumbling head over heels?

[Rupert] Remember there's a mixture of velocity and displacement sensation, so it's difficult to say how many spins but it goes on for about 15 seconds. At the same time, the experience [illusion] was that they were pointing almost straight down while they were tumbling forward. In other words, they had [felt] a fixed position, but that they were tumbling forward, but the reality is that they were seated as upright as you are now [Rupert is referring to the paradoxical sensation of velocity without displacement].

[Oman] I think the thing that fascinated all of us is [that] Fred [Guedry] has been concerned with was: what is the right psychophysical technique to use when you're asking questions of subjects who are experiencing paradoxical sensations? There's a real problem of description, and what's the effective attentional focus, and the nature of the questions you ask? I don't think we have really good answers to that. Sometimes we do other things in an attempt to deal with it other than [by] asking subjects questions; we give them pointers and ask them to point down, but when you're tumbling and you have this very bizarre strong sensation -- that is really hard to capture.

The other thing we tried to ask ourselves is, "What is the best way to model this?" The classic approach to describing the Coriolis sensation is to essentially apply the Euler equation (which at least the engineers in the group are familiar with from studying mechanics) which says that basically if you're in a rotating or planetary coordinate frame, that the laws of mechanics apply as if it was a stationary frame if you add an additional term, which is a product of the planetary rotation, in this case the centrifuge, and the angular velocity of the head movement [slide 6, page 57]. So here's a little subject making a rolling head movement about the axis of omega-two and if the planetary is going at omega one you get the cross-product acceleration, which in this case would be a pitch down. This is the way the classic textbooks on this subject were presented, but there's a problem for modelers, as you'll see, it's probably a lot easier to stay in an inertial frame. In fact Alan [Benson] and Fred [Guedry] realized this, and some of you remember their paper which I think was written in 1974 (help me out Alan or Fred), "Coriolis Cross-Coupling Effects: Disorienting Nauseogenic or Not?" … right? [This appeared in 1976 as a technical report and 1978 as a journal article.] These guys said in a non-mathematical way, that it's easier to predict or understand what's going on with Coriolis if you stay in the inertial frame, but look at the velocity changes [Guedry and Benson 1978]. I suspect that probably this figure [slide 7] is familiar to everybody in this room, because when you had to go and explain Coriolis to students, or anybody, your colleagues, you often refer to this basic figure, just because it's so easy to follow.

So, how do we turn this approach into a mathematical model? Around the same time, as Larry [Young] mentioned, at MIT Bob Steer, later myself, and Bill van Goskirk (at Tulane, I guess)… we had been trying to look at what are the fluid mechanics of the cupula pendulum system in a deeper way. Ian Curthoys who asks provocative questions of everyone (everybody in this room knows what I mean), said, “You know I’ve had enough of these sort of hose and tin can models that you put together; the real canal doesn’t look like that, it kind of looks like this, this is a human horizontal canal, what should we be measuring?” Eddy Marcus and I (he was one of my undergraduate students) -- we both have been trained in fluid mechanics and we said, “Let’s just look at this -- we’ll model the fluid behavior of an element of endolymph in the duct actually all the way around and try to write Newton’s Second Law for that, just force balance.” We came up with a scheme, it was kind of an extension of the torsion pendulum model. We listed the assumptions from a fluid mechanics point of view that the system would have to have in order to have approximately second-order dynamic response. We argued in an article published in Acta [Otolaryngologica] that these were all reasonable assumptions and we defined some inverse area and inverse area squared functions which were essentially the answer to Ian’s [Curthoys] question, “What should you measure if you’re an anatomist and you’re trying to figure out what the fluid mechanics of the canal are, for applications and allometry or maybe some clinical applications?” The point of showing this slide [7, page 58] is if you look over here, what are the angular accelerations stimuli to this thing, and how do they act on the fluid elements integrating all the way around the canal? There’s a centripetal acceleration term, which is always outwards relative to the flow so the integral around the canal is zero. There is a Coriolis term in the equation, the angular velocity of the fluid or the head times the linear velocity of the fluid in the duct, but the force always acts perpendicular to the fluid flow direction, and the magnitude of the term is really small because the relative velocities are so small, so that term disappears. So what you’re left with here in the end is the product of angular acceleration in the radius and you integrate it around the canal and applying Stoke’s Theorem (if any of you remember that), what you find is that basically the stimulus is the angular acceleration of the head in the plane of the canal. If you tilt the plane of the canal out of the plane of rotation the effective stimulus drops, because what really counts is the projection of the plane of the canal into the plane of rotation, and you could tilt the canal all the way perpendicular and find an orientation where this gets no response. So, this is the “fluid mechanician’s” point of view of why keeping track of the stimulus in an inertial frame is the right thing to do, and it validates what Fred [Guedry] and Alan [Benson] were saying [slide 8, page 58]. So to model this (this was 1988), all we had was Larry’s [Young] nystagmus models and Jay’s [Goldberg] models for the end organs, but sort of tweaked to describe nystagmus, so we tried just a very simple model, this is not an Observer model, we just said in head coordinates that the horizontal component of nystagmus should be just driven by the semicircular canal, and the vertical component is driven by a combination of canals and Larry’s nystagmus term (I’ll call it L-nystagmus term) of 4 degrees per second and we’ll see where that takes us, and so that’s what Brad [McGrath] did for his master’s thesis and the fits captured obviously the steady state component pretty well but, fits were not good, not as good as we wanted for the transient. So, what to do about that?

Well, Dan [Merfeld] at the same time was interested in modeling centrifuge data as well. He had been spinning some monkeys out at [NASA] Ames [research center], and we also had (with Ian I think in Australia) done an experiment on perception of the vertical and so around 1990-91, we said, “Let’s see what we could do if we could kind of take a fresh look at this, just staying with the simplest set of assumptions, capturing the flavor of the Kalman filter model [slide 9, page 59].”

One thing we’re aware of (and I’ll come back to this later) is that the Kalman filter model that Josh Borah and Larry [Young] had developed was a Kalman filter in terms of its structure but it was not something that was derived from first principles of knowledge of the noise disturbances that humans are exposed to and measurement noise and things like that [Borah, Young, and Curry, 1978, 1988]. So, Kalman wouldn’t call it a Kalman filter, he’d just say it was an Observer whose parameters had been tuned to match experimental data and the Kalman filter of the day had a major mutation and it was that the equations in it all had to be linear, so it was well suited for describing (for example) the perceptions in experiments where down deviated a little bit from the normal upright position, but you couldn’t run the Borah model for a case where the subject was tumbling. So what we did was just acknowledged the fact that the model had to be nonlinear and we put into it a quaternion representation of where down was, and (the key thing about this model) -- we’re going to throw out all the assumptions about nonlinear sacculi and things like that. We’re just going to assume (I think Jay [Goldberg] had pretty much convinced us from the physiological data in the monkey) that dynamics of the utricle and saccule (at least at the end organ) look pretty much the same and our view was that there was an ensemble coded signal about the direction of the net gravito-inertial stimulus that was going to the brain, and at least in some familiar orientation the brain knew how to interpret that. There was a neural network that could read that and tell the net GIF [gravito-inertial force] direction with respect to the body. If the brain kept track of where down was at the same time, the difference would mean those two measurements would tell you what acceleration was and that could be used to model perceived acceleration.

So, the inputs to this model were the actual linear acceleration and the actual velocity of the head, and some of you may have read this paper (this was in JVR also, an old JVR), so the actual velocity of the head goes through the real semicircular canals and in the central nervous system there’s an estimator for the angular velocity of the head, and the primary driver for this is that it’s an expectancy conflict estimator. You take the current estimate of the angular velocity, put it through an internal model of the semicircular canals and predict for moment to moment what the actual semicircular canal input is going to be, and you take the difference and multiply it by (again) K omega (Kω) here and use it to correct the internal estimate of angular velocity. The magic in this model really had to do with the way the linear acceleration data was treated. Obviously linear acceleration and gravity act together through the otoliths, and then there was that internal model scheme that kept track of where down was and predicted what the otilith output would be, and the difference between actual and anticipated otolith output was used to do two things. One was that if you were being rotated passively the otolith signals would be going around in a circle in a way that you weren’t expecting, and a weighted version of that was added into the angular velocity signals, and that was used to explain the oscillatory component for example of OVAR [off-vertical axis rotation]. Then the rotating otolith error signal was also used to update the internal estimate of where down was.

So we didn’t have any nonlinear sacculi or anything else, all we had were the assumptions that were involved in this model, and there were four weighting coefficients in this, as opposed to 16 in the Borah model, but this model could do loops, so it had some advantages for modeling the kind of data that Dan [Merfeld] was getting from centrifuges and so forth.

I think those of you who are into modeling sort of know the rest of the story and so, Van Ginsbergen and group in Europe [Vingerhoets, Mendendorp, and Van Ginsbergen, 2006; Vingerhoets, Van Ginsbergen, and Mendendorp, 2007] and Thomas Haslwanter [Haslwanter, Jaeger, Mayr, and Fetter, 2000] and Dora Angelaki and others started using this model, and Dan [Merfeld] has kept on with it [Merfeld, et al., 1993], and I think the notion that has emerged is that this model works pretty well for perception. It seems that there's a dynamic difference between eye movements and perceptions, in that you need different model parameters or perhaps maybe a simpler model to describe the VOR, and of course, that's what Fred [Guedry] said back in 1992 about the centrifuge data that we had.

[Slide 10, page 59] So, 20 years later another very smart graduate student showed up on my doorstep from Villanova and he's sitting in the back -- Mike Newman, raise your hand. Mike is now working for Bill Mitchell at ETC NASTAR and we had some support from NSBRI working with Ron Small of Orion corporation to try and extend the Observer model, and what we decided we wanted to do was add vision to it. Now, the Borah model (I remind you) had vision whereas the original Merfeld model was just vestibular, so we knew this was going to be a big jump because we could keep track of the direction of visual down and the robust situations. We added another sort of synthetic visual cue, visual tilt, with respect to down. The other thing we wanted to do was see [if] the model [could] keep track not just of where down is and what your angular accelerations and velocities are, but we wanted to tackle position and we wanted to go all the way to path integration if we could. The reason we were interested in that was [from] talking with Fred [Guedry], I called him up a couple of years ago and said, "Fred, what do we know really about perception of vertical motion?" He reminded me of some experiments that had been done, Dick Malcom [Malcom and Melvill Jones, 1973] for example, and Walsh [1964] was another. People do pretty well at judging small scale vertical motions, but you put them in a helicopter or a large throw device, and they know they're moving but are often guessing [i.e., uncertain] as to what the phase is, so why is that? I had been doing some work with Jeff Taube at Dartmouth [Calton and Taube, 2005] in the previous decade looking at head and place direction cell responses in the limbic system, and got used to thinking that a lot of the information coming from the brainstem's going somewhere. And [when] we ask subjects questions about where they are, or even what their velocity is, their perceptions may be more driven by what goes on in the limbic level, and the brainstem level. One of the central ideas that came out of the work with Taube from laboratory experiments (and we also took it into parabolic flight) was the notion that fundamentally we are Flat Landers and that a lot of our navigation and the path integration that we do is in a two-dimensional plane. So, Mike [Newman] and I decided we wanted to see if we could put that idea into this model and I'll show you how we did that [slide 11, page 60].

So, these are the inputs and outputs [slide 12, page 60] and I'm not going to take you through the details, the bottom down here is the original Merfeld vestibular model and the top up here and a little bit down here are the visual additions. The general scheme we used was consistent with the Observer but the difference between visual cues and expected visual cues goes through some weighting function, which would be a common gain if it was a Kalman filter, and then gets integrated to produce the estimate of velocity or position, and the integrator here is important because it assures that there's no steady state error, and for the modeling aficionados in the group, some of you might have noticed or were aware that there's no integrator in Dan's [Merfeld] angular velocity estimator, it really isn't a true Kalman filter of the Observer for vestibular inputs. But that's a detail.

One other thing we decided we wanted to do was set up the model so that the visual cue components can be turned on and off during a simulated experiment, and so they can be world or vehicle [slide 13, page 61]. To make this accessible, we wanted people to be able to use it who were not MATLAB® gurus. Mike [Newman] sat down and studied the MATLAB® manuals and learned to build GUI's [graphical user interface], and so what we built was a MATLAB® model using graphics extension, where you can set all the parameters or you can just choose some of the defaults, and then you can also visualize the results in either two-dimensions or three-dimensions looking at angular velocities, you can even plot stuff [slide 14, page 61].

Since we were going all the way to position with the model, we could actually show where (some people call this Mini-Mike) Mini-Mike is [the avatar in the GUI], what his orientation is and so forth. I think both of us have this on our laptops if you want to play around with it, we have a compiled version, which if you don't have a MATLAB® license you can run. It isn't quite as flexible as the full implementation [slide 15, page 62]. So what Mike [Newman] did for his thesis is go back and try and validate it against the predictions made by the Borah model but also against some data [Newman, 2009]. I think we came out of the exercise feeling that there's much more perceptual data that is really needed to validate a model like this across many cases, and I'll come back to that later in the discussion section [slide 16, page 62]. But the significant thing was at least the vestibular core had the parameters for human perception and for VOR and was different, but there was a fair bit of data behind them.

[Slide 17, page 63] So, we ran the model and it had some interesting emergent properties. Some of them maybe weren't all that surprising. This, of course, corresponds to the plot that Larry [Young] showed you earlier of the Borah model for both real rotation and circular vection rotation, where the environment rotates around you. The model exhibits velocity storage, no surprise there, Dan's [Merfeld] did. If you turn on the lights you see the circular vection rise and there's actually an interesting sort of two component response that is seen experimentally but was not predicted by Borah. [Slide 18, page 63] This corresponds to the second one Larry[Young] showed you, somatogravic illusion during horizontal linear acceleration. We can show that the somatogravic illusion is suppressed by vision, and it's interesting that this model suggests it's the visual down cue not the linear velocity cues that suppress the tilt. That's a different conclusion than Borah made, but it's consistent with recent experiments of Tokumaru [Tokumaru et al., 1998] which we discovered after we had done the modeling, so it's another emergent property [slide 19, page 64]. The path integration aspects of the model I'd say are experimental, what we did was we assumed that the relationship between velocity and perceived acceleration was low pass filtered and that there was a sort of a leaky integrator leak down in the vertical direction, and in some gross sense the model does mimic the Malcolm kind of loss of phase information for large amplitude vertical motion. I'll come back to that at the very end.

[Slide 20, page 64] Another thing we wanted to do was to model the vestibular Coriolis reaction for the centrifuge cases and here is the centrifuge case, and what's new here is that for large amplitudes we can actually try to predict pitch angles, and we modeled the Coriolis case that Fred [Guedry] and Alan [Benson] had done and you get a similar result, and it's predicting the illusory pitch sensation. What's different here from the classic canal driven model we developed 20 years before? Well, the angular velocity vector orientation in space changes as a result of interaction with the down cue. That, of course, was a feature of the Merfeld model too, but now it does this with vision [slide 21-23, pages 65-66]. I want to end this part of the talk by talking about pseudo Coriolis. Pseudo Coriolis I think you know was originally for our community sort of an oddity, but of course then when we got wide screen theaters at Disney Land and things like that and things started swinging around in those and our flight simulators, some of the sickness you get in the theaters is pseudo Coriolis. So what we did was simulate a case that corresponds exactly to the vestibular Coriolis reaction that Alan [Benson] and Fred [Guedry] had described in their paper, (by the way Fred has always made the point that we shouldn't perhaps be calling it Coriolis reaction to begin with -- it's not a Coriolis effect. I think that's obvious from my discussion of the fluid mechanics, so he was happier calling it the vestibular Coriolis reaction). So we did this pseudo Coriolis simulation and we found that relative to the direction of perceived or real orientation, it predicts a transient pitch sensation which follows a right angular, but here's the take-home message: the side is opposite to vestibular Coriolis, it's smaller in magnitude and slower in decay [Newman, et al., 2010]. So this is predicting (if you like) the pseudo Coriolis time course, which previous models did not. [Slide 24, page 66] What's happening, the blue is the perceived head angular velocity in head coordinates, and the first insert over here is just after you've made a right shoulder head movement in a clockwise stimulus so you feel you're going counterclockwise, it corresponds to the case that they consider. What basically happens is a visual angular velocity storage phenomenon, where you tilt your head over and initially the velocity vector goes with the head and then it gradually swings back in the direction of vertical [slide 25, page 67]. After the fact, we went back (as many of us have done) [to] this wonderful chapter that Fred [Guedry] wrote in 1974 called *The Psychophysics of Vestibular Sensation*, and I suspect that everybody in the room has had the experience of discovering something and then discovering that Fred had written something very prescient about it 30 years earlier and basically got the main things right, and here's what Fred said about pseudo Coriolis in the chapter:"The pseudo Coriolis effect is an optokinetic after-effect that locates the velocity vector relative to the head, which moves with the head to produce a tumbling sensation". So, he had that right, now the model is predicting some additional dynamics and it has it tracking back towards the vertical and not just diminishing in magnitude which I think was Fred's hypothesis then, but he got that right [slide 26, page 67]. But of course, if you read about the pseudo Coriolis experiment, particularly in Thomas Brandt's thesis or Johnson's paper with Thomas about this, it was consistently described as being like Coriolis.

Let me tell a story, because it's relevant. In 1972, we had gone down to the big dome at [NASA] Langley to do sort of the first three axis vection experiments, we had done tumbling drums (things like that) at MIT and they [Dichgans, Brandt, and colleagues at the Department of Neurology and Neurophysiology] had the big vertical axis drum at Freiberg [Freiberg University, Germany]. So here we are with this wonderful polka-dotted display that could swing around us in all three directions, so we quantified pitch and roll vection susceptibility, that was sort of the first time, and there were some interesting non-linearities. Ian Howard later did the experiment even better than we did. But, one of the things we never published was [that] we all made head movements, because we were all interested in pseudo Coriolis at the time and I remember afterwards it was frustrating because Johnson and I were talking about the data, and I said its really interesting data but it's funny how the direction of pseudo Coriolis is opposite real Coriolis, he looked at me and said, "Oh, you must have a tumor" [laughter]. So, just to make sure it wasn't me and the tumor, what Mike [Newman] did in his final week of his thesis effort, was to get Larry Young's drum and flip it up, bolted to a bookcase in his office, and without telling the human use committee at the time (we have since cleared ourselves) got a couple of subjects in, [to] make the necessary movements, and confirmed…. We got the direction right. So, here's something that is an emergent property of a model, and the model is telling you something important about the mechanism and it's also suggesting that multiple factors, not just the semicircular canal dynamics are affecting the axis.

We shouldn't call it pseudo Coroiolis because it really is misleading, you'll get the direction wrong if you remember it that way. Let's just remember it as a visually-induced angular velocity storage cross-coupling [slide 27, page 68].

I want to end with a brief comment; I have another very talented young graduate student from the University of Toulouse who just submitted his dissertation last Fall. His name is Pierre Selva, and he spent the year with me, and we were interested in going back and taking a broader look at what are the possible estimation techniques that we should be looking at these days to carry on the general theme of internal model based orientation estimation. Let's start with Observer; it's an internal model system, with empirically driven filter gains. The Kalman filter works if the system is linear, and a real Kalman filter makes some assumptions about noise, both measurement noise -- that would be variability of semicircular canal and otolith afference -- and also process noise -- the noise that the human is exposed to from the outside, motion noise. There, in the interim between Borah, Young, and Curry there were several other techniques that were developed. One was called an extended Kalman filter which basically updates the Kalman filter for what it knows about the current state and sort of reevaluates the model, and that was a possible thing to use, and in fact, we had two students, talented students, who built models on extended Kalman filters around 1990 and '92, but we never published them, and one of the reasons was at the time we were having technical problems getting the models to behave stably and also some other issues with the assumptions we made. They predicted that a human should be doing much better than humans actually do at keeping track of what was going on. So Pierre [Selva] came back and took a look at this and said, "Well, maybe we should also be looking at unscented Kalman filters," which are nonlinear models. They are Kalman family so they are expectancy-conflict-driven, but they don't have a lot of the baggage of Gaussian noise assumptions, either the measurement or the process noise. Then, finally, particle filters which are something which Jean Laurens [Laurens and Droulez, 2007] and others are looking at now, Dan [Merfeld] and some of us at MEEI [Massachusetts Ear and Eye Infirmary] are playing around with these. So what Pierre did was sort of compare all these techniques, his thesis papers are in press. By the way he also was an expert on finite element modeling and there's a paper that's just out in JVR on his cupula modeling work for those of you interested in cupula [slide 28, page 68].

One of the things that was interesting to me was that we were able to show that the Merfeld Observer model is in fact sort of a reduced order equivalent of the Borah model, and I won't go into the details except just to say that if you take the Borah model for say (this is a simplified version) angular velocity, this is Merfeld's Observer over here which I showed you before. Angular velocity goes through the real semicircular canal, goes in the Observer, there's some gain that goes through an expected semicircular canal model and back, and the difference is used to update the estimate -- pretty simple. In the Borah model because of the particular values of gains chosen, there were (as I mentioned) not just 4 parameters, but 16, but when you look at the values that were set to match empirical data you come up with, many of the 16 terms are very small, so essentially there are 4 dominant parameters so the 2 models are equivalent to one another [slide 29, page 69].

So then we began to think, “If there is equivalence between these two, is there any implication to the Borah numbers?” Borah got his model parameters empirically fitting the data as Jay [Goldberg] and Alan [Benson] were talking about, but should we consider them free? Shouldn’t the process noise covariance and bandwidth assumptions that we make when we’re doing a Kalman filter-like model or even the unscented variety reflect what we know about the statistics of accelerations of motions in daily life? We know something for example about the frequency content of locomotion and we know something about the amplitudes that the VOR system works at, and what we did (we have a paper in review right now) was to estimate the process noise covariance in bandwidth, that solves half the problem. We also worked backwards and said, there’s measurement noise, canal and otolith noise which percolates through the Observer, and that causes noise in the estimate; shouldn’t that correspond approximately to the human angular and linear motion thresholds? And if so, you could work backwards and come up with the noise covariance, and when you’re done all you need to know is the noise covariance for the process and measurement noise, and the bandwidth assumptions and you can go back and solve for the common gains. What you get are numbers that are very close to Borah and Merfeld, so we don’t claim this as unique, but what we say is the implication of these models is maybe that the parameters can be perhaps justified based on some reasonable assumptions as to the order of magnitude of human motion experience. Then finally, suppose you go and put yourself in an extreme motion environment, maybe you go out ocean racing for a couple of weeks or you’re a gymnast, and that change increases the bandwidth in your internal model and that should lower your Kalman gain, and that experience driven switch there [slide 30, page 69].

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Models for Coriolis and Pseudo-Coriolis Response

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Slide 1

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VESTIBULAR
STIMULATION
DURING A SIMPLE
CENTRIFUGE RUN

F.E. GUEDRY AND C.M. OMAN

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Spatial Disorientation

THE DYNAMICS OF SPATIAL ORIENTATION DURING COMPLEX AND CHANGING LINEAR AND ANGULAR ACCELERATION

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☐ **Abstract – The dynamics of spatial orientation perception were examined in a series of experiments in which a total of 43 subjects were passively exposed to various combinations of linear and angular acceleration during centrifuge runs. Perceptual effects during deceleration were much stronger than effects during acceleration. The dynamics of spatial orientation perception differed substantially** … **tions to complex combinations of linear and angular accelerations.**

☐ **Keywords – spatial orientation; perception; VOR; models; dynamics.**

In activities of every day life, dynamic spatial orientation during whole body movement rel-

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Original Contribution

VESTIBULO-OCULAR RESPONSE OF HUMAN SUBJECTS SEATED IN A PIVOTING SUPPORT SYSTEM DURING 3 G_z CENTRIFUGE STIMULATION

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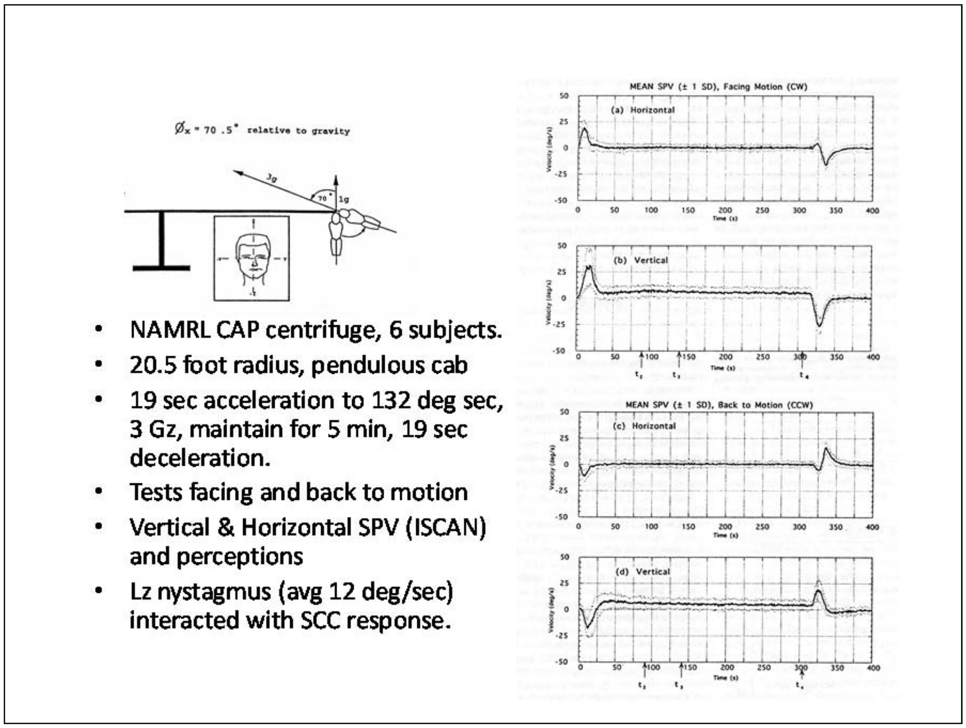
☐ **Abstract – The vestibulo-ocular reflex (VOR) and spatial orientation perceptions were recorded in 15**

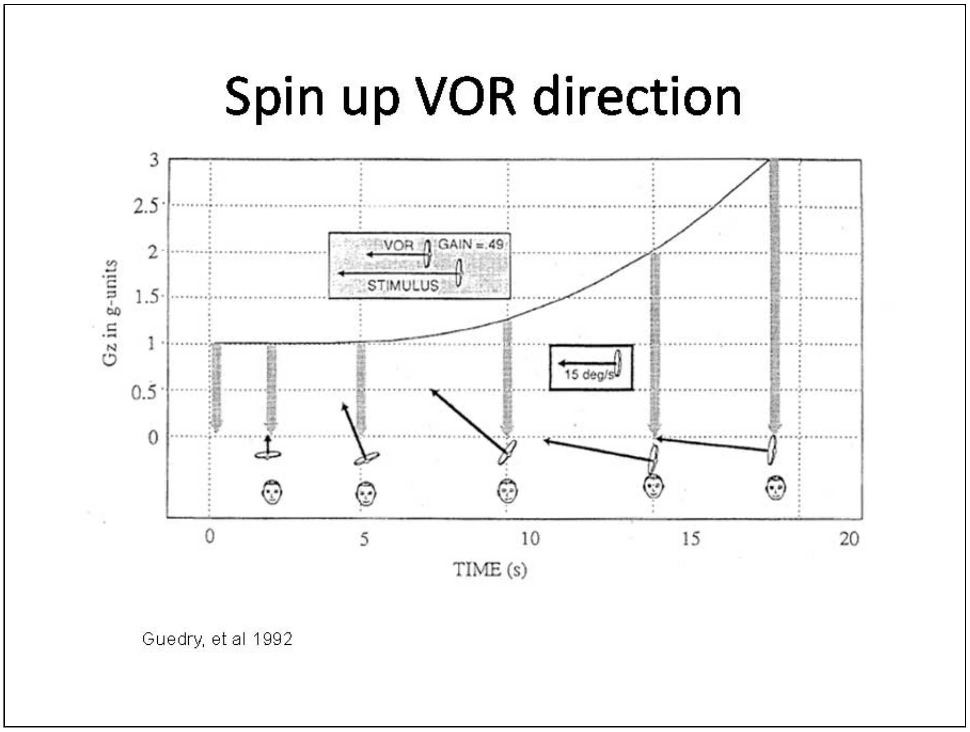
☐ **Keywords – VOR; spatial orientation; nystagmus; centrifuge.**

Slide 2



- NAMRL CAP centrifuge, 6 subjects.
- 20.5 foot radius, pendulous cab
- 19 sec acceleration to 132 deg sec, 3 Gz, maintain for 5 min, 19 sec deceleration.
- Tests facing and back to motion
- Vertical & Horizontal SPV (ISCAN) and perceptions
- Lz nystagmus (avg 12 deg/sec) interacted with SCC response.

Slide 3

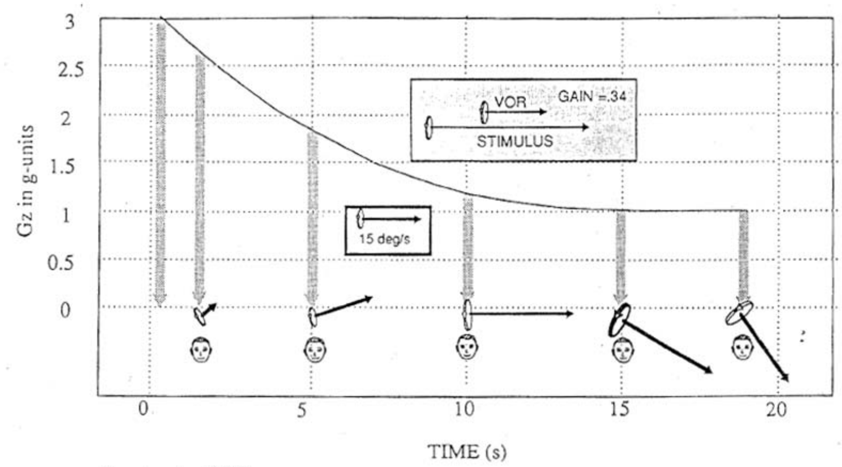


Spin up VOR direction

Guedry, et al 1992

Slide 4

Spin Down VOR direction



Guedry, et al 1992

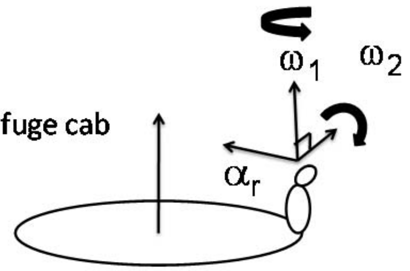
Coriolis Stimulus

Two approaches:

- Acceleration in the rotating centrifuge cab frame (e.g. Schubert, 1932):

  $\alpha_r = \omega_1 \times \omega_2 = \omega_1 \omega_2 \sin\phi$ (Euler)

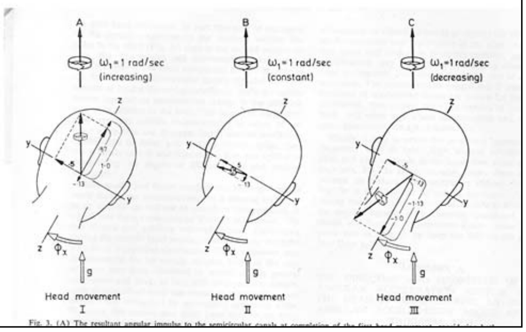
- Velocity changes in an inertial (laboratory) frame:

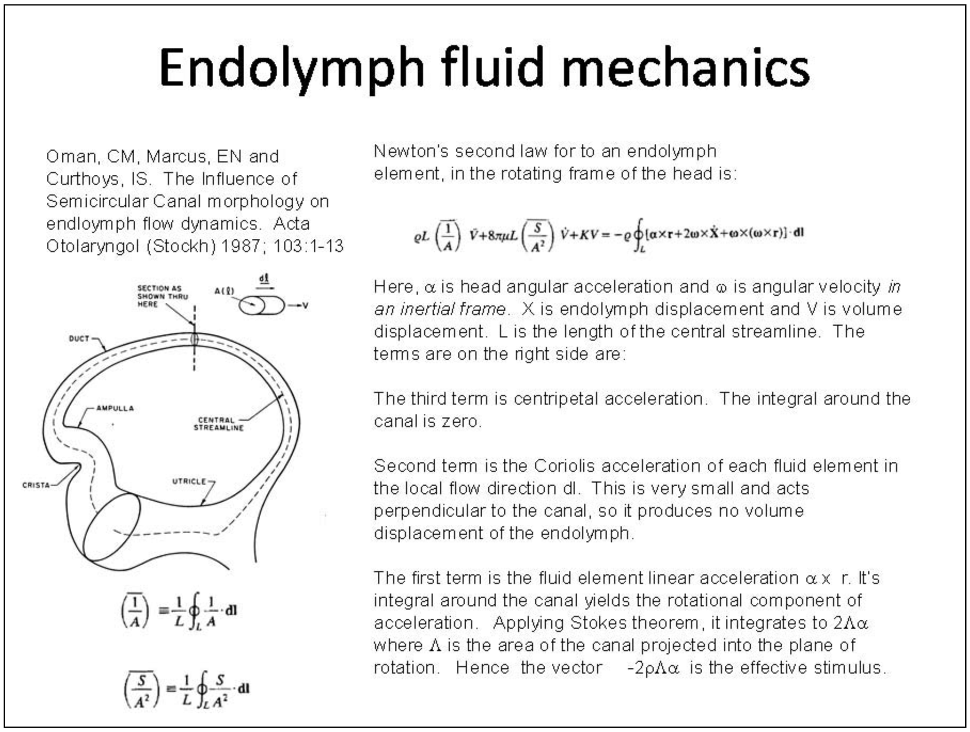


Coriolis Cross-Coupling Effects: Disorienting and Nauseogenic or Not?

Fred E. Guedry, Jr., and Alan J. Benson

Naval Aerospace Medical Research Laboratory, NAS Pensacola, Florida, and RAF Institute of Aviation Medicine, Farnborough, England.





Endolymph fluid mechanics

Oman, CM, Marcus, EN and Curthoys, IS. The Influence of Semicircular Canal morphology on endloymph flow dynamics. Acta Otolaryngol (Stockh) 1987; 103:1-13

$$\left(\overline{\frac{1}{A}}\right) \equiv \frac{1}{L}\oint_L \frac{1}{A}\cdot \mathbf{dl}$$

$$\left(\overline{\frac{S}{A^2}}\right) \equiv \frac{1}{L}\oint_L \frac{S}{A^2}\cdot \mathbf{dl}$$

Newton's second law for to an endolymph element, in the rotating frame of the head is:

$$\varrho L\left(\overline{\frac{1}{A}}\right)\ddot{V}+8\pi\mu L\left(\overline{\frac{S}{A^2}}\right)\dot{V}+KV=-\varrho\oint_L[\boldsymbol{\alpha}\times\mathbf{r}+2\boldsymbol{\omega}\times\dot{\mathbf{X}}+\boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r})]\cdot\mathbf{dl}$$

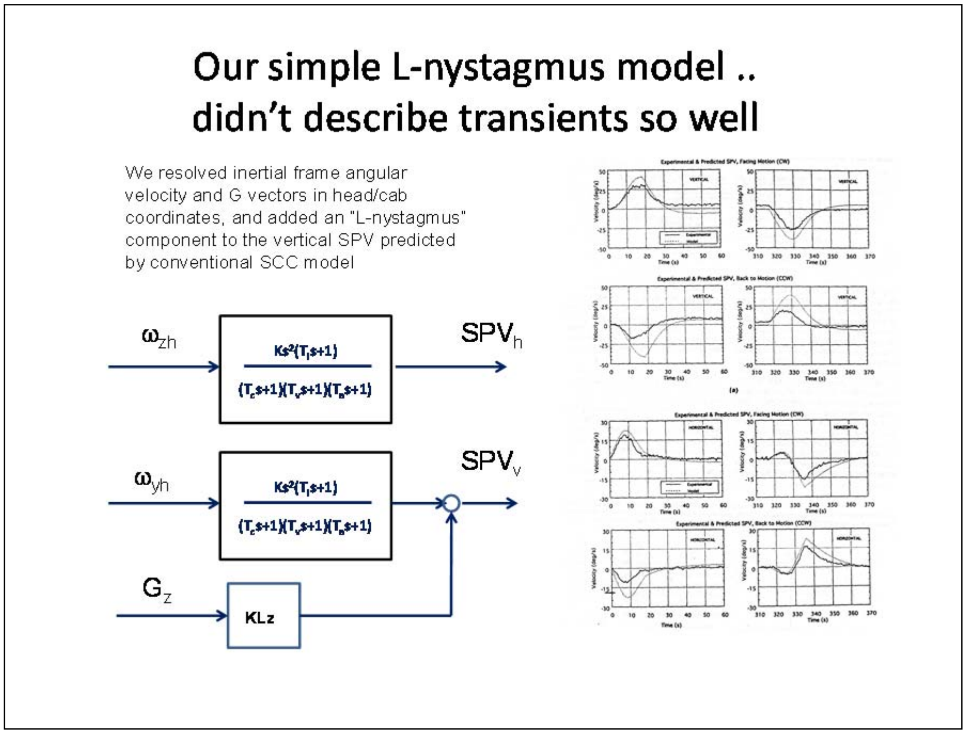
Here, α is head angular acceleration and ω is angular velocity *in an inertial frame*. X is endolymph displacement and V is volume displacement. L is the length of the central streamline. The terms are on the right side are:

The third term is centripetal acceleration. The integral around the canal is zero.

Second term is the Coriolis acceleration of each fluid element in the local flow direction dl. This is very small and acts perpendicular to the canal, so it produces no volume displacement of the endolymph.

The first term is the fluid element linear acceleration $\alpha \times r$. It's integral around the canal yields the rotational component of acceleration. Applying Stokes theorem, it integrates to $2\Lambda\alpha$ where Λ is the area of the canal projected into the plane of rotation. Hence the vector $-2\rho\Lambda\alpha$ is the effective stimulus.

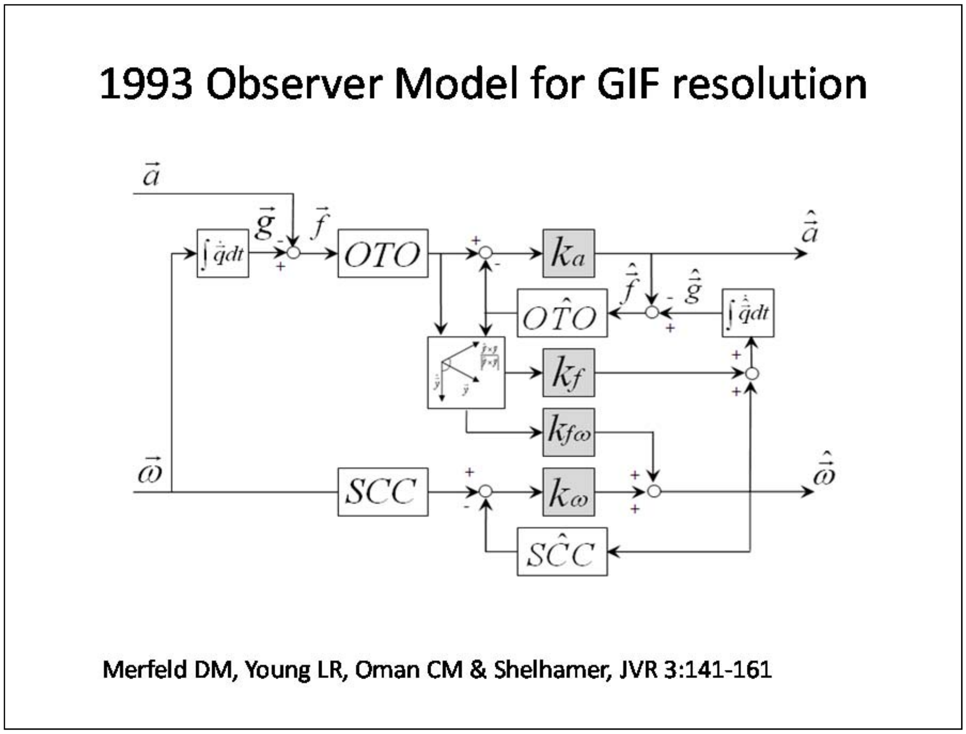
Slide 7



Our simple L-nystagmus model .. didn't describe transients so well

We resolved inertial frame angular velocity and G vectors in head/cab coordinates, and added an "L-nystagmus" component to the vertical SPV predicted by conventional SCC model

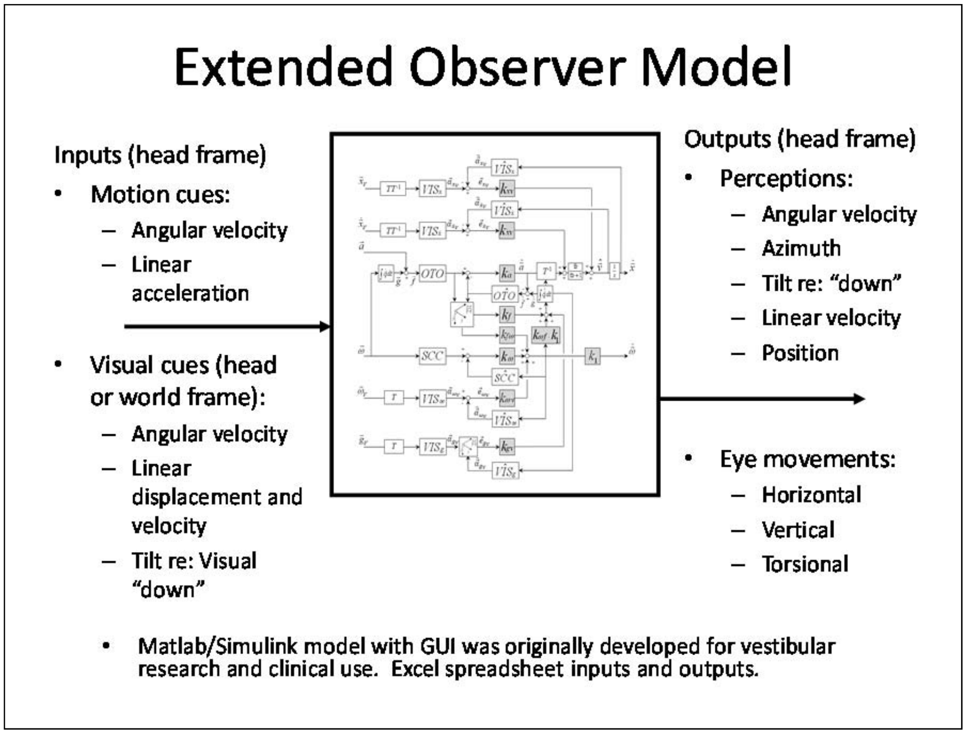
Slide 8



1993 Observer Model for GIF resolution

Merfeld DM, Young LR, Oman CM & Shelhamer, JVR 3:141-161

Slide 9



Extended Observer Model

Inputs (head frame)

- Motion cues:
  - Angular velocity
  - Linear acceleration
- Visual cues (head or world frame):
  - Angular velocity
  - Linear displacement and velocity
  - Tilt re: Visual "down"

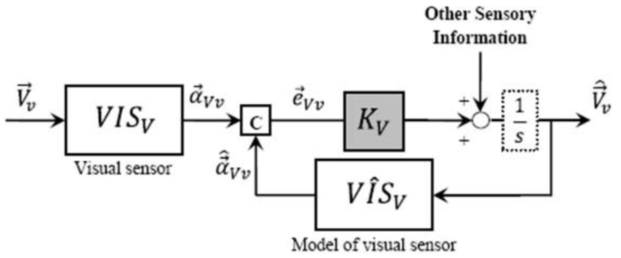
Outputs (head frame)

- Perceptions:
  - Angular velocity
  - Azimuth
  - Tilt re: "down"
  - Linear velocity
  - Position
- Eye movements:
  - Horizontal
  - Vertical
  - Torsional

- Matlab/Simulink model with GUI was originally developed for vestibular research and clinical use. Excel spreadsheet inputs and outputs.

Slide 10

Visual Cue Processing Scheme

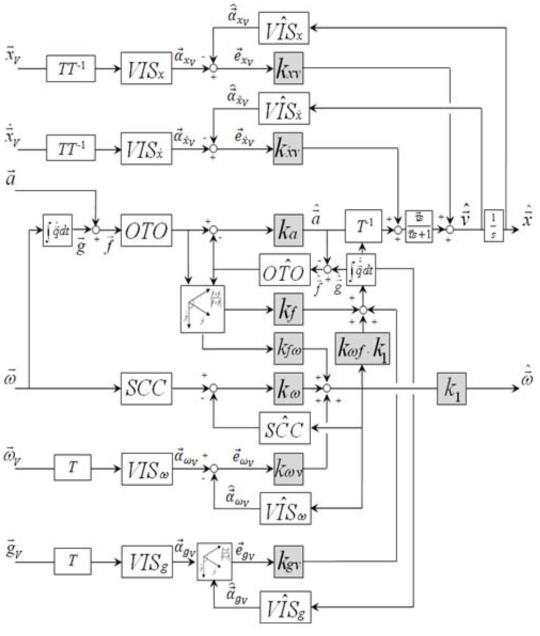


- Weighted sensory conflict drives rate of change of estimated state. Eliminates steady state errors.

Slide 11

Extended Observer Model

- Visual cues:
  - Linear displacement and velocity
  - Angular velocity
  - Visual "down"
- Visual cue components can be turned on or off
- Visual cues can be world or vehicle referenced.



Newman MIT SM Thesis, 2009; Newman and Oman, 2009

Slide 12

GUI

Current Directory:
C:\Documents and Settings\Charles Oman\My

.
..
3dOFF.jpg
3dON.jpg
BBQ_Spit_60_light.xls
Eccentric_rotation.xls
Eccentric_rotation10.xls
Eccentric_rotation20.xls
Eccentric_rotation5.xls
GUEDRY_CORIOLIS_RIGHTSHOULD.xls
GUEDRY_PSEUDO_CORIOLIS_RIGHTSHOULD.xls
GUEDRY_VISON_CORIOLIS_RIGHTSHOULD.xls
Lin_acc_Borah_no_vision.xls
Lin_acc_Borah_vision.xls
Lin_acc_Borah_visionNO_G.xls
Lin_acc_Borah_visionNO_OMEGA.xls
Linear_vection_Borah.xls
Man.WRL
Man_est.WRL
OTTR_Tilt_Gain_no_vision.xls
OTTR_Tilt_Gain_vision.xls
OVAR_no_vision.xls
OVAR_vision.xls

File Name: Eccentric_rotation5.xls
Duration: 19.01
Sampling Rate: 100 HZ
Simulation Time: 1.9291 secs

○ ○ ○ ● ○

Vestibular Parameters
Set Values or Choose a Default Scheme

SCC Time Constant 5.7
SCC Adaptation Constant 80.0
SCC LPF Frequency 2.0
Otolith LPF Frequency 2.0
SCC Feedback Gain (kww): 8.0
GIF Feedback Gain (kfg): 4.0
GIF Omega Feedback Gain (kfw): 8.0
Acceleration Feedback Gain (Kaa): -4.0
Omega GIF Feedback Gain (Kwg): 1.0
☐ Idiotropic
Preset Feedback Schemes

Visual Parameters
Set Values or Leave at Default Settings

Position LPF Frequency 2.0
Velocity LPF Frequency 2.0
Angular Velocity LPF Frequency 0.2
Linear Position Gain (kxvv): 0.1
Linear Velocity Gain (kxdotva): 0.75
Angular Velocity Gain (kwvw): 10.0
Tilt Angle Gain (Kgvg): 5.0

Leaky Integration Frequencies (Rad/Sec)
Velocity: X 0.6 Y 0.6 Z 10.0

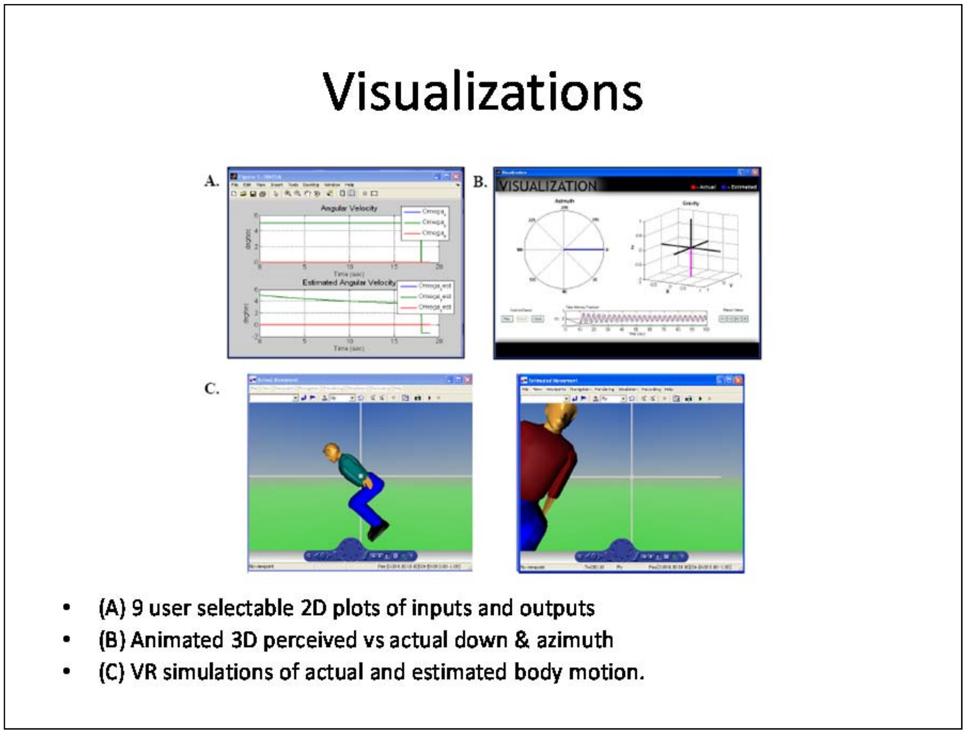
Initial Conditions
Tilt Angle: X 0.0 Y 0.0 Z -1.0

Plot Customization
Select Variables and Axes to Display

☑ Gravity
☑ ...
☑ Tilt & SVV
☑ Angular Velocity
☑ Displacement
☑ Linear Velocity
☑ Linear Acceleration
☑ Stimulis Cues
☑ Euler Angles
☐ Scale Axes
☑ Naso-Occipital (X)
☑ Inter-Aural (Y)
☑ Dorso-Ventral (Z)

Version 1.2 ©2009 Massachusetts Institute of Technology

Slide 13



Visualizations

- (A) 9 user selectable 2D plots of inputs and outputs
- (B) Animated 3D perceived vs actual down & azimuth
- (C) VR simulations of actual and estimated body motion.

Slide 14

Model Experimental Validations

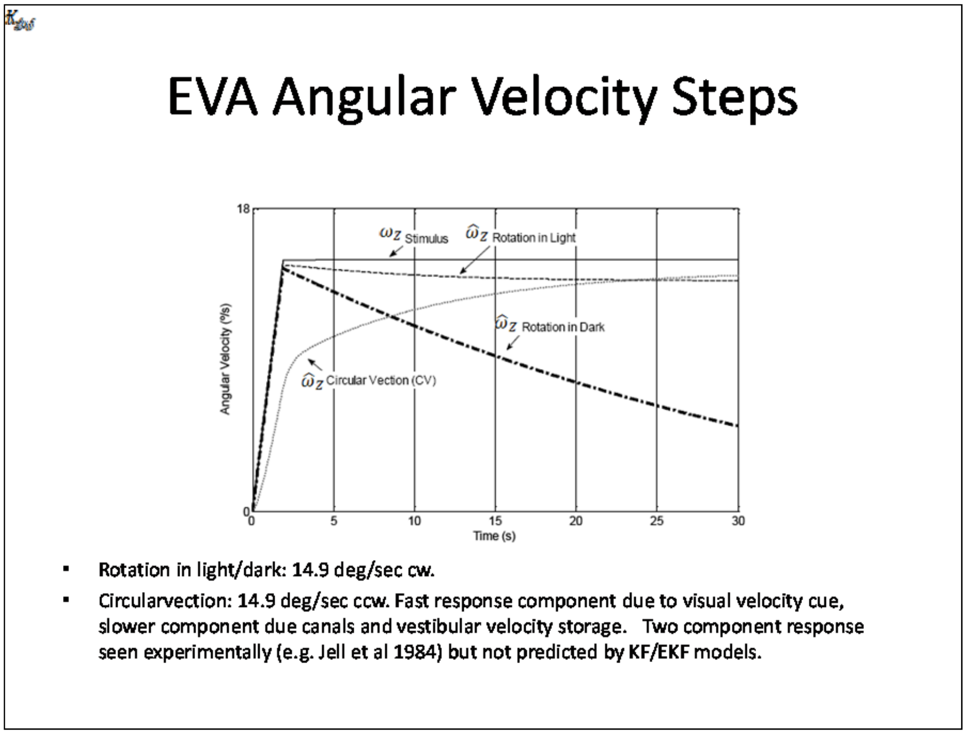
1. Linear and angular acceleration steps
2. Postrotatory tilt
3. Constant velocity Earth vertical yaw rotation (dark)
4. Somatogravic Illusions
    - Sled forward linear acceleration
    - Fixed and variable radius centrifugation
5. Static and dynamic roll tilt
6. Off vertical axis rotation (OVAR)
7. Large amplitude horizontal and vertical sinusoidal displacements
8. Constant velocity Earth vertical yaw rotation (light)
9. Circular vection
10. Somatogravic illusion due to forward linear acceleration in a lighted cabin
11. Forward linear vection
12. Coriolis Illusion
13. Pseudo-Coriolis Illusion
14. Variable radius dynamic swinging
15. Perceived orientation in NASA Ames VMS simulator

Parameters

TABLE 2. *Residual Weighting Parameters*

	Vestibular Parameters					Visual Parameters				Leaky Time Constants		
	K_a	K_f	$K_{f\omega}$	K_ω	$K_{\omega f}$	K_{x_v}	$K_{\dot{x}_v}$	K_{g_v}	K_{ω_v}	τ_x	τ_y	τ_z
Value	-4	4	8	8	1	0.1	0.75	10	10	16.67	16.67	1

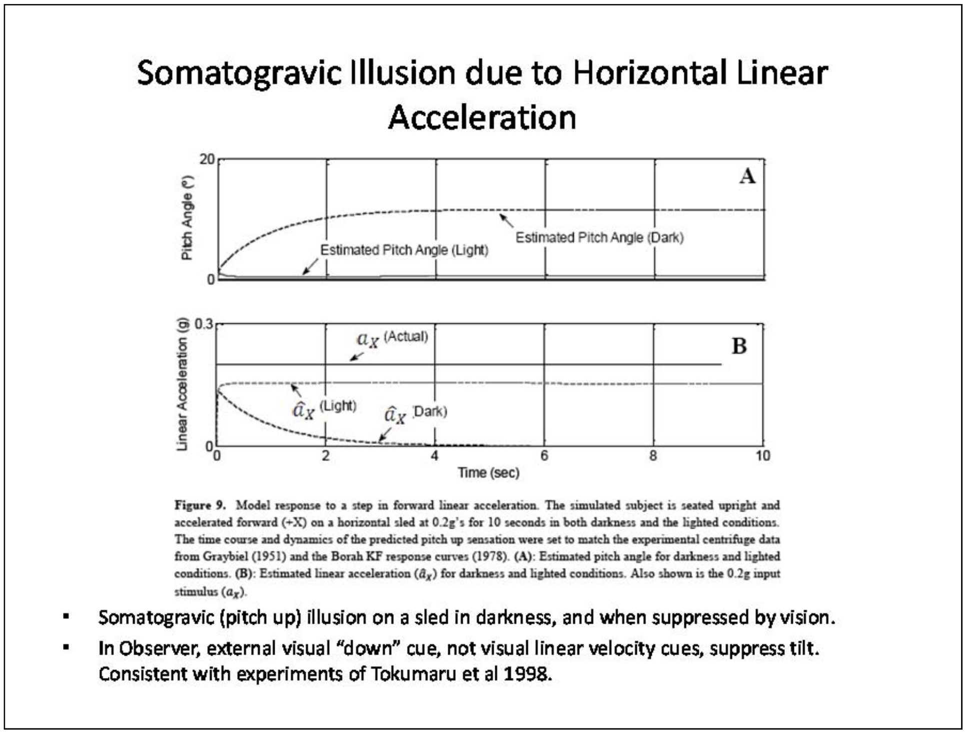
- **Defaults (Vestibular: Vingerhoets 2007; Visual: Newman 2009)**
- **GUI provides user selectable vestibular parameter sets: Haslwanter 2000 human, Merfeld 1993 monkey, Merfeld 2002 human, Merfeld 2002 monkey, Vingerhoets 2007 human.**
- **All Observer parameters can be set via interface**
- **Switches in input array can be used to turn on/off individual visual components and or vary g during the simulation.**



EVA Angular Velocity Steps

- Rotation in light/dark: 14.9 deg/sec cw.
- Circularvection: 14.9 deg/sec ccw. Fast response component due to visual velocity cue, slower component due canals and vestibular velocity storage. Two component response seen experimentally (e.g. Jell et al 1984) but not predicted by KF/EKF models.

Slide 17

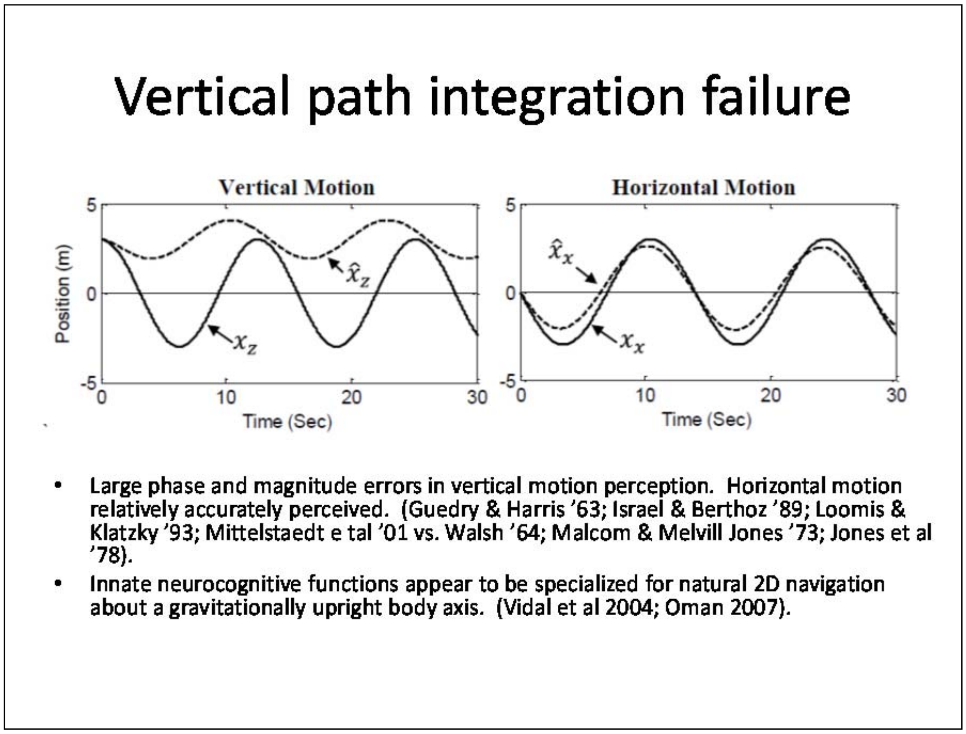


Somatogravic Illusion due to Horizontal Linear Acceleration

Figure 9. Model response to a step in forward linear acceleration. The simulated subject is seated upright and accelerated forward (+X) on a horizontal sled at 0.2g's for 10 seconds in both darkness and the lighted conditions. The time course and dynamics of the predicted pitch up sensation were set to match the experimental centrifuge data from Graybiel (1951) and the Borah KF response curves (1978). **(A)**: Estimated pitch angle for darkness and lighted conditions. **(B)**: Estimated linear acceleration ($\hat{a}_X$) for darkness and lighted conditions. Also shown is the 0.2g input stimulus (a_X).

- Somatogravic (pitch up) illusion on a sled in darkness, and when suppressed by vision.
- In Observer, external visual "down" cue, not visual linear velocity cues, suppress tilt. Consistent with experiments of Tokumaru et al 1998.

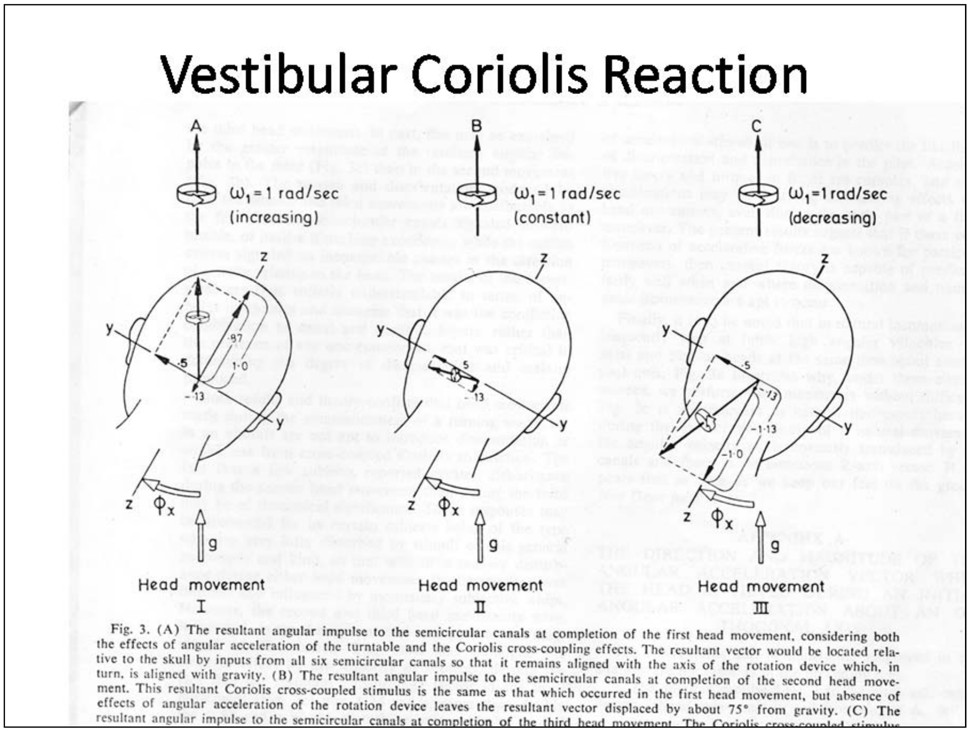
Slide 18



Vertical path integration failure

- Large phase and magnitude errors in vertical motion perception. Horizontal motion relatively accurately perceived. (Guedry & Harris ’63; Israel & Berthoz ’89; Loomis & Klatzky ’93; Mittelstaedt e tal ’01 vs. Walsh ’64; Malcom & Melvill Jones ’73; Jones et al ’78).
- Innate neurocognitive functions appear to be specialized for natural 2D navigation about a gravitationally upright body axis. (Vidal et al 2004; Oman 2007).

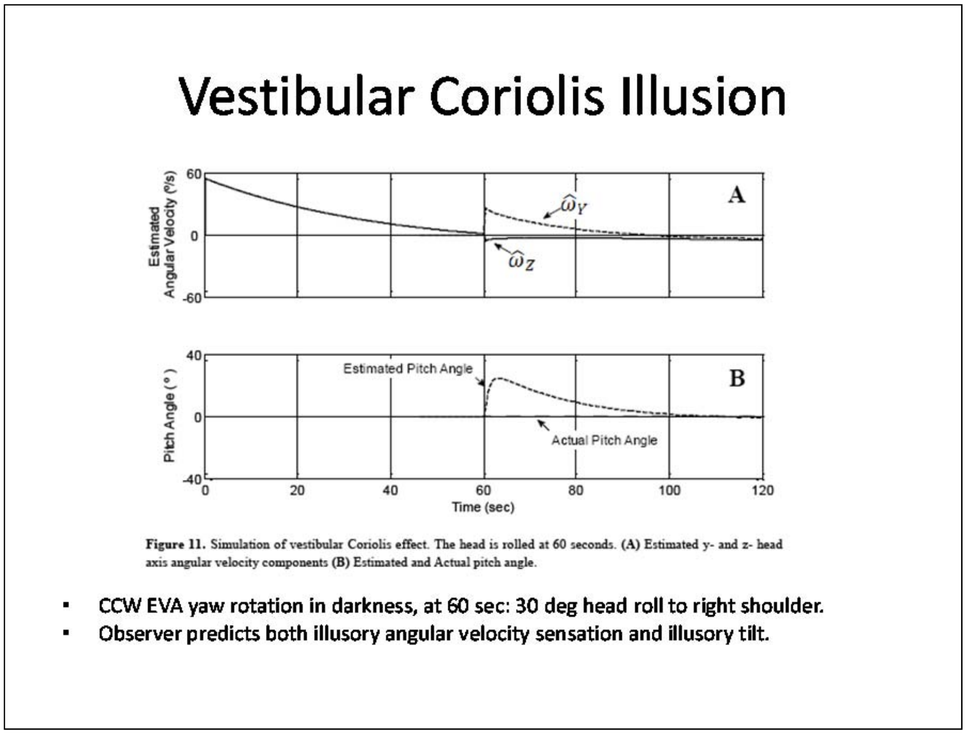
Slide 19



Vestibular Coriolis Reaction

Fig. 3. (A) The resultant angular impulse to the semicircular canals at completion of the first head movement, considering both the effects of angular acceleration of the turntable and the Coriolis cross-coupling effects. The resultant vector would be located relative to the skull by inputs from all six semicircular canals so that it remains aligned with the axis of the rotation device which, in turn, is aligned with gravity. (B) The resultant angular impulse to the semicircular canals at completion of the second head movement. This resultant Coriolis cross-coupled stimulus is the same as that which occurred in the first head movement, but absence of effects of angular acceleration of the rotation device leaves the resultant vector displaced by about 75° from gravity. (C) The resultant angular impulse to the semicircular canals at completion of the third head movement. The Coriolis cross-coupled stimulus

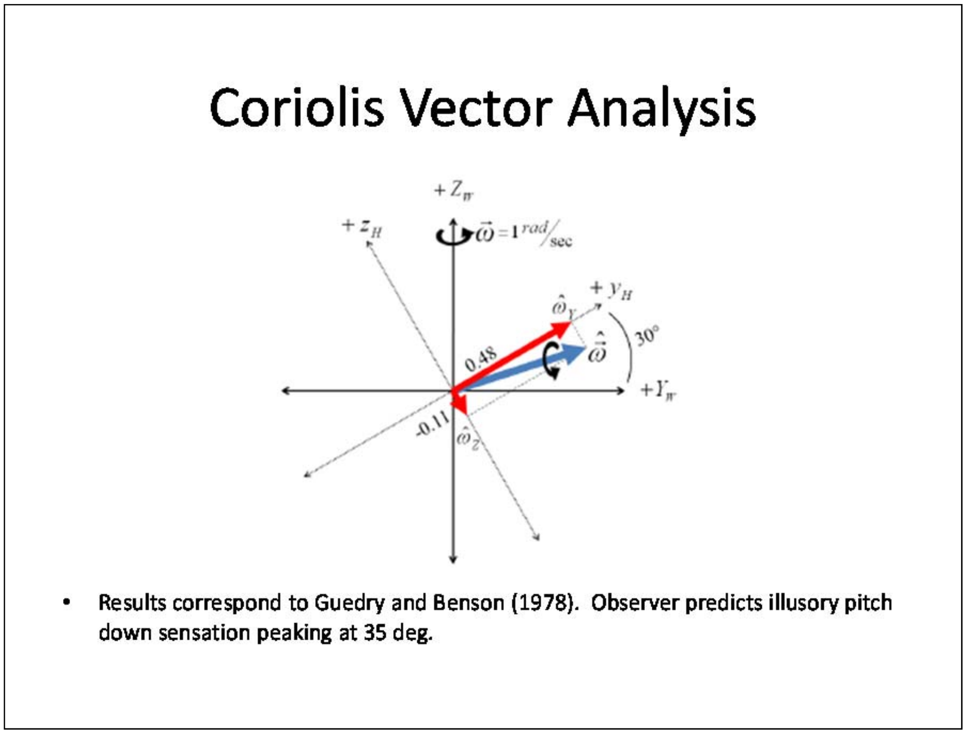
Slide 20



Vestibular Coriolis Illusion

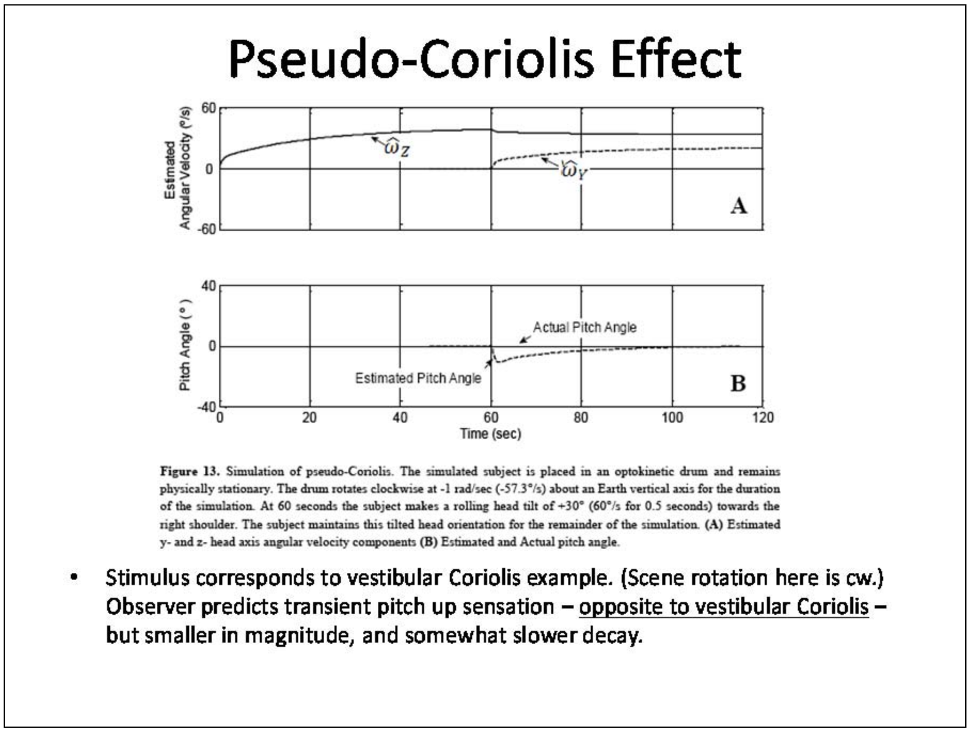
Figure 11. Simulation of vestibular Coriolis effect. The head is rolled at 60 seconds. (A) Estimated y- and z- head axis angular velocity components (B) Estimated and Actual pitch angle.

- CCW EVA yaw rotation in darkness, at 60 sec: 30 deg head roll to right shoulder.
- Observer predicts both illusory angular velocity sensation and illusory tilt.



Coriolis Vector Analysis

- Results correspond to Guedry and Benson (1978). Observer predicts illusory pitch down sensation peaking at 35 deg.

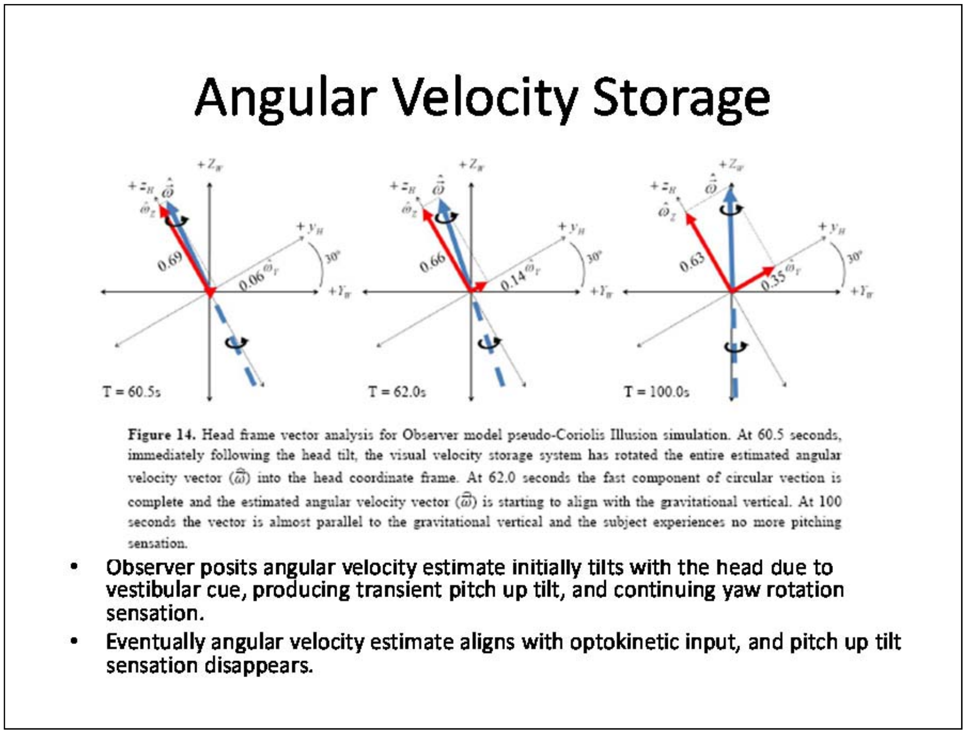


Pseudo-Coriolis Effect

Figure 13. Simulation of pseudo-Coriolis. The simulated subject is placed in an optokinetic drum and remains physically stationary. The drum rotates clockwise at -1 rad/sec (-57.3°/s) about an Earth vertical axis for the duration of the simulation. At 60 seconds the subject makes a rolling head tilt of +30° (60°/s for 0.5 seconds) towards the right shoulder. The subject maintains this tilted head orientation for the remainder of the simulation. (A) Estimated y- and z- head axis angular velocity components (B) Estimated and Actual pitch angle.

- Stimulus corresponds to vestibular Coriolis example. (Scene rotation here is cw.) Observer predicts transient pitch up sensation – opposite to vestibular Coriolis – but smaller in magnitude, and somewhat slower decay.

Slide 23

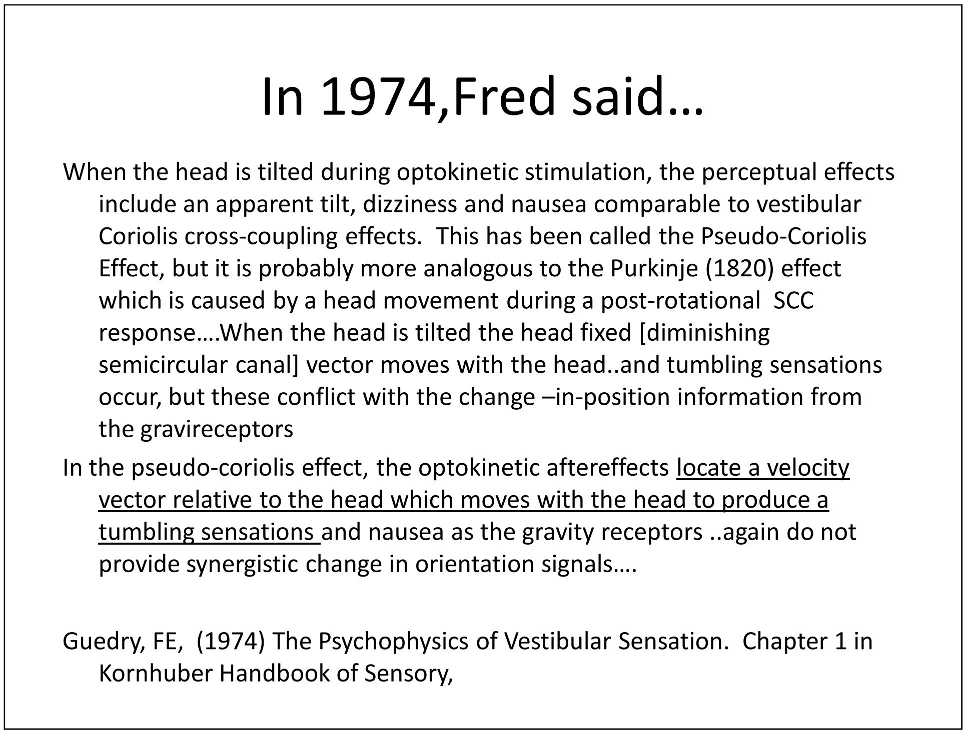


Angular Velocity Storage

Figure 14. Head frame vector analysis for Observer model pseudo-Coriolis Illusion simulation. At 60.5 seconds, immediately following the head tilt, the visual velocity storage system has rotated the entire estimated angular velocity vector ($\hat{\vec{\omega}}$) into the head coordinate frame. At 62.0 seconds the fast component of circular vection is complete and the estimated angular velocity vector ($\hat{\vec{\omega}}$) is starting to align with the gravitational vertical. At 100 seconds the vector is almost parallel to the gravitational vertical and the subject experiences no more pitching sensation.

- Observer posits angular velocity estimate initially tilts with the head due to vestibular cue, producing transient pitch up tilt, and continuing yaw rotation sensation.
- Eventually angular velocity estimate aligns with optokinetic input, and pitch up tilt sensation disappears.

Slide 24



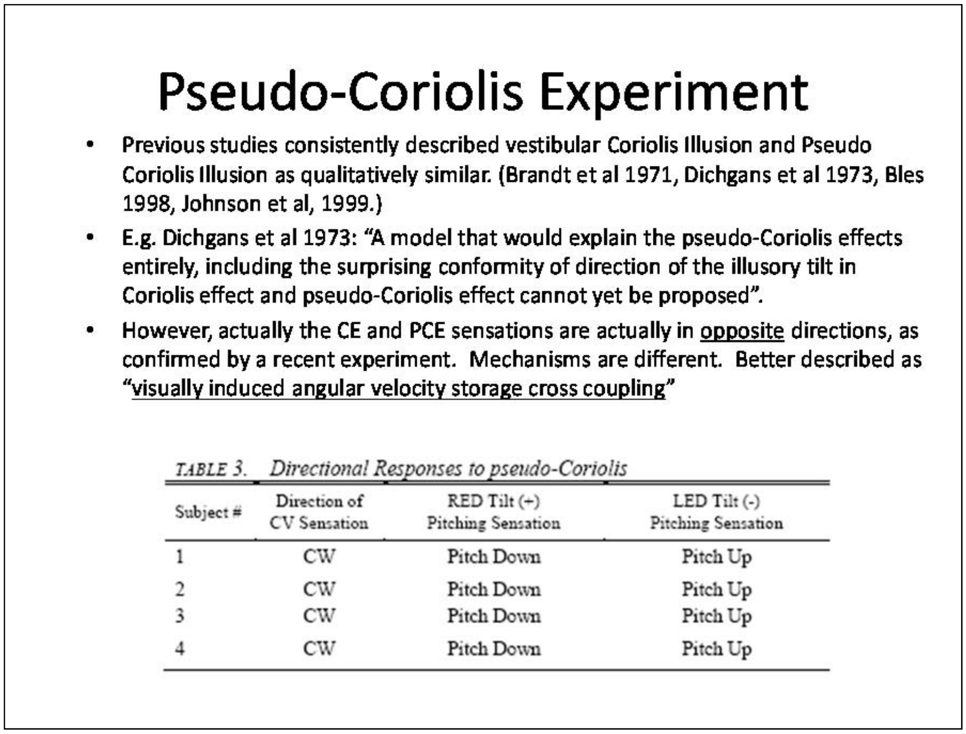
In 1974,Fred said…

When the head is tilted during optokinetic stimulation, the perceptual effects include an apparent tilt, dizziness and nausea comparable to vestibular Coriolis cross-coupling effects. This has been called the Pseudo-Coriolis Effect, but it is probably more analogous to the Purkinje (1820) effect which is caused by a head movement during a post-rotational SCC response….When the head is tilted the head fixed [diminishing semicircular canal] vector moves with the head..and tumbling sensations occur, but these conflict with the change –in-position information from the gravireceptors

In the pseudo-coriolis effect, the optokinetic aftereffects <u>locate a velocity vector relative to the head which moves with the head to produce a tumbling sensations</u> and nausea as the gravity receptors ..again do not provide synergistic change in orientation signals….

Guedry, FE, (1974) The Psychophysics of Vestibular Sensation. Chapter 1 in Kornhuber Handbook of Sensory,

Slide 25



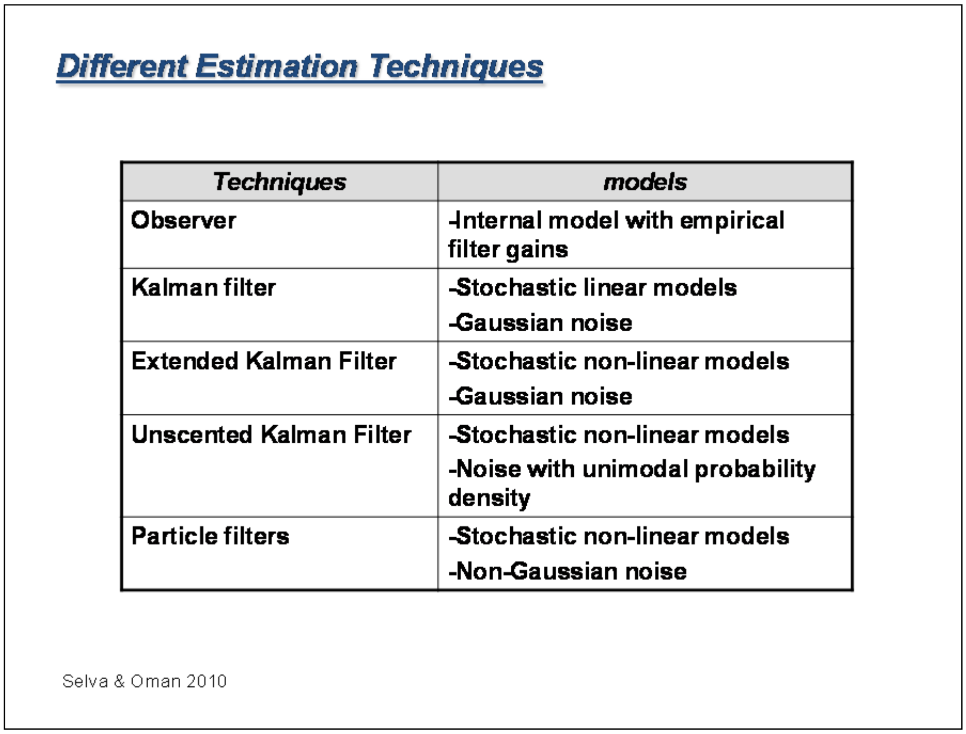
Pseudo-Coriolis Experiment

- **Previous studies consistently described vestibular Coriolis Illusion and Pseudo Coriolis Illusion as qualitatively similar. (Brandt et al 1971, Dichgans et al 1973, Bles 1998, Johnson et al, 1999.)**
- **E.g. Dichgans et al 1973: "A model that would explain the pseudo-Coriolis effects entirely, including the surprising conformity of direction of the illusory tilt in Coriolis effect and pseudo-Coriolis effect cannot yet be proposed".**
- **However, actually the CE and PCE sensations are actually in <u>opposite</u> directions, as confirmed by a recent experiment. Mechanisms are different. Better described as "<u>visually induced angular velocity storage cross coupling</u>"**

TABLE 3. Directional Responses to pseudo-Coriolis

Subject #	Direction of CV Sensation	RED Tilt (+) Pitching Sensation	LED Tilt (-) Pitching Sensation
1	CW	Pitch Down	Pitch Up
2	CW	Pitch Down	Pitch Up
3	CW	Pitch Down	Pitch Up
4	CW	Pitch Down	Pitch Up

Slide 26

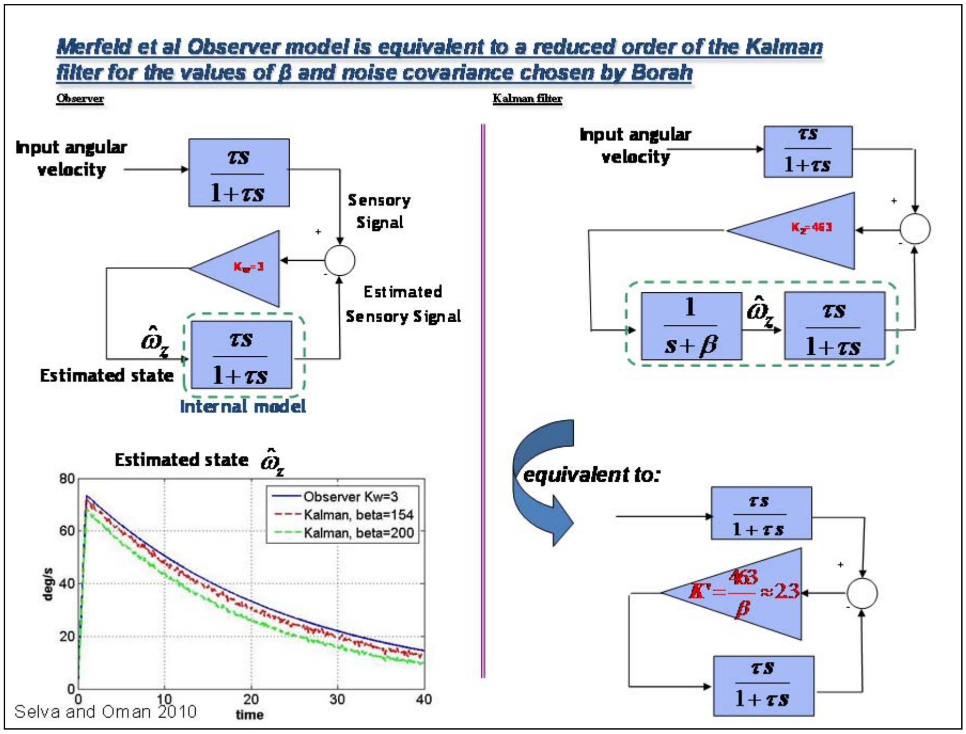


Different Estimation Techniques

Techniques	*models*
Observer	-Internal model with empirical filter gains
Kalman filter	-Stochastic linear models -Gaussian noise
Extended Kalman Filter	-Stochastic non-linear models -Gaussian noise
Unscented Kalman Filter	-Stochastic non-linear models -Noise with unimodal probability density
Particle filters	-Stochastic non-linear models -Non-Gaussian noise

Selva & Oman 2010

Slide 27



Merfeld et al Observer model is equivalent to a reduced order of the Kalman filter for the values of β and noise covariance chosen by Borah

Selva and Oman 2010

Slide 28

Ecologic Basis for KF parameters ?

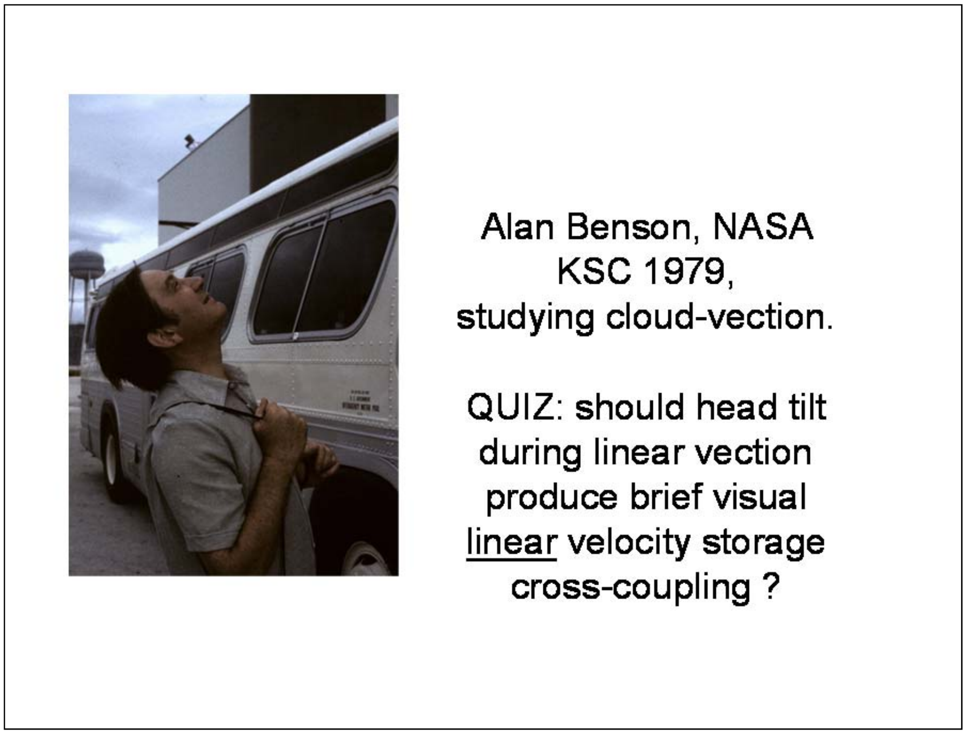
- Borah et al (1979) adjusted KF process and measurement noise covariances and process noise bandwidth to fit experimental data – they were considered free parameters.
- But are they free ? Shouldn't process noise covariance and bandwidth reflect motions of daily life ? E.g. Locomotion to 2-4 hz, yaw head movement amplitudes to 200 deg/sec ? If so, then process noise covariance (600) and bandwidth (25 rad/sec) can be estimated.
- Exposure to higher bandwidth motion lowers Kalman gain and shortens model time constants.
- Measurement noise percolates through KF to produce noise in angular velocity estimate. Shouldn't this noise correspond approximately to human angular motion threshold of 2 deg/sec? If so, measurement noise covariance (.06) can be back estimated.
- Given the process noise/measurement noise covariance ratio (10^4), solving for Kalman gain (78), close to Merfeld & Borah.

Slide 29

For discussion

- Internal models must also capture the subject's knowledge of what motions are deterministically possible. (e.g. Rader, 2009)
- Do aeronautical "leans" illusions "latch" – i.e. last for many minutes ? If so why are gravireceptor cues apparently being ignored ?
- Observer typically predicts larger linear displacements than are usually described. Path integration model needs further development and validation. Does path integration fail when cue conflicts are large ?

Slide 30



Alan Benson, NASA
KSC 1979,
studying cloud-vection.

QUIZ: should head tilt
during linear vection
produce brief visual
linear velocity storage
cross-coupling ?

Slide 31

Question and answer session

[No audience questions, but Dr. Charles Oman suggested some items for later discussion.]

[Oman] I have some issues I want to discuss. Let me suggest what we might discuss later, in that Andrew Rader (who's another Ph.D. student of mine), working with Dan [Merfeld], used Mike's [Newman] Observer model to model perceptions of motion during dynamic swinging [Rader, Oman, and Merfeld, 2009], and he compared the results of that model with a Jean Laurens particle model [Laurens and Droulez, 2007], and actually Observer did better, provided that they included in the model knowledge of what motions are possible. The subject knew in this case that only certain kinds of motion could be made. One question that I've been thinking about (and this is probably a segway into Brad's [McGrath] talk a little bit), we've been asking ourselves, "Can we model aeronautical leans illusion?" I think most of you probably know what that is, and we've been trying to back-track in the literature and find descriptions of the dynamics of the leans illusion, and also we've been talking to several dozen pilots about this, and the thing that concerns us that isn't matched by the existing model, is that we're hearing stories that occasionally the leans illusions latch. In other words, you roll out of a procedure turn and the subjective vertical goes over to one side, but it stays over there and doesn't come back to be aligned with your body with the somatogravic time constant. What's going on there? One interpretation is that gravi-receptor cues are being ignored, but if so, why? That's probably something that Larry [Young] was talking about, gain switching.

Then as far as the limbic system and modeling displacement, Observer, as it is now, typically is predicting larger linear displacements than are usually described, this is always implicit in

Dan’s [Merfeld] model. Dan’s model produced accelerations, but no one ever integrated them out to see what the implied positions are. So this part of it needs further development, and the same question there: does path integration fail when cue conflicts are large [slide 30, page 69]?

[Slide 31, page 70] Alright, here’s the quiz to see if you understood what I was talking about, here’s Alan [Benson] at Kennedy Space Center in 1979 and he’s studying cloud vection. I don’t know if he’s looking up wind or down wind, let’s say he’s looking down wind so he’s feeling forward motion, if he makes a pitch up or pitch down head movement, should he feel the effects of a brief linear visual velocity storage cross-coupling? Is there a linear component to the pseudo Coriolis effect that I described earlier? I’d like to hear some insightful answers to that.

The Shape of Self-Motion Perception − Jan Holly

[Slide 1, page 78] I'm going to state the take-away message from this talk, right here at the beginning: that perception is shaped by experience from the 3-D world [slide 2, page 78]. In fact, Larry [Young] mentioned this as well, in terms of expectations. Depending on the sensory input what we perceive tends toward the expected value. If you want to say it in Bayesian modeling terms or Kalman filters -- we use this to make sense of experimental results. Chuck [Oman] has given the perfect introduction to some of the experimental work that is going to run through this talk, I'll talk about a few other motions as well [starting with] this particular paper [slide 3, page 79]... I'm so excited that all four authors are in the room here.

This paper [Guedry, Rupert, McGrath, and Oman, 1992] was inspiring to me when I entered the field because it demonstrated perceptions that were not completely easy to explain. This was in a centrifuge -- there were a number of different ones, but I'll talk about a subject who is upright facing forward, and centrifuge and the carriage tilts to keep the subject aligned with (at the time some papers and Fred [Guedry] called this) the resultant linear acceleration vector; it is also called the "GIF" [Gravito-inertial force]. I call it the "GIA" [Gravito-inertial acceleration]. In any case, some of the results [are] here, I extracted a few passages out of the paper [slide 4, page 79]. First of all, the perceptional effects in deceleration were much stronger than during acceleration. Particularly in pitch and during deceleration, there is a sensation of tumbling to a face-down or head-down position while rising or ascending from the Earth. The experience during deceleration was confusing like that, it was unreal and only happening in my brain and in fact I have an old [hard] copy of this paper here [with me]. The mention of the paradoxical perception is also described in the paper. I'll read another passage here, that the reports of dizziness or confusion usually meant that the subject experienced the paradoxical perception of motion velocity without appropriate change in angular position.

"Typically, the perception consisted of having pitched forward to a nose-down position relative to gravity, but with continuing tumble velocity even though the pitched position remained nose-down," [Guedry, Rupert, McGrath, and Oman, 1992, p 266]. So this is what people were talking about earlier, actually.

How do we explain these results? Since people have talked about modeling already today, I better explain what I am going to talk about is similar and [yet] different to what other people have talked about. First of all, I am specifically focusing on perception; I'm not going to talk about the eye movements, which have been found to be different than the perception as [has] been discussed in some cases. I'm also specifically talking about perception without vision available and whole-body passive motion perception. The other main focus that I have is on complex motion perception rather than repeating other people's work where they do very careful quantitative fits, to say, VOR data and getting the parameters tuned properly given the particular data. I'm focusing more on the big picture, the overall, can we just explain the general perception, the direction of the perception, the shape of the perception that's going on and specifically in 3-D.

I just want to show this briefly, this was also shown by Chuck [Oman] [slide 5, page 80]. In the paper [referencing slide 5] there is some analysis of why subjects felt more tumbling during deceleration than acceleration and so on. I want to focus a little bit on during the acceleration. The angular velocity that increases initially the most is the z-axis angular velocity. Whereas, deceleration, it's the y-axis angular velocity that increases first, the pitch. (Chuck [Oman] already showed this but you can look at the changing linear vector along with the changing angular vector). So there is some discussion in the paper about how this combination of vectors might make sense [McGrath, Guedry, Oman, and Rupert, 1995]. I looked at this paper and said, "Well, okay, could we put this together, this analysis of vectors together in a three-dimensional model." Of course, various models have been talked about. I'm going to talk about it not from a historical viewpoint but from a logical viewpoint. From a logical viewpoint, if you look at all these vectors the first thing that the human nervous system grows up in [is] 3-D [and] has to do with the laws of physics, of course, [the human] understands acceleration, understands Coriolis cross-coupling, hopefully living in a 3-D world. We grow up within the 3-D laws of physics, so the very first thing to do to try to explain what's going on is a model that contains the 3-D laws of physics. These are the 3-D laws of physics, you don't need to worry about them but I just want to point out there are equations you can write down [slide 6, page 80]. [This is] the way you want to use these if you want to predict: a perfect processor of acceleration information would perceive during deceleration of a centrifuge perfect[ly], as it perfectly integrates in the laws of physics [slide 7, page 81]. The key is to initialize it with the subject's perceived orientation. Here, the subject's perceived orientation during constant velocity is upright. You can also do it with a subject's perceived tilt [slightly] pitch back, which is commonly perceived, but you're going to get basically the same result. Here in the upper left is just to show you what subject we are looking at, this person down in the lower left is the one that is actually going to move. If you initialize it that way and you give the subject exactly all three degrees of freedom of linear and angular acceleration that are happening during the deceleration [of the] centrifuge, this is what the subject would perceive. This animation shows the rising from the Earth and pitching forward and tumbling. I should mention, Ian [Curthoys] gets the credit for starting my 3-D modeling [animations] because years ago he sent me a video of an animation of perception. So I gave this video to one of my research assistants and this is what my research assistant created. Ian's [Curthoy] subject looked like a male character in a tank top and so my research assistant said, "Well in Australia they have a male character in a tank top -- I'm going to make a female character wearing a turtle neck," so that's where this came from. (Obviously, as you see it has position and orientation output.)

The much stronger effects during acceleration are explained straightforwardly by 3-D laws of physics. I should also show an animation of the acceleration to compare but because the subject perceives their correct orientation at the beginning, that simulation would just show the subject's actual motion, which doesn't have any pitch [slide 8, page 81]. This explains why there is more pitch perception during deceleration. As you notice, the description [involves] tumbling to a face-down or head-down position while rising from the Earth. Well, we got the rising from the Earth, but the tumbling to a face-down position -- this subject did not end up looking like they were facing down. If we really want to model the perception somehow the model has to demonstrate that they end up feeling face-down or head-down. The next step, is to say, "How can we do that?"

This is [a] classic [approach]… [to] add to this model known perceptional properties [slide 9, page 82]. The perceived vertical tends toward the GIA vector. In terms of our 3-D experiences, a sustained linear vector is usually gravity (so we tend to interpret it that way), and [on the slide are] a couple other classic known properties of perception (that of course Fred [Guedry] and others here have studied): that perceived angular velocity decays, as does perceived linear velocity. The time constant on linear velocity is a bit hard to measure, and I'm glad Chuck [Oman] mentioned the linear translation issue, I think that is one big area of potential research (some research is obviously being done but a lot more could be done). [So we] add these properties to the model, and we end up with what I will call here a standard model [slide 10, page 82] (don't worry about the technicalities of this slide unless you are modeler).

A side remark: we were discussing earlier the reasons to do modeling. We have heard several reasons, but I want to point out another, [which is] not necessarily to [be able to] say you are successful when you match the data. Sometimes you can be successful even if you don't match the data because what the modeling does is it tests hypotheses. [Referring to the slide], like these up here [gestures to same slide concerning classical known perceptual properties]. You can then test these hypotheses by inserting these hypotheses into a model and then doing the simulation. Then, that simulation is a success whether it matches the data or not. Either, it matches the data, and you say, "Great, my hypothesis seems reasonable" or it does not match and you have successfully identified a gap in our knowledge… "These are great hypotheses but now we know to look for another hypothesis or another explanation or to do another experiment." The modeling can guide experiments, so a lot of modeling can be successful.

How does this relate to other models? The cross-coupling stuff is implicitly in here as part of the laws of physics. We talked about internal models; Larry [Young] mentioned that the nervous system presumably has an internal model of its peripheral sensors. I don't go into any detail of how the peripheral sensors are modeled or anything in here. Basically, the goal here is not to figure out fluid dynamics of the semicircular canals. My goal here is to understand perception in general, going from what accelerations or what motions are going on to what is going to be perceived during this motion and why, in a general sense, we relate it to the real world and use [it] in a predictive way (within certain constraints).

The other things we talked about in the other models -- you can insert them into here and do a lot of fine tuning especially with VOR. The idea is exactly the same, this angular velocity with decay is the same thing that happens if you have a loop, and the loop could cause an additional gain. Those of you who are engineers know that anything that can be written as a loop can also be written without a loop. So that's basically what's going on here. Anyway, this captures those ideas.

Regardless of modeling, this is a test of whether those three hypotheses will fix the model of deceleration perception [slide 11, page 83]. So here's the new model. This person is without hair for a reason you'll see toward the end of the talk [laughter]. This is the person and this is the one that's going to start moving. So, same exact run of the centrifuge decelerates for nineteen seconds. Here they go [speaker starts animation of predicted perception at this point, as part of slide 11], so this was successful in some ways: it didn't keep on tumbling over and over, although there was this weird little turn at the end. We can say, "The tumbling to face-down was successful using the standard model that captures those known properties, but somehow it's turning toward the end and what's going on there [slide 12, page 83]?" Well, this is where I'm going to talk about several things. What are we missing? It actually could be that some subjects felt some turning like that towards the end and I would be interested in knowing [if] this happened [slide 13, page 84]. It's also possible the subject didn't feel this turning towards the end -- they felt that tumbling or face-down perception. I'm just going to throw out [i.e., propose] this idea (actually I mentioned it years ago): I think it's not too surprising that the beginning of the deceleration actually shapes the perception. Maybe what we should be doing is realizing that it's the pitch axis acceleration that's the strongest during deceleration, not during acceleration [Holly and Harmon, 2009]. Somehow, we need to be capturing this idea that the beginning should be enhanced. I have a figure from another paper, this happens to be for a 9.1 m radius centrifuge, but if you look at the right hand rule angular velocity vector for the first 6 seconds the first second is longer. These are not the magnitudes of angular velocity -- it's the order. It's very much a pitch stimulus; somehow we should be capturing this pitch stimulus and not treating later vectors equally with earlier vectors. We don't necessarily want to make a model that in the long run will only explain one thing so we want to compare with some other motions. In particular here -- acceleration upright centrifuge -- carriage remains upright at a vertical axis rotation.

Let's look at what the standard model would do with those. This [avatar] has hair [and] has some axes [slide 14, page 84]. (This is a number of years of research assistants making animations so you're seeing different generations of animations.) The standard model, the one that I showed you a minute ago and sort of the core of a lot of the models. [For] this person, their actual motion is to go around in a circle counter-clockwise with a radius of one meter which is actually what these squares are. This is the predicted perception by the standard model. Going forwards is expected, turning is expected but what's weird is they're actually going leftward instead of forward. So what this is saying is that the standard model predicts the turn, predicts the initial movement forward, but then has them going sideways, to the left.

It's interesting; I scoured the literature for any published data on perceived sideways motion during centrifuge runs. People focus so much on roll, (as many of you know) that I just couldn't find anything about or actual subject reports. So, Ian [Curthoy] was nice enough to let me go down to Australia, and we did some runs where subjects reported their full three-dimensional motion [Curthoys, 1996], you know in the tradition of Fred Guedry: "Report how you move, how you feel you're turning, tilting, moving," anything like that [slide 15, page 85]. I don't have time to go through all the details but basically these were done in several steps. It was a four-step acceleration, so we asked this [for these perceptions] in all steps of the acceleration. My group extracted out of this how much sideways, leftward, [or] rightward motion was reported during the acceleration. We had forward-facing, that's FF [in the slide], and backward-facing runs and discovered (as probably most of you who have ridden in centrifuges [know]), there wasn't much left-to-rightward motion reported, it was mostly forward motion, or backward if they were facing backwards. This basically confirmed what we suspected [based] upon, [the] standard model -- that this sideways motion wasn't completely capturing the subject reports.

So that's the centrifuge. Let's look at [the] off-vertical axis rotation [case]. Same thing, this is off-vertical axis rotation and here's what the standard model predicts the perception of off-vertical axis rotation is going to be [animation initiated on slide 16, page 85]. Those of you who know about off-vertical axis rotation, are probably saying, "This isn't quite right." Basically, this is a cone motion but the cone has its pivot in the wrong place. It's a pivot with a pivot at the top instead of at the bottom. It's got the tilt and it's got the translation and the pivot is at the top instead of at the bottom, and by the way we tried every set of parameter values [and] ended up proving that you cannot get a pivot at the bottom. This is what we all know as the perception during offward axis rotation, at least the most common perception [slide 17, page 86]. In fact, Scott Wood quantified this with phase reports during translation of the rotation and basically confirmed that the numerical timing of the perception actually matched the 3-D perception [Wood, 2002].

So what we're saying is that the standard model works for different components of the motion. It has worked for years for different components of the motion, whether it's the roll in the centrifuge or the amplitude of tilt in off-vertical axis rotation, or a lot of things but, as far as the full 3-D motion, the modeling finds some kind of gap in our knowledge. There is some type of gap in our knowledge in terms of the full 3-D picture of what we're perceiving. Looking at those three [cases reviewed], this is where I think we need a lot more data because this is just three complex motions [slide 18, page 86]. There are some commonalities, for example [in] the two centrifuges runs, it seems like the beginning of the motion may be shaping the perception. Perhaps the beginning should be weighting our perception more in our model than it is. Between the acceleration upright centrifuge and the off-vertical axis rotation, it turns out that the translation and perceived tilt are somehow linked. The results of other work show that -- if you say that during forward motion [in a centrifuge] that a subject is accustomed to a turn causing a centripetal acceleration (and that just means they are turning not moving sideways), then that makes much more sense. Or during off-vertical axis rotation: if a subject in everyday life is accustomed to a tilt being accompanied by translation in the same direction as [occurs when] we move around -- we don't usually go like this [Holly does a pure translation movement sideways to demonstrate translation without tilt] unless we're dancers or something.

That is a commonality there. In general, my way of saying this would be "[That] perception [is] shaped by experience from the 3-D world." If you take that idea [and] put it into the model (I'll call this a whole-motion model -- meaning take the 3-D motion as a whole) [then look at] prediction of acceleration perception (this is back to the original Guedry, Rupert, McGrath, and Oman paper), what will that predict [slide 19, page 87]? If you say that instead of z-axis /yaw motion being the predominant stimulus, there is more pitch (I included roll in here too because it is sort of secondary), then what is the perception? Well, you get ascent from the Earth and tilt forward, pitch forward, essentially to a face-down orientation. I might mention a lot of this translation part is still [preliminary], I didn't do anything special with it because there's not enough data to say what we should really do with the translation part of the model. With the upright centrifuge during acceleration you can do the same thing, [you can] say the initial direction stimulus is forward and that centripetal acceleration should be interpreted as such [Holly, Vrublevskis, and Carlson, 2008] [slide 20, page 87]. By the way, these all still have the same decay of acceleration, decay of angular perception, tilt according to the GIA, and so on.

So that one now moves forward and in terms of the off-vertical axis rotation, it now has the cone going the right way. I might also mention that previous off-vertical axis rotation has some vertical motion in it [Holly, Wood, and McCollum, 2010] [slide 21, page 88]. Again, a translation issue, I know there's a model by Haslwanter where, for the eye movements, they had to make an adjustment to take that into account. Basically, the whole 3-D motion model will [take] everything into account, but then we still have a mystery about this paradoxical deceleration [slide 22, page 88]. If you were looking really closely at that early model, you can extract the angular velocity separately from the change in orientation [slide 23, page 87]. If the change in orientation is affected by the GIA (and this is what has been demonstrated in all of these animations I've shown), [and] if you extract the angular velocity out as a separate entity, you can model them separately and this is why that early subject was bald, because our group wanted to put stripes on the subject [i.e., his head] to indicate the change in angular velocity separately from the change in orientation [Holly, and Harmon, 2009] [slide 24, page 89]. This is what we did a few years ago. If you do that, this person is actually moving in the same way they were a second ago, but now we've got the angular velocity shown by the stripes.

So, we're finally getting somewhere here. The paradoxical model can explain that. That's all the modeling that I want to show here [slide 25, page 90]. In summary, explaining this perception of complex motions requires properties unique to 3-D motion perception, things that we hadn't been able to say when looking at one component at a time and trying to tack them together [slide 26, page 90]. It's really a full three-dimensional picture. Again, perception is shaped by experience from the 3-D world.

In conclusion, bringing you back to Fred Guedry, who was [the] inspiration of all of this [type of work], Fred Guedry's tradition of looking at motion as a three-dimensional whole continues to advance our understanding of 3-D self-motion or perception. I think it would be great to have a lot more experimental data on the full three-dimensional perception of all kinds of complex motion -- anything we can get.

Thanks to a whole lot of people [slide 27, page 91], a lot of these are my research assistants involved in animations, but [also] Ann [Burgess], Omino [Abedin], Ian [Curthoys] in Australia, and co-authors, Jim McCollum, Scott Wood, etc. Thank you.

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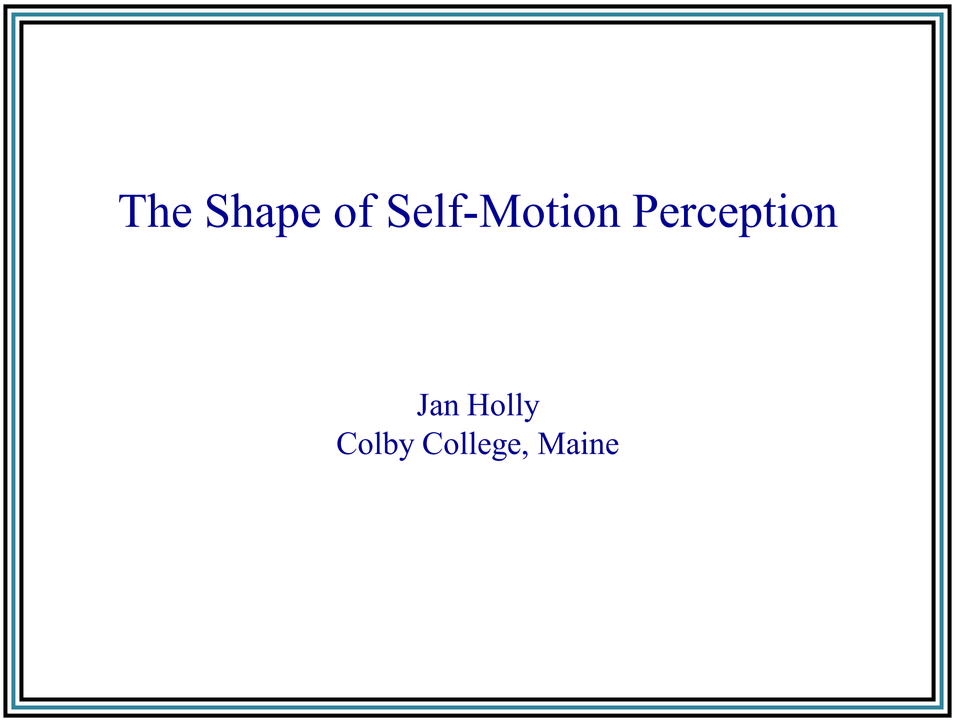
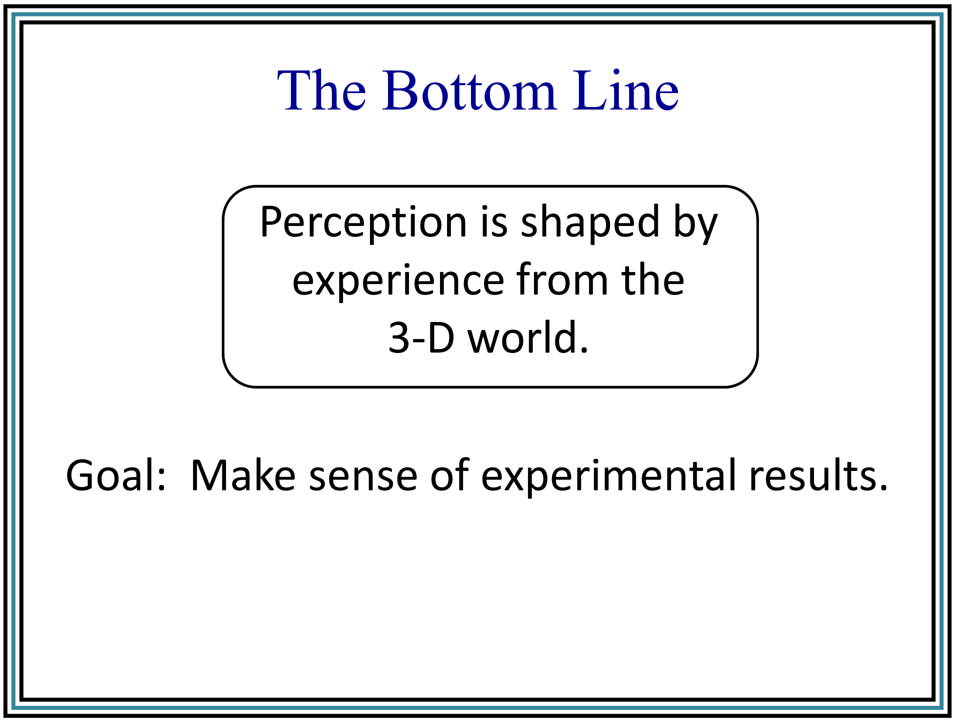


The Shape of Self-Motion Perception

Jan Holly
Colby College, Maine

Slide 1

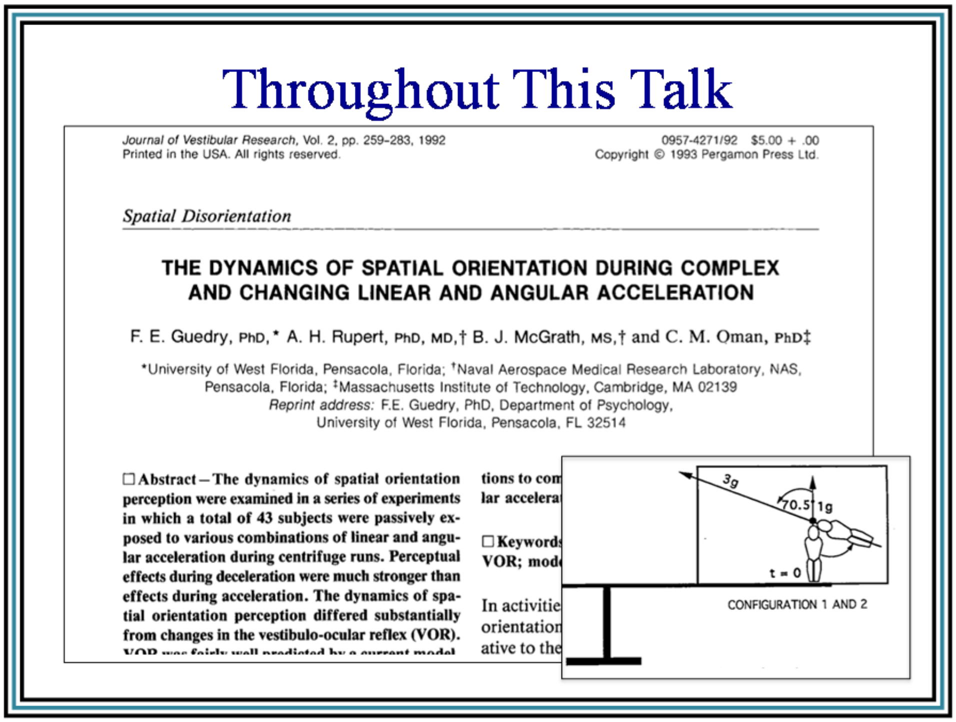


The Bottom Line

Perception is shaped by experience from the 3-D world.

Goal: Make sense of experimental results.

Slide 2



Throughout This Talk

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Spatial Disorientation

THE DYNAMICS OF SPATIAL ORIENTATION DURING COMPLEX AND CHANGING LINEAR AND ANGULAR ACCELERATION

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☐ Abstract – The dynamics of spatial orientation perception were examined in a series of experiments in which a total of 43 subjects were passively exposed to various combinations of linear and angular acceleration during centrifuge runs. Perceptual effects during deceleration were much stronger than effects during acceleration. The dynamics of spatial orientation perception differed substantially from changes in the vestibulo-ocular reflex (VOR). VOR was fairly well predicted by a current model

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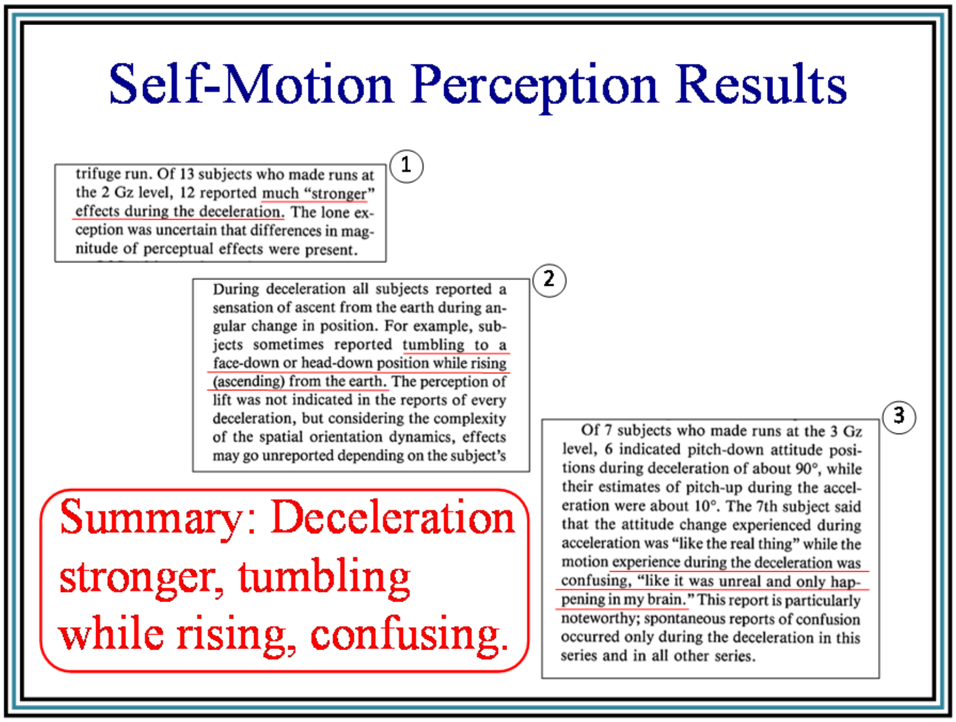
Slide 3



Self-Motion Perception Results

①

trifuge run. Of 13 subjects who made runs at the 2 Gz level, 12 reported much "stronger" effects during the deceleration. The lone exception was uncertain that differences in magnitude of perceptual effects were present.

②

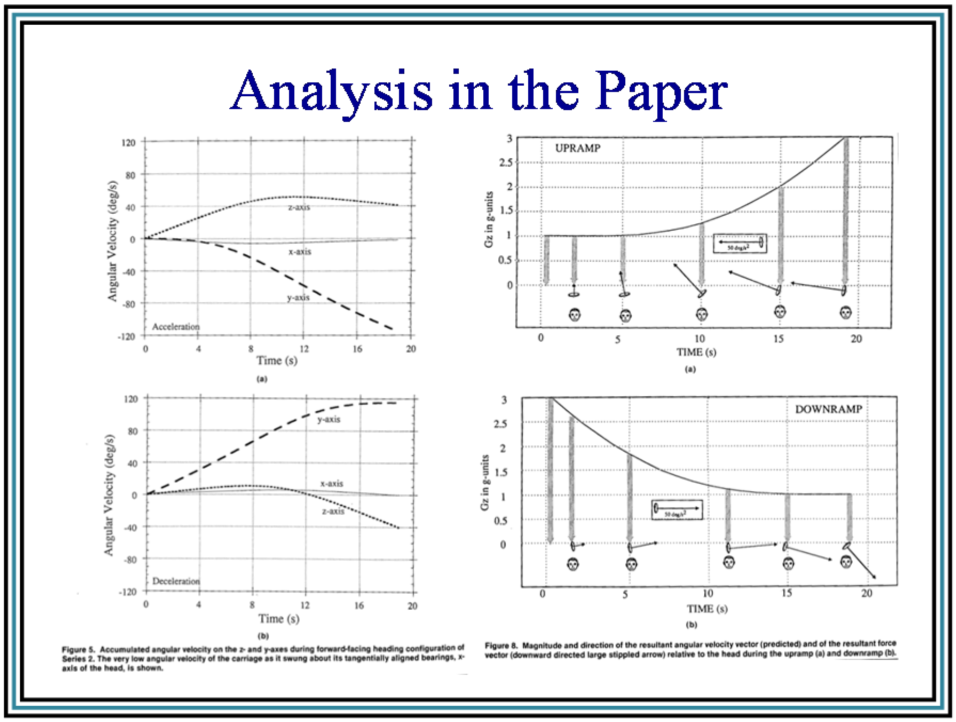
During deceleration all subjects reported a sensation of ascent from the earth during angular change in position. For example, subjects sometimes reported tumbling to a face-down or head-down position while rising (ascending) from the earth. The perception of lift was not indicated in the reports of every deceleration, but considering the complexity of the spatial orientation dynamics, effects may go unreported depending on the subject's

③

Of 7 subjects who made runs at the 3 Gz level, 6 indicated pitch-down attitude positions during deceleration of about 90°, while their estimates of pitch-up during the acceleration were about 10°. The 7th subject said that the attitude change experienced during acceleration was "like the real thing" while the motion experience during the deceleration was confusing, "like it was unreal and only happening in my brain." This report is particularly noteworthy; spontaneous reports of confusion occurred only during the deceleration in this series and in all other series.

Summary: Deceleration stronger, tumbling while rising, confusing.

Slide 4



Analysis in the Paper

Figure 5. Accumulated angular velocity on the z- and y-axes during forward-facing heading configuration of Series 2. The very low angular velocity of the carriage as it swung about its tangentially aligned bearings, x-axis of the head, is shown.

Figure 8. Magnitude and direction of the resultant angular velocity vector (predicted) and of the resultant force vector (downward directed large stippled arrow) relative to the head during the upramp (a) and downramp (b).

3-D Laws of Physics

$$\frac{d^h\vec{i}_E}{dt} = {}^h\vec{i}_E \times {}^h\vec{\omega}$$

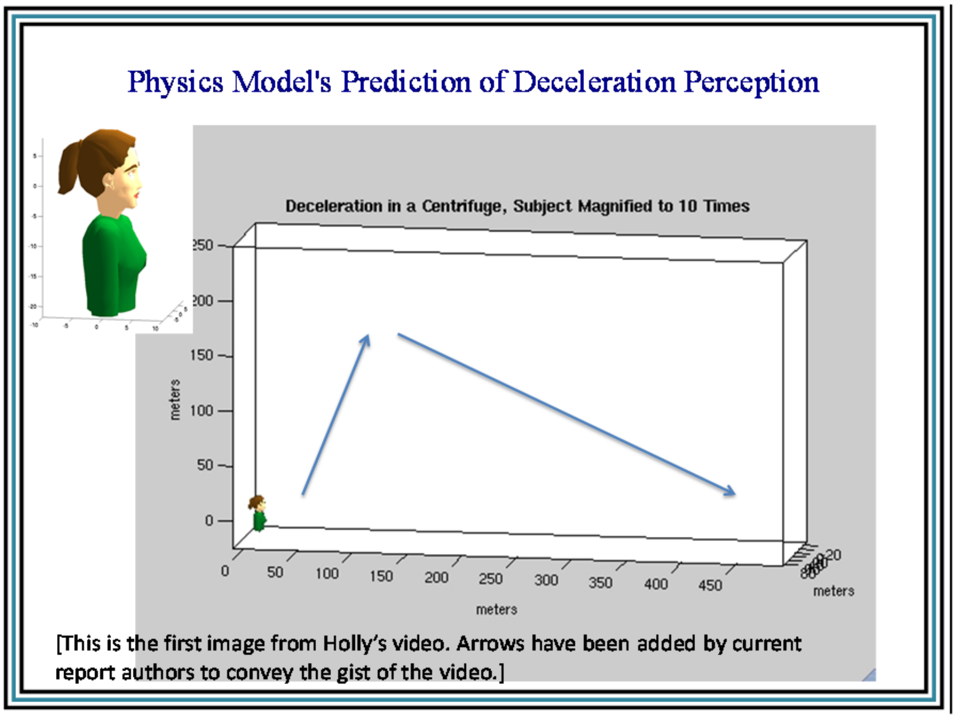
$$\frac{d^h\vec{j}_E}{dt} = {}^h\vec{j}_E \times {}^h\vec{\omega}$$

$$\frac{d^h\vec{k}_E}{dt} = {}^h\vec{k}_E \times {}^h\vec{\omega}$$

$$\frac{d\vec{r}}{dt} = {}^E\vec{v}$$

$$\frac{d^h\vec{\omega}}{dt} = {}^h\vec{\alpha}$$

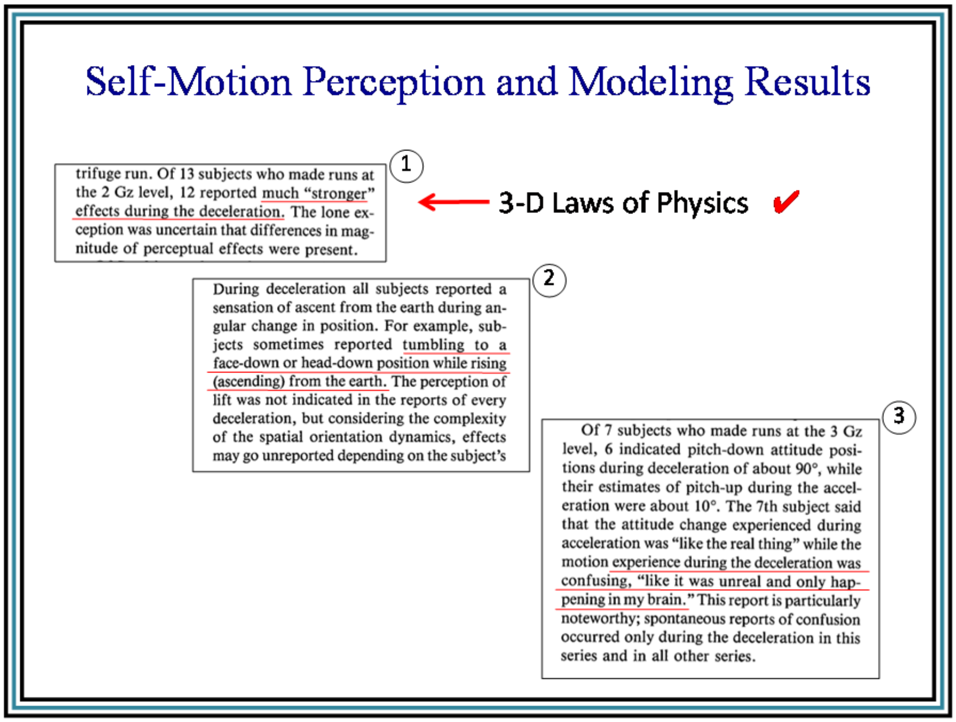
$$\frac{d^E\vec{v}}{dt} = S^h\vec{A} - {}^E\vec{g}$$



Physics Model's Prediction of Deceleration Perception

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

Slide 7



Self-Motion Perception and Modeling Results

① trifuge run. Of 13 subjects who made runs at the 2 Gz level, 12 reported much "stronger" effects during the deceleration. The lone exception was uncertain that differences in magnitude of perceptual effects were present.

← 3-D Laws of Physics ✔

② During deceleration all subjects reported a sensation of ascent from the earth during angular change in position. For example, subjects sometimes reported tumbling to a face-down or head-down position while rising (ascending) from the earth. The perception of lift was not indicated in the reports of every deceleration, but considering the complexity of the spatial orientation dynamics, effects may go unreported depending on the subject's

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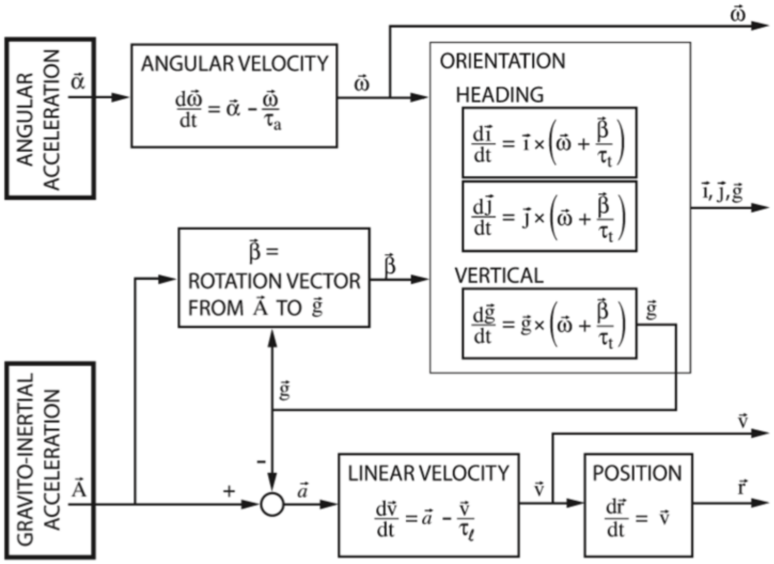
Slide 8

Add Known Perceptual Properties:

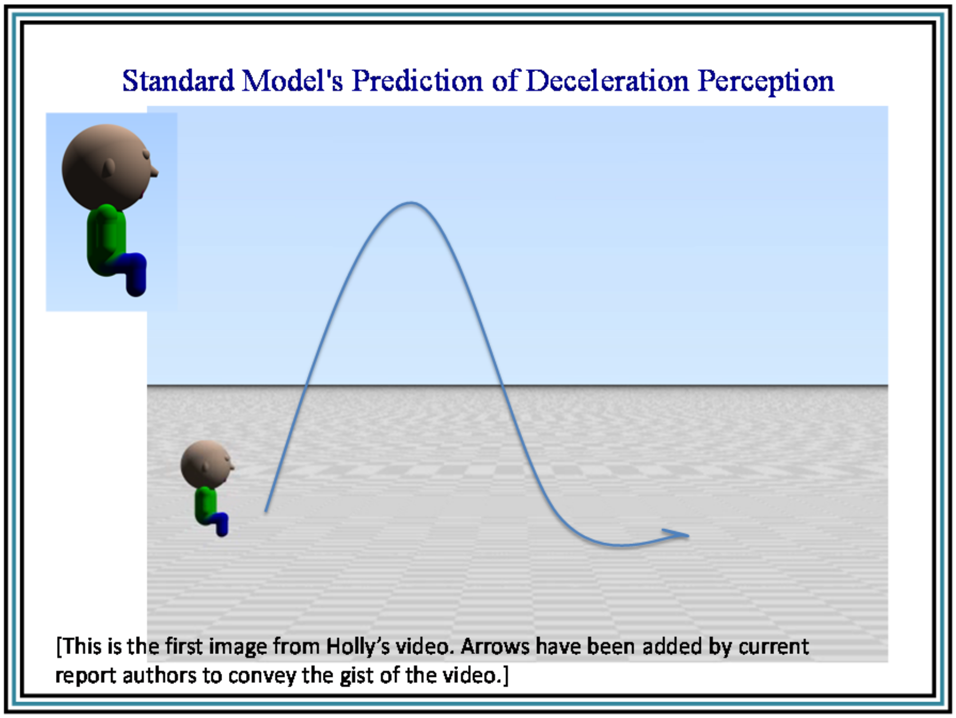
- Perceived vertical tends toward the GIA (gravito-inertial acceleration) vector.
- Perceived angular velocity decays.
- Perceived linear velocity decays.

Slide 9

Standard Model



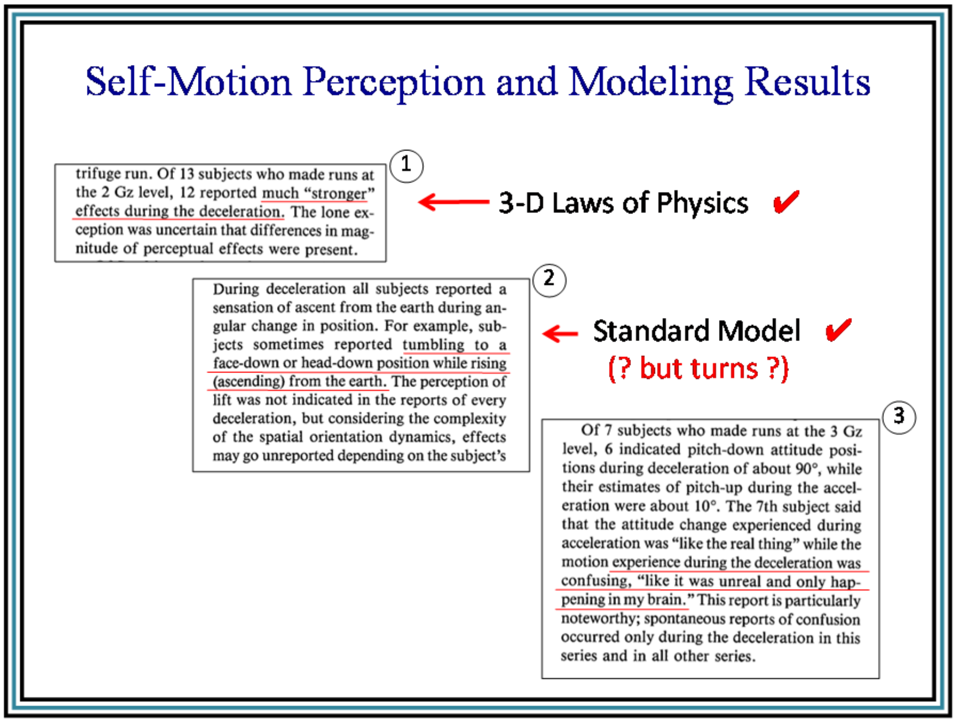
Slide 10



Standard Model's Prediction of Deceleration Perception

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

Slide 11



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(? but turns ?)

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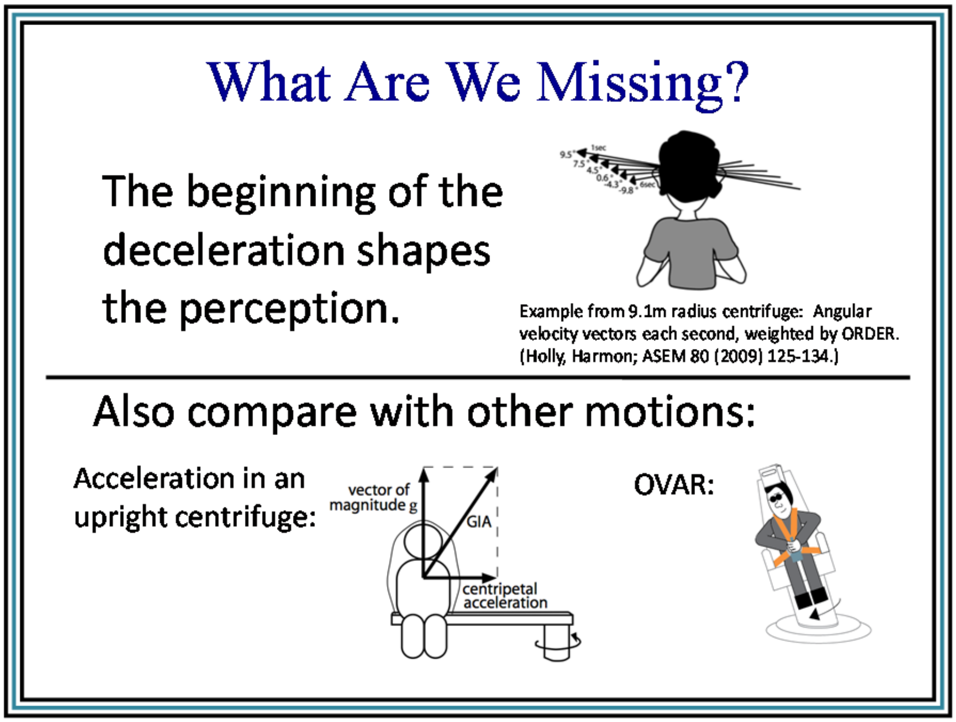
Slide 12



What Are We Missing?

The beginning of the deceleration shapes the perception.

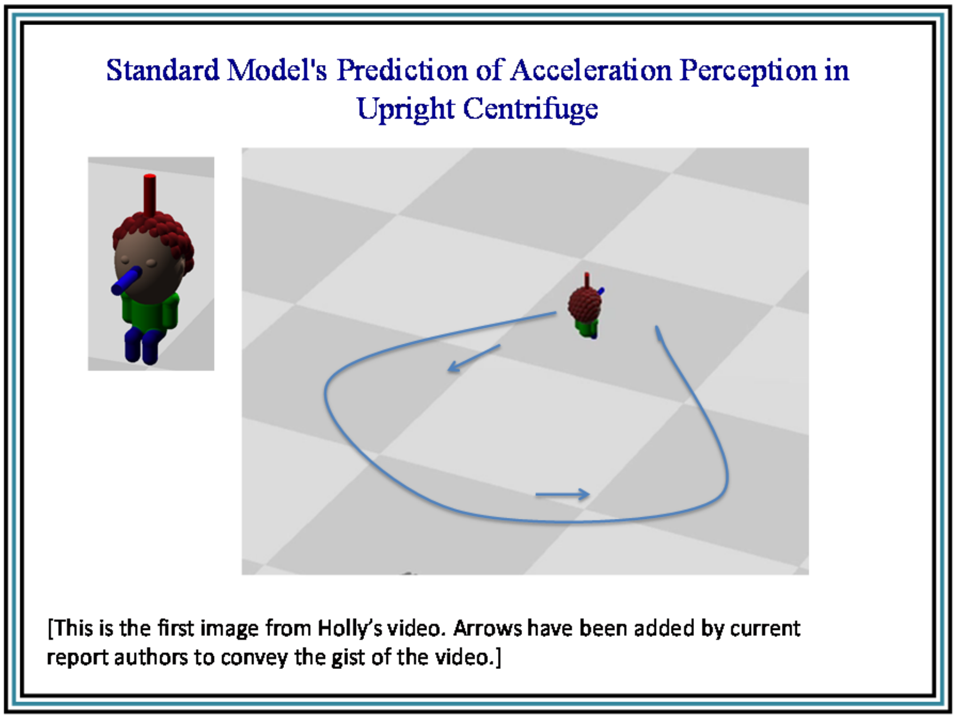
Example from 9.1m radius centrifuge: Angular velocity vectors each second, weighted by ORDER. (Holly, Harmon; ASEM 80 (2009) 125-134.)

Also compare with other motions:

Acceleration in an upright centrifuge:

OVAR:

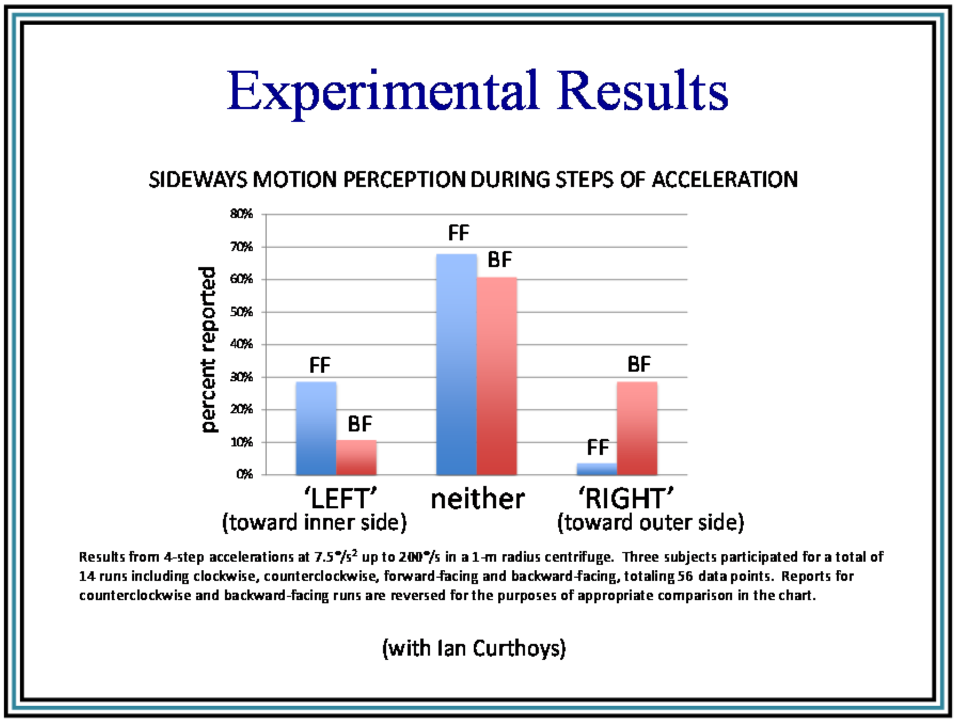
Slide 13



Standard Model's Prediction of Acceleration Perception in Upright Centrifuge

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

Slide 14



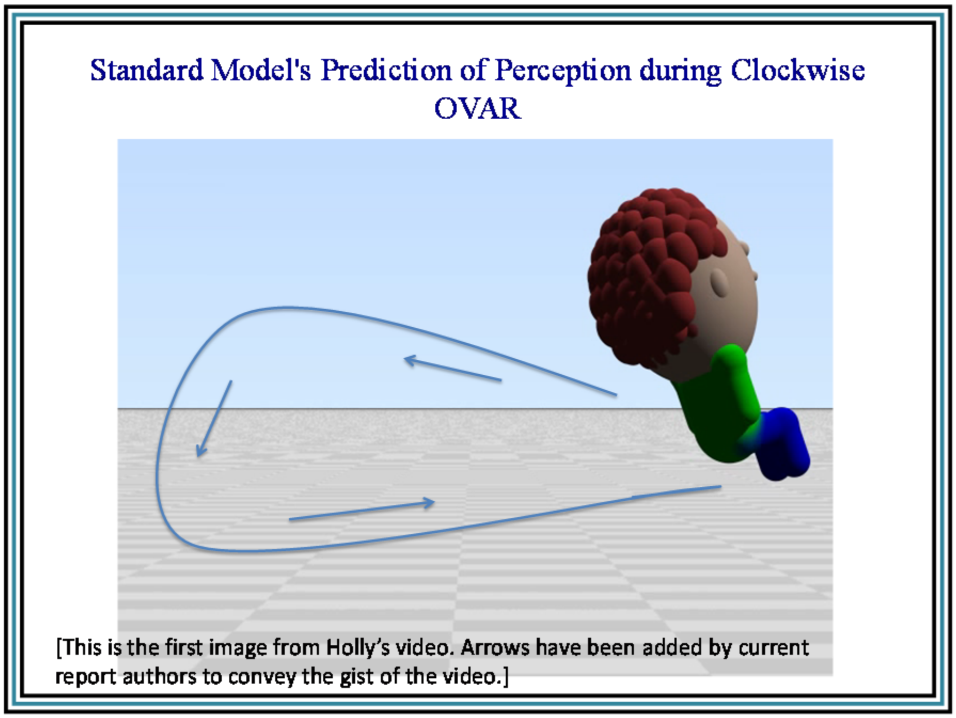
Experimental Results

SIDEWAYS MOTION PERCEPTION DURING STEPS OF ACCELERATION

Results from 4-step accelerations at $7.5°/s^2$ up to 200°/s in a 1-m radius centrifuge. Three subjects participated for a total of 14 runs including clockwise, counterclockwise, forward-facing and backward-facing, totaling 56 data points. Reports for counterclockwise and backward-facing runs are reversed for the purposes of appropriate comparison in the chart.

(with Ian Curthoys)

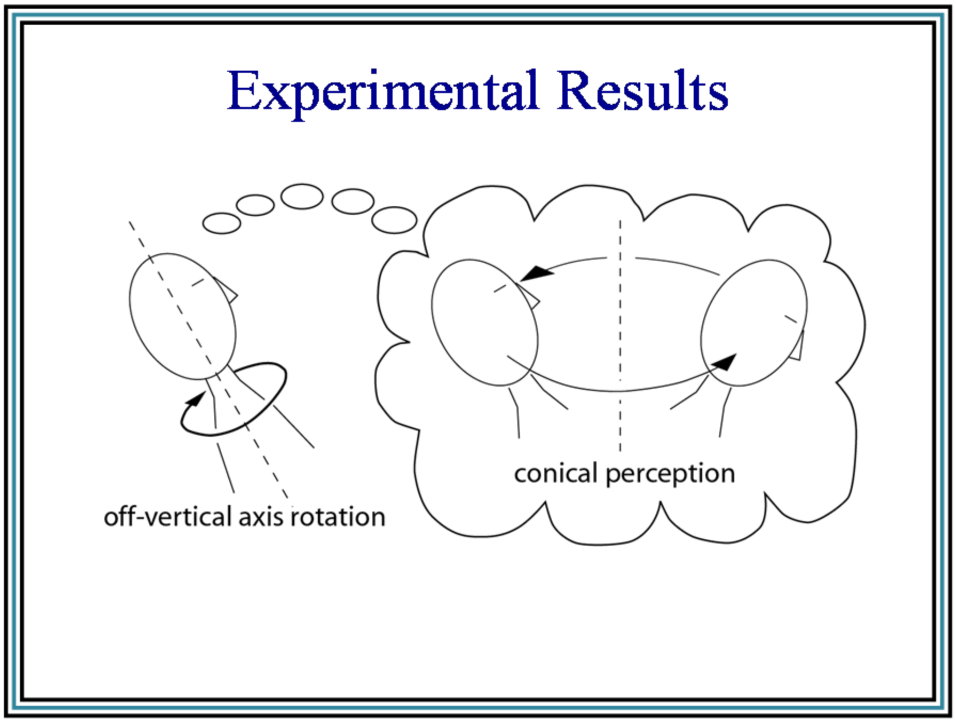
Slide 15



Standard Model's Prediction of Perception during Clockwise OVAR

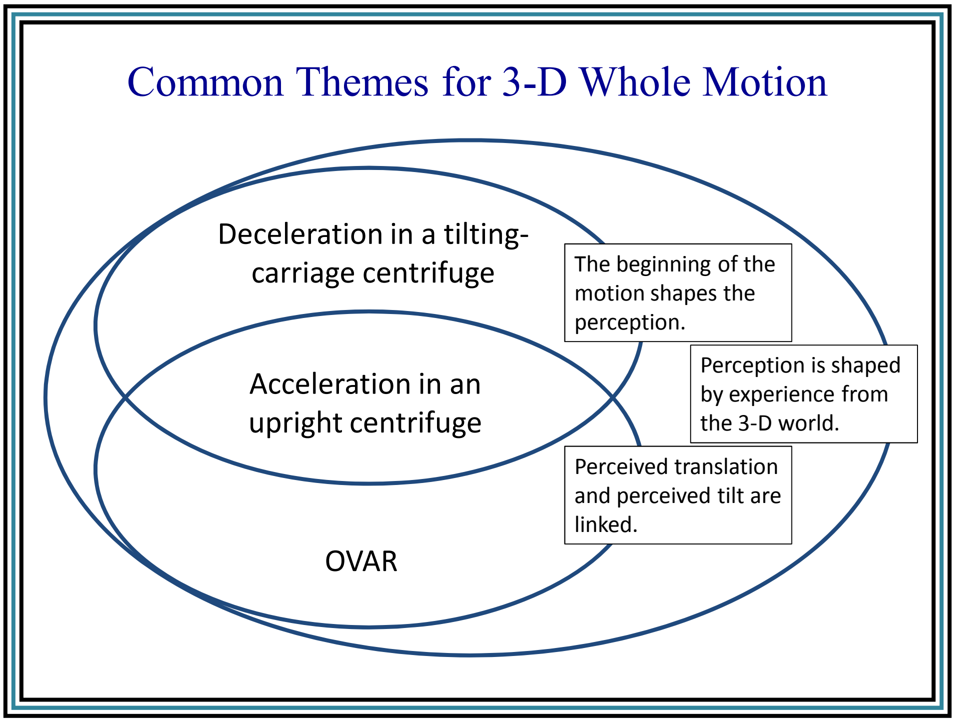
[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

Slide 16



Experimental Results

Slide 17



Common Themes for 3-D Whole Motion

Deceleration in a tilting-carriage centrifuge

Acceleration in an upright centrifuge

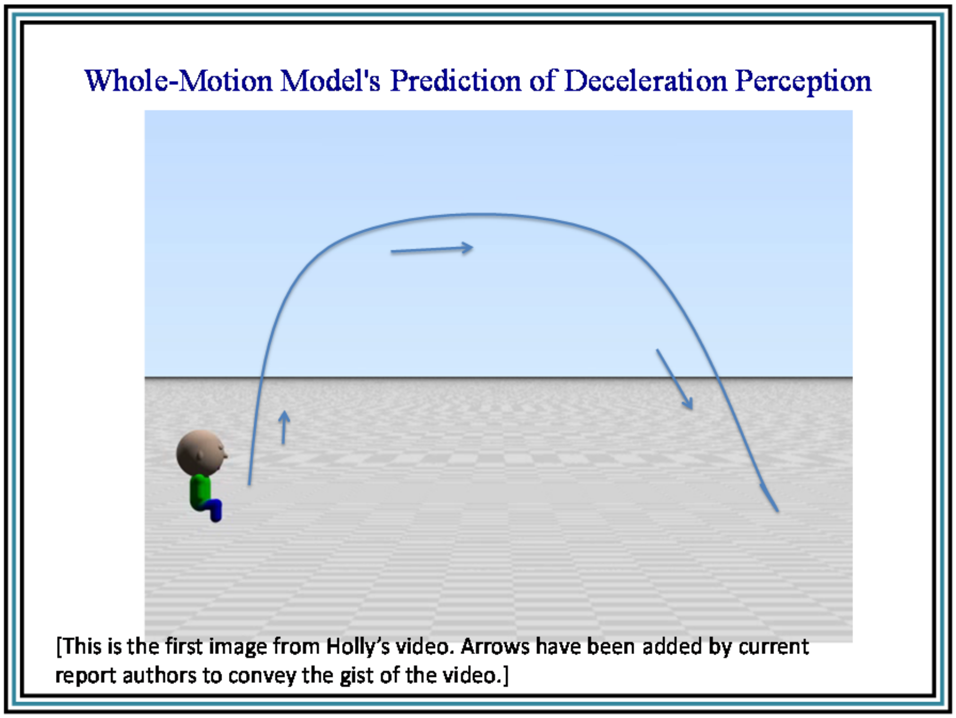
OVAR

The beginning of the motion shapes the perception.

Perception is shaped by experience from the 3-D world.

Perceived translation and perceived tilt are linked.

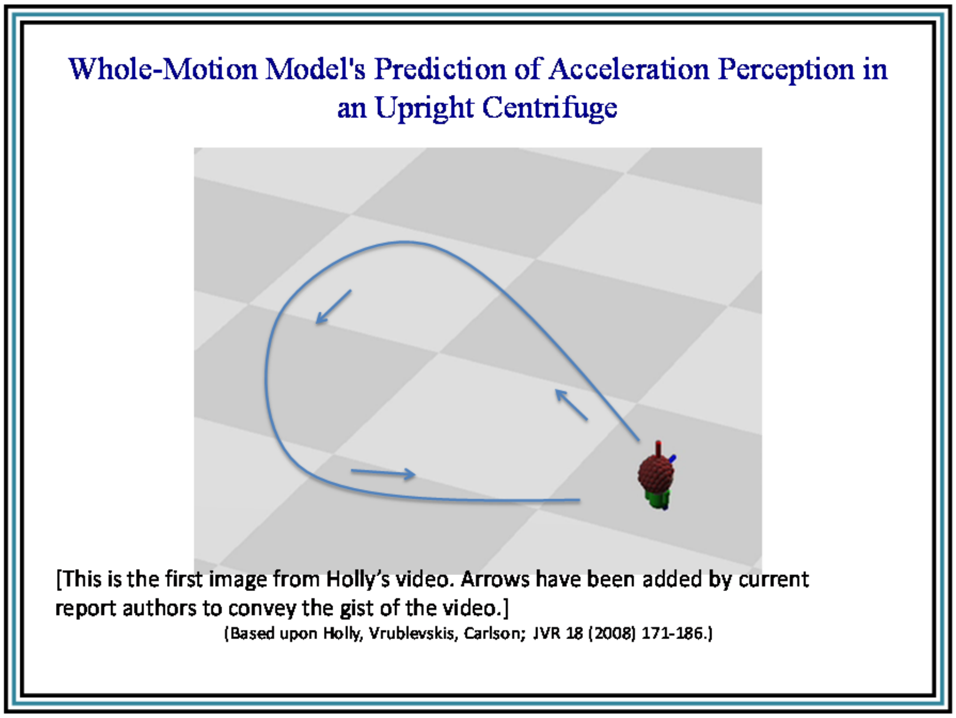
Slide 18



Whole-Motion Model's Prediction of Deceleration Perception

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

Slide 19

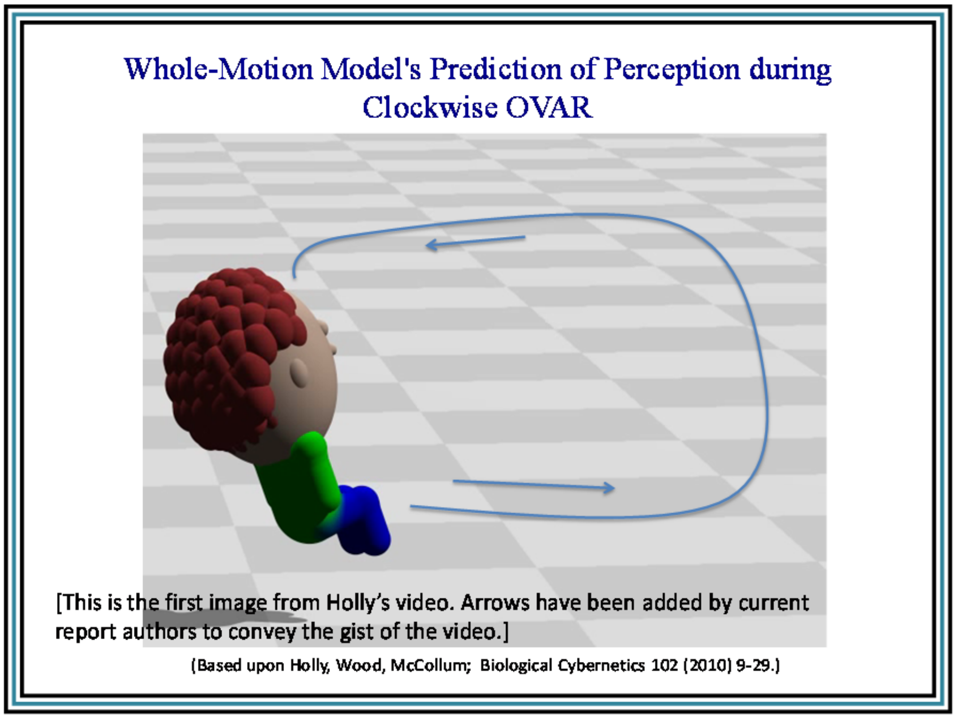


Whole-Motion Model's Prediction of Acceleration Perception in an Upright Centrifuge

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

(Based upon Holly, Vrublevskis, Carlson; JVR 18 (2008) 171-186.)

Slide 20

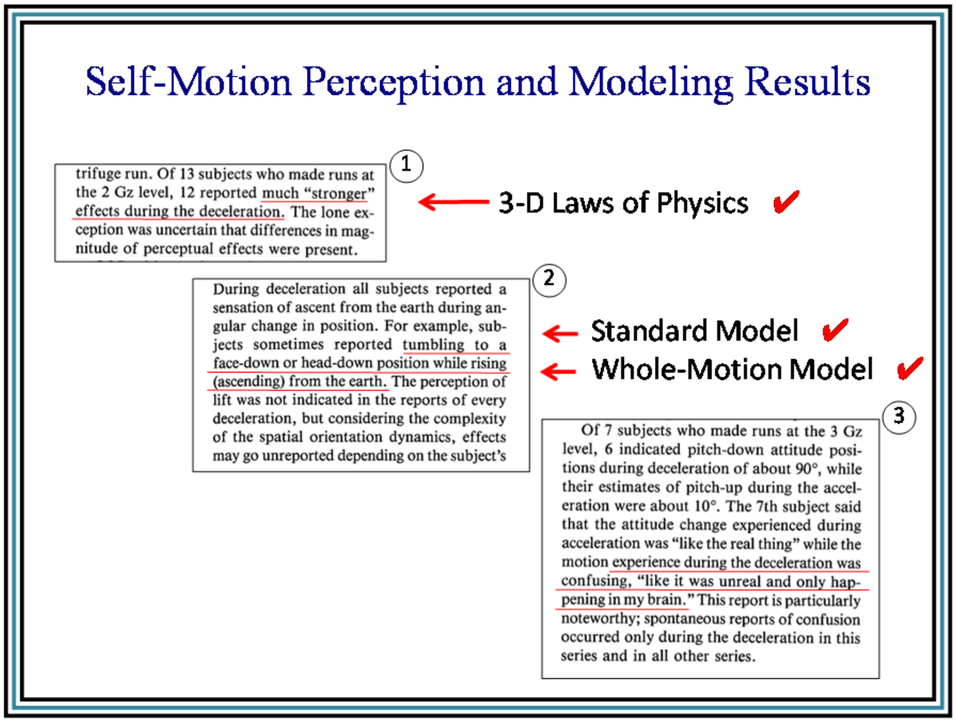


Whole-Motion Model's Prediction of Perception during Clockwise OVAR

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

(Based upon Holly, Wood, McCollum; Biological Cybernetics 102 (2010) 9-29.)

Slide 21



Self-Motion Perception and Modeling Results

① trifuge run. Of 13 subjects who made runs at the 2 Gz level, 12 reported much "stronger" effects during the deceleration. The lone exception was uncertain that differences in magnitude of perceptual effects were present.

← 3-D Laws of Physics ✔

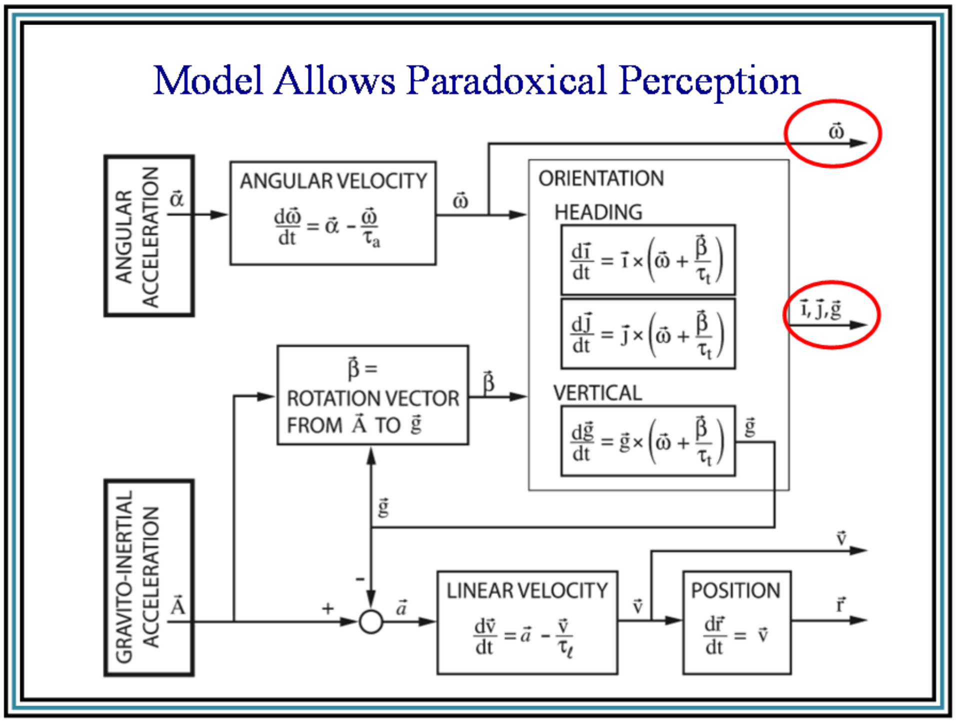
② During deceleration all subjects reported a sensation of ascent from the earth during angular change in position. For example, subjects sometimes reported tumbling to a face-down or head-down position while rising (ascending) from the earth. The perception of lift was not indicated in the reports of every deceleration, but considering the complexity of the spatial orientation dynamics, effects may go unreported depending on the subject's

← Standard Model ✔

← Whole-Motion Model ✔

③ Of 7 subjects who made runs at the 3 Gz level, 6 indicated pitch-down attitude positions during deceleration of about 90°, while their estimates of pitch-up during the acceleration were about 10°. The 7th subject said that the attitude change experienced during acceleration was "like the real thing" while the motion experience during the deceleration was confusing, "like it was unreal and only happening in my brain." This report is particularly noteworthy; spontaneous reports of confusion occurred only during the deceleration in this series and in all other series.

Slide 22



Model Allows Paradoxical Perception

$\vec{\omega}$

ANGULAR ACCELERATION $\vec{\alpha}$

ANGULAR VELOCITY

$\frac{d\vec{\omega}}{dt} = \vec{\alpha} - \frac{\vec{\omega}}{\tau_a}$

$\vec{\omega}$

ORIENTATION

HEADING

$\frac{d\vec{i}}{dt} = \vec{i} \times \left(\vec{\omega} + \frac{\vec{\beta}}{\tau_t}\right)$

$\frac{d\vec{j}}{dt} = \vec{j} \times \left(\vec{\omega} + \frac{\vec{\beta}}{\tau_t}\right)$

$\vec{i}, \vec{j}, \vec{g}$

$\vec{\beta}$ = ROTATION VECTOR FROM $\vec{A}$ TO $\vec{g}$

$\vec{\beta}$

VERTICAL

$\frac{d\vec{g}}{dt} = \vec{g} \times \left(\vec{\omega} + \frac{\vec{\beta}}{\tau_t}\right)$

$\vec{g}$

$\vec{g}$

GRAVITO-INERTIAL ACCELERATION $\vec{A}$

$\vec{v}$

−

+

$\vec{a}$

LINEAR VELOCITY

$\frac{d\vec{v}}{dt} = \vec{a} - \frac{\vec{v}}{\tau_\ell}$

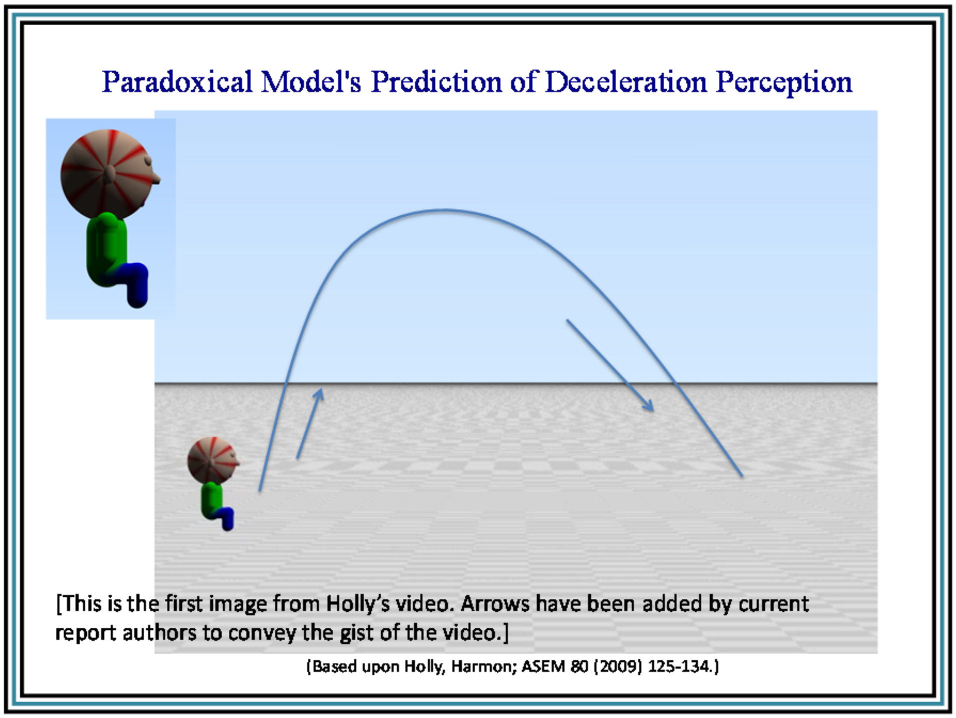
$\vec{v}$

POSITION

$\frac{d\vec{r}}{dt} = \vec{v}$

$\vec{r}$

Slide 23

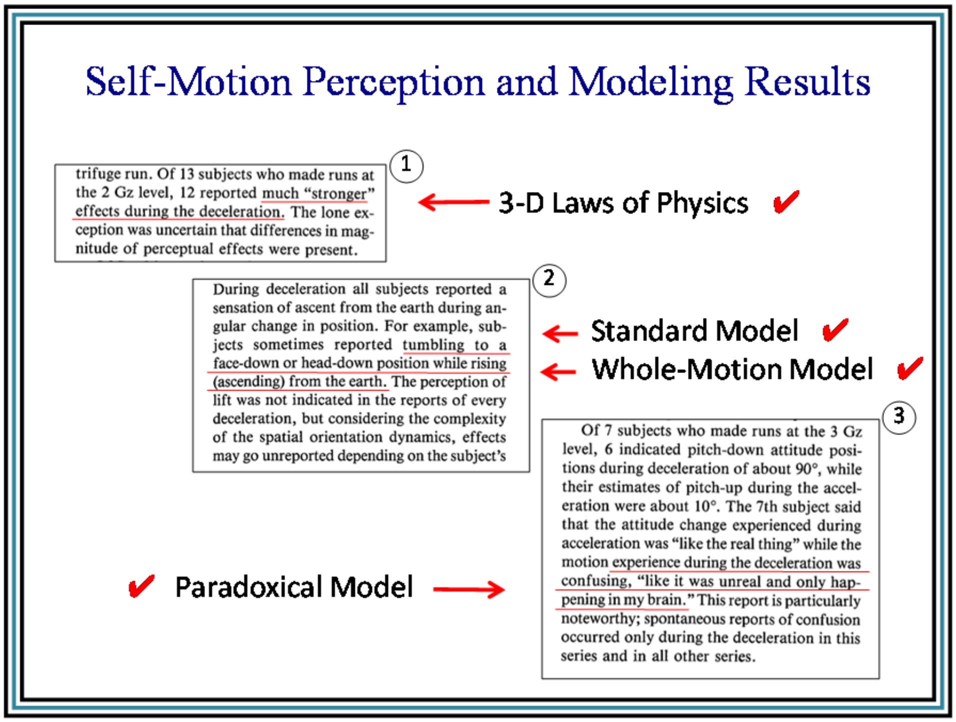


Paradoxical Model's Prediction of Deceleration Perception

[This is the first image from Holly's video. Arrows have been added by current report authors to convey the gist of the video.]

(Based upon Holly, Harmon; ASEM 80 (2009) 125-134.)

Slide 24



Self-Motion Perception and Modeling Results

① trifuge run. Of 13 subjects who made runs at the 2 Gz level, 12 reported much "stronger" effects during the deceleration. The lone exception was uncertain that differences in magnitude of perceptual effects were present.

← 3-D Laws of Physics ✓

② During deceleration all subjects reported a sensation of ascent from the earth during angular change in position. For example, subjects sometimes reported tumbling to a face-down or head-down position while rising (ascending) from the earth. The perception of lift was not indicated in the reports of every deceleration, but considering the complexity of the spatial orientation dynamics, effects may go unreported depending on the subject's

← Standard Model ✓

← Whole-Motion Model ✓

③ Of 7 subjects who made runs at the 3 Gz level, 6 indicated pitch-down attitude positions during deceleration of about 90°, while their estimates of pitch-up during the acceleration were about 10°. The 7th subject said that the attitude change experienced during acceleration was "like the real thing" while the motion experience during the deceleration was confusing, "like it was unreal and only happening in my brain." This report is particularly noteworthy; spontaneous reports of confusion occurred only during the deceleration in this series and in all other series.

✓ Paradoxical Model →

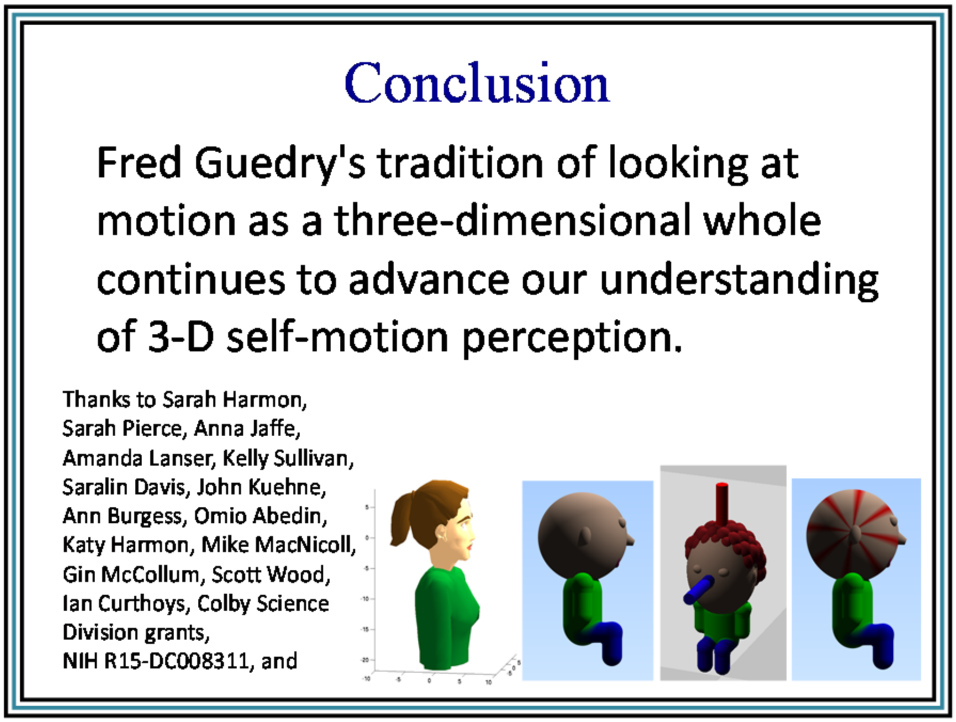
Slide 25

Summary

Explaining (mis)perception of complex motions requires properties unique to 3-D motion perception.

Perception is shaped by experience from the 3-D world.

Slide 26



Conclusion

Fred Guedry's tradition of looking at motion as a three-dimensional whole continues to advance our understanding of 3-D self-motion perception.

Thanks to Sarah Harmon,
Sarah Pierce, Anna Jaffe,
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Ian Curthoys, Colby Science
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NIH R15-DC008311, and

Slide 27

Question and answer session

[No questions recorded.]

Visualization of Spatial Disorientation Mishaps in the U.S. Navy: Case Study − Braden McGrath

[Slide 1, page 100] First of all, Fred [Guedry], it is good to see you again after so many years. I received a phone call from Angus [Rupert] a couple of weeks ago and he invited me to this [conference]. I look around and it is just incredible to see the names, and the people here–we have read all their papers. For those who have just graduated or are working on their thesis, this is a room of really incredible people. I do want to apologize first up; you should never start a talk with an apology, but I am the last guy before lunch and you are probably all getting a bit hungry, so I will talk quickly. As you know, I worked down here for a number of years with Fred and Angus, but for the last couple of years, I have worked for a large UK defense company. I am actually in management, so I have not used my brain for the last four years, but if you want to know anything about Excel spreadsheets, I can give you a little tip [laughter].

It was really wonderful to listen to the talks this morning. Specifically, I want to acknowledge two individuals, Larry [Young] and Chuck [Oman], because while I was a student at MIT, after hearing a talk by Fred [Guedry] at MIT, they [Larry and Chuck] had the good sense to send me down here and it was life changing. My personal and career paths were really set through working with Fred for those years, and later working with Angus [Rupert]. That is really why I am here and I just want to acknowledge those main players in my career and my personal life.

It has been a great thing to work with Fred [Guedry], but one of the things that happens when you are a young researcher who has come up with a great idea and solved some problems is you go talk to Fred and he will say, “Oh yea, I did that experiment back in… *hmph*” [laughter]. Then, next week you will try a new idea and his response will be, “Yea we did that, in *hmph*.” We all know that Fred has a wealth of knowledge and experience. One thing, though, that maybe is not completely clear to this audience, especially those that are in academia or industry, is that Fred is practical as well. This is addressing your question, Alan [Benson], “How do we use models to predict stuff?” What we had to do in the Navy was use models to predict what a pilot was feeling. We would have [mishap] investigations in which there were legal ramifications and obviously safety ramifications. We would have to ask questions like, “Why did that pilot do what he did?” or “What was the pilot perceiving?” Luckily, being unencumbered by any sort of academic rigor, I did not have to work within a validated model and I could make some assumptions. So, we took the models that were out there and used them far outside of their intended purpose and far outside of what they were validated [to do]. We did it because we had to though, and this is where Fred [Guedry] came in. As an engineer, I could come up with ones and zeros all day long; I could wield a MATLAB® tool like most young engineers could. Angus [Rupert] had the aviation experience and his knowledge of the neurophysiological system was immense, but Fred could always tie it [all] together. That is why I always felt comfortable that when we released these reports back to the Navy, because of Fred’s knowledge and experience, we could take models that were completely unvalidated in the area that we used them in and make some sense of it. There were some subtle points that I will get to as we move through. I am just going to start with one [mishap] [slide 2, page 100]. This was the very first one that we did back in 1996 [United States Congress, 1996], and there are three key points I want to make when it comes to modeling. One is any model has to have inputs. Now, in the academic world and in my experiments, I was able to instrument the person. I had a centrifuge that was able to instrument out the ying-yang. I had a fairly good idea of what the input was to the human head.

In a mishap investigation in a military aircraft you might think you have a black box recorder, but in most of our military aircraft (especially our older ones) there is no black box recorder. So, there was always a big effort up front just reconstructing the mishap, then having to model it, but luckily a good friend of mine, Dan Merfeld who could not be here, was a student at the same time I was [and was able to help with the modeling]. I had helped him on the quaternion part of his [orientation] model [Merfeld, et al., 1993] and I had actually written a lot of those subroutines. So I called Dan [Merfeld] up in '96 and said, "Dan, can I borrow your model?" Of course there were all these caveats about: "Well, it has nothing to do with airplanes and it was from squirrel monkeys at NASA and all this," and I said, "Hey, we have got to start somewhere." Therefore, we used Dan Merfeld's [model]. Dan's model was modified to accept these [mishap] inputs. Similarly, Jim Grissett, who is here, had developed a classical model [Grissett, 1993] of angular and linear acceleration based upon a concept that Fred had put forward at the Palo Alto [California] meeting in '92, I think it was [Guedry, 1992]. The idea is that this linear vector shifts depending on the angular accelerations and the direction that they shift is dependent upon that. As a result, we had these two sorts of models.

We then flipped it and Angus [Rupert], being Angus said, "Well, we have got to display this information," and "Because explaining 3-D perception to people is really difficult, we have got to come up with 3-D stuff." This tool was put together and it was actually used [on] some very serious legal questions that had to be answered. People died, so this was used in safety stand-downs. This was used quite extensively over the last few years. For those who have not seen it before, this [slide 2, page 100] was a mishap in 1996. It was an F14 that took off from a Tennessee airport and crashed in the Vice President's neighborhood, killing both aircrew on board, plus three civilians on the ground. Obviously, because it happened in the Vice President's neighborhood, it was elevated quite high. In fact, this little movie [recreating the mishap], was used by the Chief of Naval Operations to brief Congress, who then briefed the Vice President as to why one of their airplanes was crashing near his house [laughter]. So, very quickly I will start off [showing a video animation of the mishap], and I will stop it as we get a little bit down the runway. First off, we just have a sort of God-view, and that is the sort of 3-D view of the actual environment; the key ones here are the actual orientation of the pilot and the perceived orientation. Over here, we have a standard instrument panel and also a graph of what his actual and perceived orientation was. Now, for this mishap, it is all in pitch and here we see a gravity vector, both a Gx and a Gz. The pilot lifts off then "cleans up" the aircraft -- this is a high performance take-off. He gets nice and clean (he is really accelerating down the runway now), he pulls it into about a 3G pull up, and at about 2000 feet which is just about here now [references animation] he ascended into clouds. Now he has lost all his visual cues, a sort of a classic mishap [situation]. I know Alan [Benson] will have looked at many of these over the years. What we have here is a situation where we have gone from VMC (visual meteorological conditions), [where] you can see the horizon, to [entry] in[to] the clouds. We have some classic features here. We have some confusion going on here [in the original flight recording]. There is now a discussion going on between the pilot, the copilot, and the air traffic controller as to where he is leveled out at—the pilot thought he was supposed to level out at 15,000 feet. The copilot is saying, "No, you're cleared to 5000 feet," so [there is] confusion in the cockpit. Well, the pilot acts on his 5000 foot [command] and starts to level off, and we will get to a point here where you will start to see he has leveled off. We start to see a very small Gx vector, about a third of a G in x and a very small Gz vector, but it is negative. So I just want to make this point: Dan's [Merfeld] model and Dr. Grissett's model were never validated with this type of negative Gz, but we have to use something. This again was really important to acknowledge that Fred's [Guedry] experience in this space allowed us to make those projections. What happens here is, if you keep an eye on the perceived [pilot orientation animation], you will see that he keeps perceiving that he is moving up. In fact, he is actually [pitched forward and] moving down, and this is an insidious Somatogravic mishap, in that his reaction to a pitch up, is to push the stick forward, which pushes him back into the seat more, which actually exacerbates the sense of being pitched up, so everything he does makes it worse.

I just want to bring up a very important part of the modeling effort, and this is what we would look for in these mishaps, and this is where the modeling can become very important. If I was to throw in a model, I would use Jan's [Holly] -- it had that great animation. If the guy was feeling like he was tumbling head over heels and [had a] classic type vertigo of motion, any of those types of things, he would feel very disoriented, he would get on his instruments -- he would do something to get himself out of the situation. What we see in mishaps [is different], and this is an important, subtle point here: When our perceived (that little red line) orientation matches our expected orientation and matches our CONOPS, our concept of operations (the mental model of the pilot), that's when we see mishaps. The pilot doesn't have any reason not to trust what he is feeling. So if our models predicted an orientation pathway that matched what we would expect a normal pilot to be doing in that situation, that's when we would see problems. That would be a real big validation check as to whether we had a good explanation sample or not. So, in this situation, he's expecting to come up, and he's doing exactly what he thinks he's doing, his perception: "Eh, probably pitched up a little, just need to knock the nose [down] a little." So he's really feeling exactly what he wants to feel. He has no reason [to be concerned], but he's actually already pitched down 45 degrees. Now for the non-aviators in the room, you are probably thinking, "Hang on, you're trying to tell me that this guy is pointing down to the ground 45 degrees and he doesn't realize it?" Well, I can tell you that I have been in situations just like this and you have no idea that you are in that orientation, because of that subtlety – you have no reason not to trust your inner ear. Remember, this is all happening in 6 seconds, very quickly, and at this point it is too late. He breaks out of the clouds, sees the ground, pulls back on the stick, and unfortunately doesn't pull up in time and he impacts a house. So, a great tragedy and something that we would use [to teach others]. Obviously, the work that Fred [Guedry] and Angus [Rupert] did was to prevent similar mishaps like this.

Unfortunately, as most things go, I have a whole talk of mishaps just like that [one]; it occurs time and time again. Part of the work that Fred [Guedry] has dedicated his life to is avoiding these. This mishap, in fact, was used in safety stand-downs, and is now part of the curriculum we use when we teach this. We are seeing a reduction in this type of mishap, but we have now created a new one, which will be the last one in my talk. I am going to run through this quickly because I know we have lunch, and I am getting hungry. I was on a plane for three days [living on] Qantas Food -- they're spending more time on their engine maintenance than they are food [laughter]. It's interesting being in mishap investigations [and then] living in Australia with Qantas. If any of their airplanes have a problem, it is front page, so these latest five or six incidents have been quite a bad rush. We have had five or six in the last week -- turn-backs with Qantas, which is probably no different from any other airline, but because it's Qantas (thank you, Rain Man) people take it [seriously]. In fact,we got on the plane, whenever it was I can't even remember, and the pilot came on and said, you will be pleased to know that the CEO of Qantas has called me up, and he doesn't want to see this flight on CNN [Cable News Network] so we will have no problem getting us there [laughter]. I am going, “That’s good.” [Presentation file opens.]

We have some good stuff here. Angus [Rupert asked me to present this], yesterday or day before -- gave me a whole heaping heads-up [slides 3-4, page 101]. This is a talk we did at the Aviation, Space, and Environmental Medicine scientific meeting in 2006 [McGrath and Rupert 2006], so I am just recycling something from the conference and I am going to get through it quickly. What I want to stress again is that whole idea of taking these models that this group has produced, [including] the psychophysics work, the anatomy work, and everything that comes out of this group, and using that information to solve real world problems. Here we have a terrible incident that occurred in 2005 [HMH-361, CH53E, 26JAN05]; a CH-53E helicopter from HMH-361 squadron “Tiger 60,” we lost a helicopter in Iraq, and we lost 31 guys, 27 Marines, and 4 crew[9]. Look, there’s no need for explanation here [i.e., no need to explain to this audience the definition of spatial disorientation in slide 5, page102]. SD is a very big detriment to U.S. Navy and Marine Corps aviation operations; obviously it is a driver for all labs like NAMRL, like USAARL.

[Slide 6, page 102] I plagiarized this blatantly from Alan’s [Benson] work, many years ago as part of my thesis, I believe I changed the helicopter. Alan, I hope that was ok. Again, it is this concept that if the force due to gravity and our sense of where down really is, versus the apparent vertical -- when those two do not match up is when we have problems with spatial disorientation. Without visual reference, the direction of that vector is the only sensory indicator of which way was down, and quite often we use that, but in detriment to [our correct perception of] the real world [slide 7, page 103]. Luckily on Earth, we’re [usually in] a very 2-D [situation], we have got continuous sources [of reliable sensory input] -- we do not need to talk about that in this group. I do not have to think about the fact that I can stand here and get these discontinuous sources coming in all the time (maybe after a few beers I have got to think about it, but not under normal circumstances) [slide 8, page 103]. Mishaps are rarely [solely due to one cause such as] SD, [slide 9, page 104] we have seen Reason’s model quite a lot. Just to give you an idea: we have got 236 mishaps, 242 fatalities of which 51 were classified SD, and 95 lives lost due to SD mishaps. So that’s that 6 or 7 year period back around early 2000.

[Slide 10, page 104] What do we use that [modeling tool] for? We use [it for] mishap boards, that is, “Why did that crash happen?” We do this so it cannot happen again. A big issue is the JAG [Judge Advocate General] investigation. Obviously, when you have got fatalities, especially civilians, there’s a very serious legal investigation. [The outcomes are also used for] training safety stand-downs: let’s reuse that knowledge, let’s reinforce that with our pilots, let’s not let this happen again. As I said, hopefully these types of modeling efforts can feed that [mishap] data back into the research community so that we can produce better models. And finally the media likes to get little clips of that, and such clips have been on Discovery, ABC [American Broadcasting Company], CNN, and we get a lot of calls for that.

[Slide 11, page 105] As I said, we gather the data, and every now and again we get radar tapes and sometimes FDRs [Flight Data Recorders], but most often it is just interviewing and eye-

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[9] Speaker gets a bit confused on the count but the stated count in this document matches http://www.popasmoke.com/kia/incidents.php?incident_id=278&conflict_id=32

witness accounts. From that we get a six-degree position and acceleration, unfortunately this is often only an estimate [slide 12, page 105]. Here's a classic: Larry [Young] mentioned the catapult launch this morning, which was a mishap, it was late '90s as well [VFA-151, F/A18C A/C crashed into water after night catapult launch from USS Constellation 20-Oct-00]. It was at night and you can see the vectors, and he went straight off, and he was actually asymmetrical. He had a fuel tank on one side and no fuel tank on the other side, so his aircraft was asymmetrically loaded which would've meant it would've actually wanted to have done something, so therefore that's a distraction. Typically, in a catapult launch, the aircraft will fly itself, but because he was asymmetrically loaded he had his hand on the stick, and was flying the aircraft. Unfortunately, he was also flying [according to] his [false] perception and he went straight in [to the water]. So, we come up with these flight paths with a resultant gravito-inertial force (that's the actual). Like I said, we had Jim's [Grisset] and Dan's [Merfeld] model [slide 13, page 106], and I never got [around to] putting Lionel's [Zupan] in, but I did use Grissett's. We would come up with an estimated perceived orientation, and then we would look at the cut-off [and ask questions like], "What was the pilot trying to do, and do we actually feel that we had a good [estimate]?" [and] "Was there a difference between the perceived orientation and what we think was an estimated orientation?" From that we would come out with an approximate perceived pilot orientation, and a spatial disorientation index. Again, a lot of this was very quantitative discussions with Fred [Guedry], with Angus [Rupert], with other experts in the military, and with academia, so that we had a good sense that our approximate perceived pilot orientation was pretty good. I am going to admit these models we used were outside of their intended or at least their validated regime.

[Slide 14, page 106] We have already heard enough about Dan's [Merfeld] model, and if you are interested, Jim [Grissett] can talk about his model at lunch, so I am going to quickly go through it. We'd [ask], "What was the pilot trying to do [slide 15, page 107]? Distraction? -- why didn't he look at his instruments?" That is always the first question you ask. Pilot age and experience come into it, and we come up with our approximated pilot position and our SD index. This is the same F18 mishap [slide 16, page 107]: the blue is his perceived pitch, whereas his actual pitch is the red, and his GIF, or his resultant vector, are the blue dots. So you start to see those classic lags that were first shown by a number of different researchers [Clark and Graybiel, 1966], that GIF lagging the gravito-inertial vector, or that perceived pitch lagging the actual GIF. We start to see adaptation, we start to see all of those features come out in a lot of these responses, but again what we see is (points at slide) the pilot doing kind of what he thinks, "I want to be slightly pitched up, I want to be climbing up into the sky, I do not want to be too high because I'll stall, so I'll just nudge the nose over a little." But what that is doing is pushing him back into the seat, which is actually driving him into the ground [slide 17, page 108]. Then finally we had to develop simulations, and I am going to start putting red dots, or red stripes on my people too [like Holly], I love it. Back in '97 we used a computer the size of this room just to do a simple 3-D animation, but now I have got something on my iPhone® that is more powerful than that thing back then. So we have come a long way in that respect.

[Slide 18, page 108] So it is sort of the same for this [CH53-E] mishap [mishap animation begins] [HMH-361, CH53E, Jan. 26, 2005]. We have what I call the God's-eye view of the world. [Next] we have added now the view of what the pilot's actually seeing. These are just approximations -- we do not know what happened in the cockpit that night, but this is our best estimate, and it's based upon some of the great work that's come out of this room. We have our perceived orientation, we have our actual orientation, and this is now 2005, so 8 years later we have gone from 2-D to 3-D, and we have gained some instruments. This is with night vision goggles, its formation flight, and here is the pilot [Referring to video on slide 18]. They've got the trial aircraft, and it is very demanding flying. We're in a very hostile environment, so the pilot flies for a little bit, and as he's watching that little flashing light on this [lead] aircraft, he gets tired, so [after approximately] 5, 10, 15, 20 minutes they switch sides, and the plane drifts off to the other side, so the pilot who's flying is closest to the lead aircraft.

I did not bring up the reason, but they were flying a three-way mission so they started here, flew down to another point, picked up the cargo or the troops that they were flying over to a point where they were going to unload them, and then [they thought], "We're gonna fly home." As they were flying along they saw a big sandstorm coming at them and they made the decision, "If we turn around we're going to have to spend the night at an outlying base (not back at our home base) without any of the support facilities there," so they made a decision, "We will push on through our mission." There was that sense of, "Our mission is to deliver this human cargo into the area," so [refers to slide] they essentially fly into a sandstorm, they lose all of their visual cues, and there's some other good bits about this that I am hoping will get some people excited [starts simulation]. So they've been flying with a slight roll about 5 degrees for a long time, so already they've got SD starting. Here, he [the pilot] starts to roll the aircraft, and we see a classic type 1 SD… Bitching-Betty goes off [the ground proximity voice warning]… And we impact the ground.

A couple of the key points were: we had no visual cues, we had a situation where he was already slightly pitched or rolled (he was slightly rolled but because he's following this other aircraft), he's "heads out" [not on instruments]. If somebody asked me, "Why wasn't he on his instruments?" [I would answer], "Well, he's flying formation flight because his job is to be looking at the other aircraft, they're flying very close together."

We reviewed a similar mishap [VMFA-323 F-18C May 2, 2005, wherein two F-18Cs disappeared from radar contact over Iraq] that was a midair collision, and we think that the guy was looking at his instruments and… [trails off] so you can't win.

A couple of key points there from the modeling perspective: his ground proximity warning sensor [GPWS] went off. By the way, if you ever work for one military [branch] and then you go work for another one you spend the first 6 months going, "I have no idea what they're saying," but you do [it is just that] they've just all got different acronyms [for the same concepts]. So the GPWS went off, so people say, "Well why didn't he respond then?" When you are completely disorientated and then you are presented with true orientation information, how long does it take you to get back on track so to speak? Is it a 2 second time constant, is it 6, is it 30 seconds? So, before he crashed, he was given at least a warning that he was in disorientation, but he did not act on it. If I rerun the model, you will see that I added this little G vector and people go, "Hang on, this guy was at 50, 60 degree roll!" Now for those of you who've done a centrifuge (ride), if you are at 50 or 60 degree roll, what's your G level?... yea, two or three G's, so why isn't he responding to the fact that he's banked over, well [because of] his vertical velocity -- he was just slicing down, he'd lost lift from his rotor head, and he's just going straight down. What that meant was his resultant GIF magnitude never moved from 1G, so even though the angle was changing and this was a mishap cause, Dan's [Merfeld] model was not tuned for large Gs so this was one that we felt gave a good indication of what happened in that space [slides 19-21, pages 109-110].

[Slide 22, page 110] This is a similar mishap -- this is Bahrain.

[Rupert] This is at night incidentally. We showed the daylight view here so you could get a feeling of what was going on, but this is [occurring] in pitch black [darkness] at night and on the second turn, as he comes around, he had a missed approach, and now he's about to come around in a second missed approach, and what he has in front of him is absolutely nothing but blackness.

[McGrath] This picture here (indicates bottom of screen) is… he's looking at nothing but ocean.

[Benson] Did you have FDR on this?

[McGrath] This is an FDR one. Hence you will see the graphs look much more realistic.

[Rupert] This was particularly nice because all of the data was available for this one including the cockpit comments, and it was very complex in terms of it had a mixture of G-excess as well as somatogravics and an incredible amount of distraction because the copilot was relatively new, just a few hundred hours.

[McGrath] So you see how he's got visual [cues at this point], there'd be all sorts of lights and stuff on the runway. He gets called off, he's completely missed it [the approach to landing]. So this is his second go around. So he's missed it twice now, and you can imagine the stress level in the cockpit is getting pretty big. He comes out over the ocean now and basically at this point he starts to lose all visuals.

[Rupert] Because of the inexperience of the copilot he's [the pilot is] really doing the copilot's job at the same time and handling flaps, etc. He's really doing two jobs at once, the pilot in the left seat.

[Money] Yea, but he had two tries to learn [laughter]. When you lose your visual cues you immediately go on instruments, you do not hesitate, and if you have got two practices doing it, the third time you should be real good at it.

[Rupert] Well, he did not get a third time, sir.

[Money] Ok…

[Benson] It was disorganization of performance under stress.

[Rupert] The first approach was a high approach coming in and he was [too] fast and he was visual. It was a visual approach -- he was not on autopilot, and this is a classic story over and over again: If the autopilot had been used, there would not have been an accident. I was at the Royal Aeronautical Society a year and a couple months ago, and the data [from the meeting] is now overwhelmingly showing that pilots do much better if they just use the autopilot.

[McGrath] Having said that, I have got one [a mishap] in here, the Gulf Air one, which is [due to] over-reliance on the autopilot. This was a landing mishap that was a takeoff mishap and their autopilot was implicated, and there was that sense they were relying on the autopilot, when in fact the autopilot wasn't doing anything, the autopilot was off and he was actually on the stick.

Oh -- I do apologize I did go way too long, so thank you very much for listening.

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VISUALIZATION OF SPATIAL DISORIENTATION MISHAPS IN THE US NAVY: CASE STUDY

Braden .J. McGrath
QinetiQ
Canberra, ACT

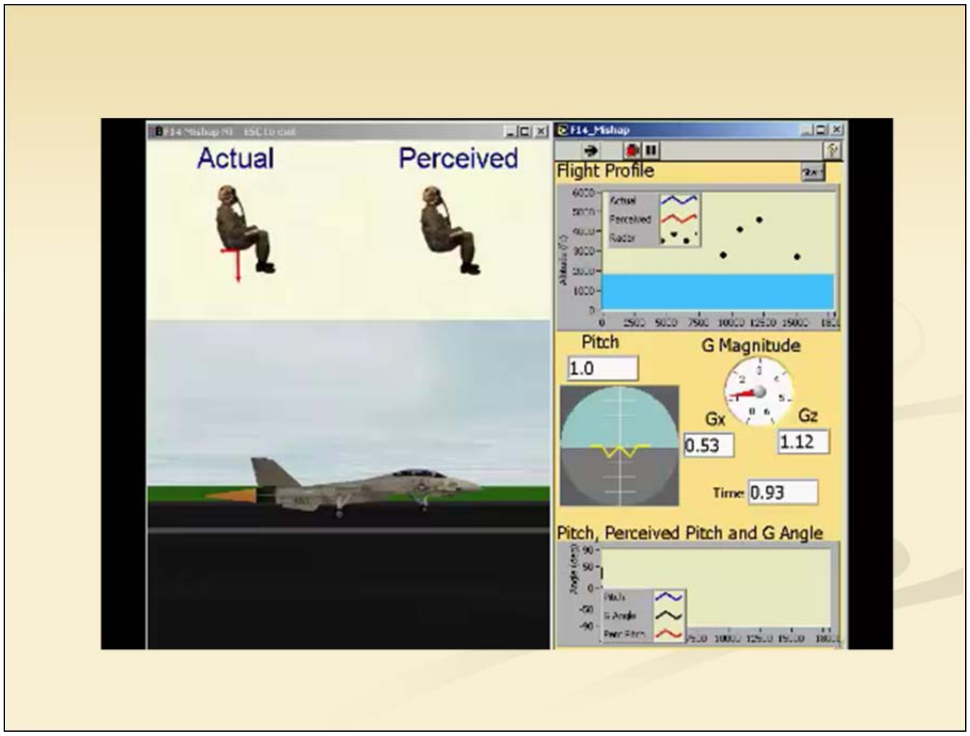
Fred Fest

"A National Treasure"

IHMC, Pensacola FL 19-20 Nov 2010

Talk adapted from presentation at ASMA 2006

Slide 1



Pitch 1.0

Gx 0.53

Gz 1.12

Time 0.93

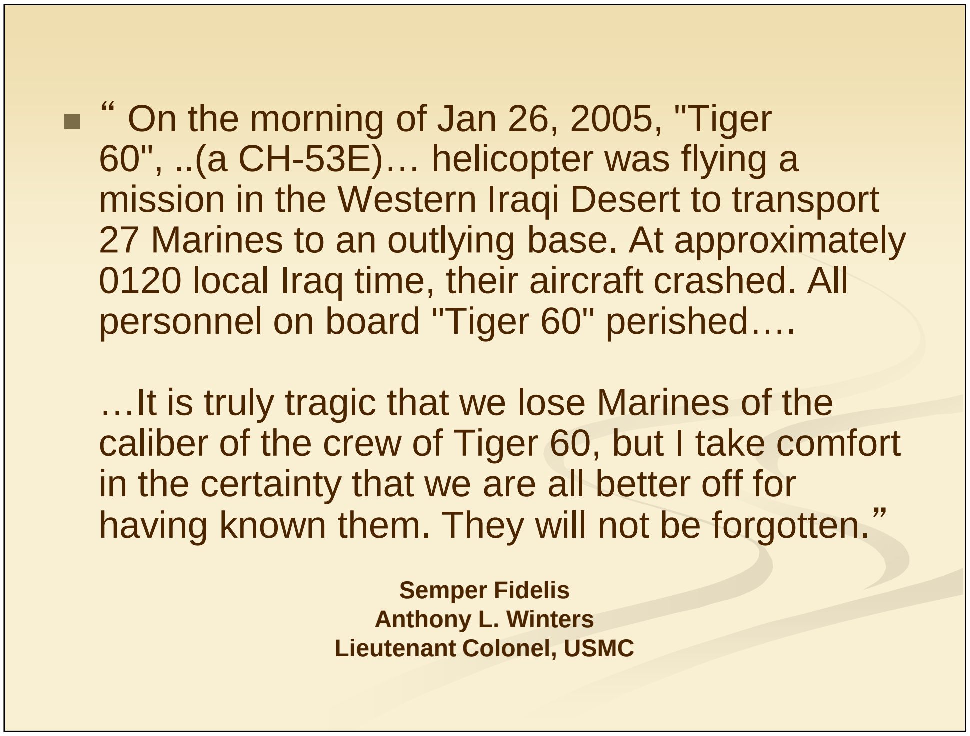
Slide 2

VISUALIZATION OF SPATIAL DISORIENTATION MISHAPS IN THE US NAVY: CASE STUDY

B.J. McGrath & A.H. Rupert

Naval Aerospace Medical Research Laboratory
Pensacola, FL. 32508

Slide 3



- " On the morning of Jan 26, 2005, "Tiger 60", ..(a CH-53E)… helicopter was flying a mission in the Western Iraqi Desert to transport 27 Marines to an outlying base. At approximately 0120 local Iraq time, their aircraft crashed. All personnel on board "Tiger 60" perished….

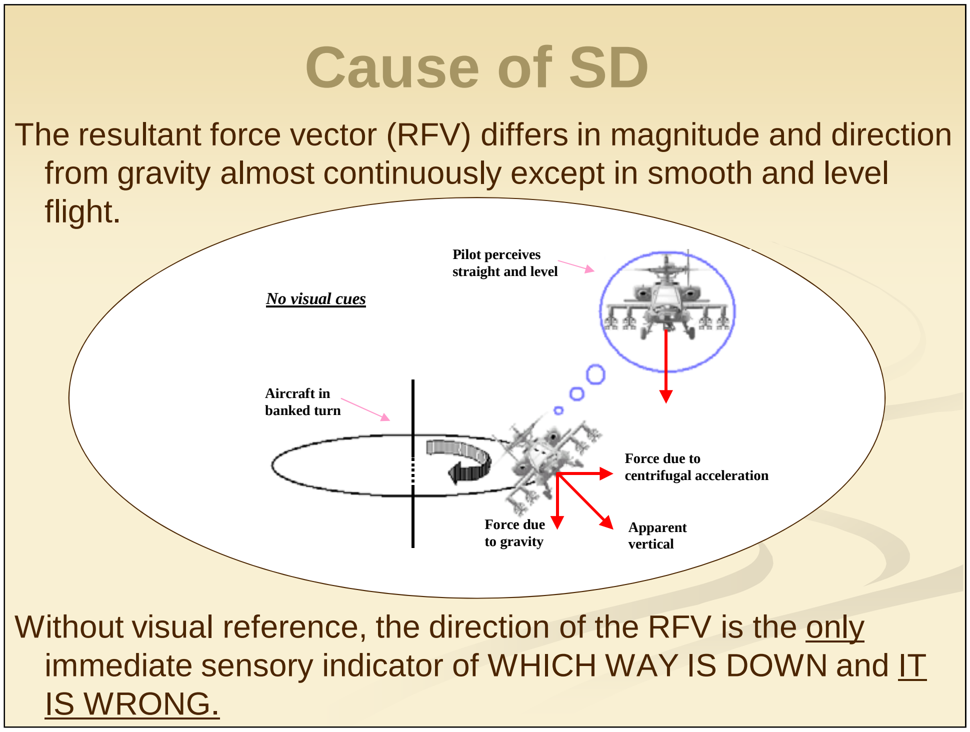
  …It is truly tragic that we lose Marines of the caliber of the crew of Tiger 60, but I take comfort in the certainty that we are all better off for having known them. They will not be forgotten."

Semper Fidelis
Anthony L. Winters
Lieutenant Colonel, USMC

Slide 4

- Spatial Disorientation (SD) is an important detriment to US Navy and Marine Corps aviation operations in terms of cost, lives lost, and mission degradation.

Slide 5

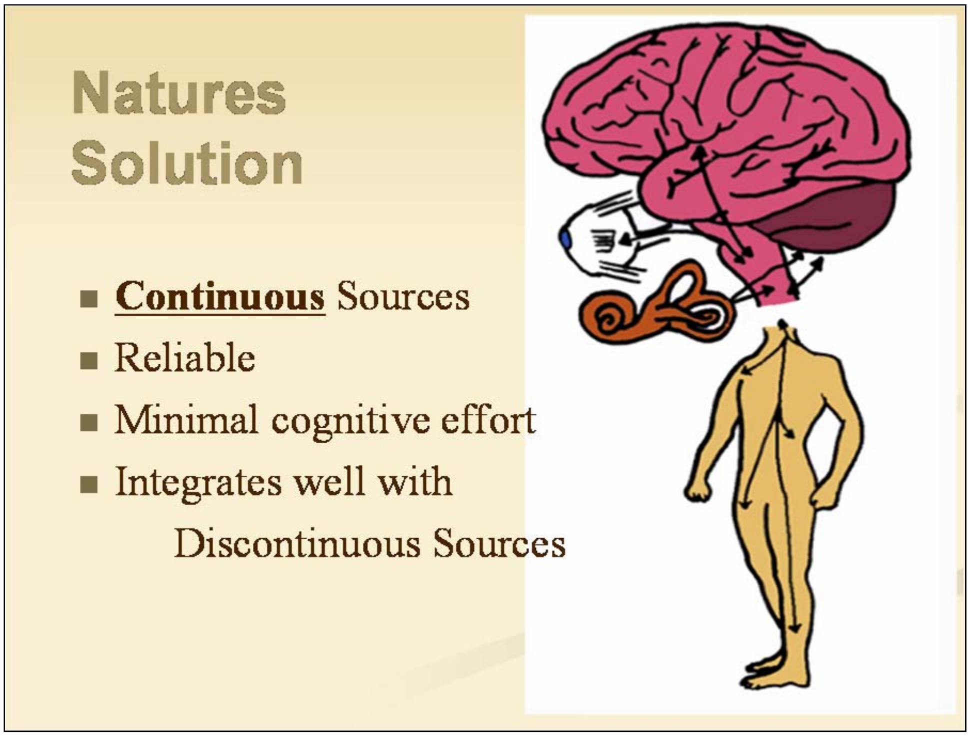


Cause of SD

The resultant force vector (RFV) differs in magnitude and direction from gravity almost continuously except in smooth and level flight.

Without visual reference, the direction of the RFV is the only immediate sensory indicator of WHICH WAY IS DOWN and IT IS WRONG.

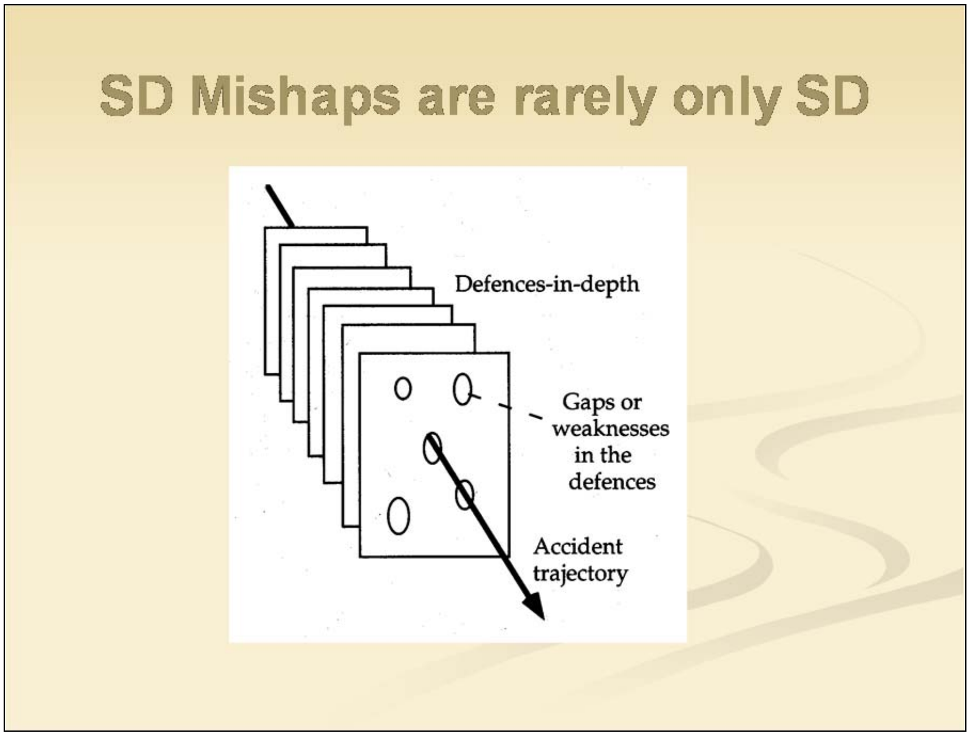
Slide 6



Natures Solution

- **Continuous** Sources
- Reliable
- Minimal cognitive effort
- Integrates well with
  Discontinuous Sources

Slide 7



SD Mishaps are rarely only SD

Slide 8

US Navy Mishaps FY 1997 to 2004

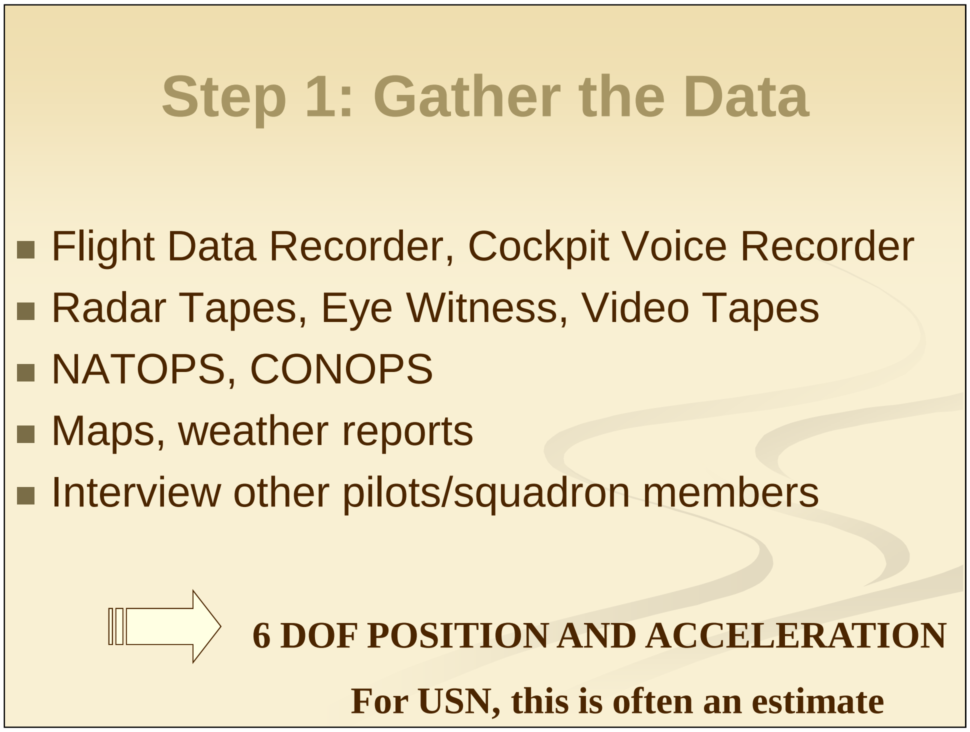
- 236 Class A Mishaps, 242 fatalities
- 22% (51/236) classified SD Mishaps
- 39% (95/242) of lives lost were due to SD mishaps
- Naval Safety Center data reanalyzed using AIR STD 61/117/07

Slide 9

Mishap Analysis Tool

- Mishap Board
- JAG Investigation
- Training, Safety Stand Down
- Research
- Media

Slide 10



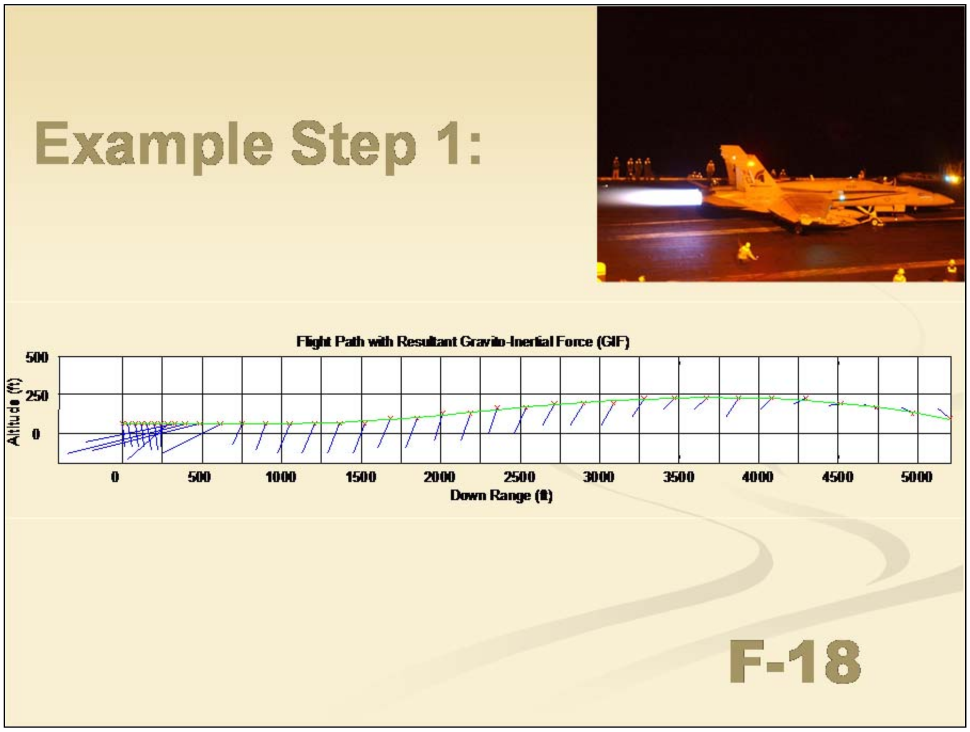
Step 1: Gather the Data

- Flight Data Recorder, Cockpit Voice Recorder
- Radar Tapes, Eye Witness, Video Tapes
- NATOPS, CONOPS
- Maps, weather reports
- Interview other pilots/squadron members

⇨ **6 DOF POSITION AND ACCELERATION**

For USN, this is often an estimate

Slide 11

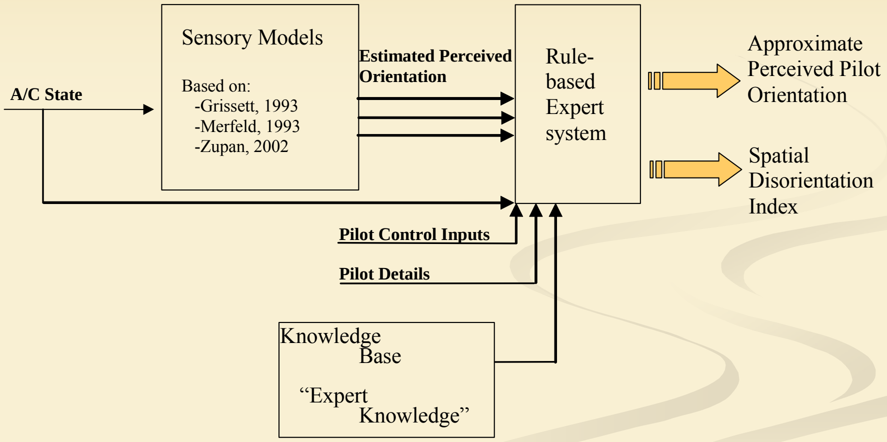


Example Step 1:

F-18

Slide 12

Step 2: Spatial Orientation Model



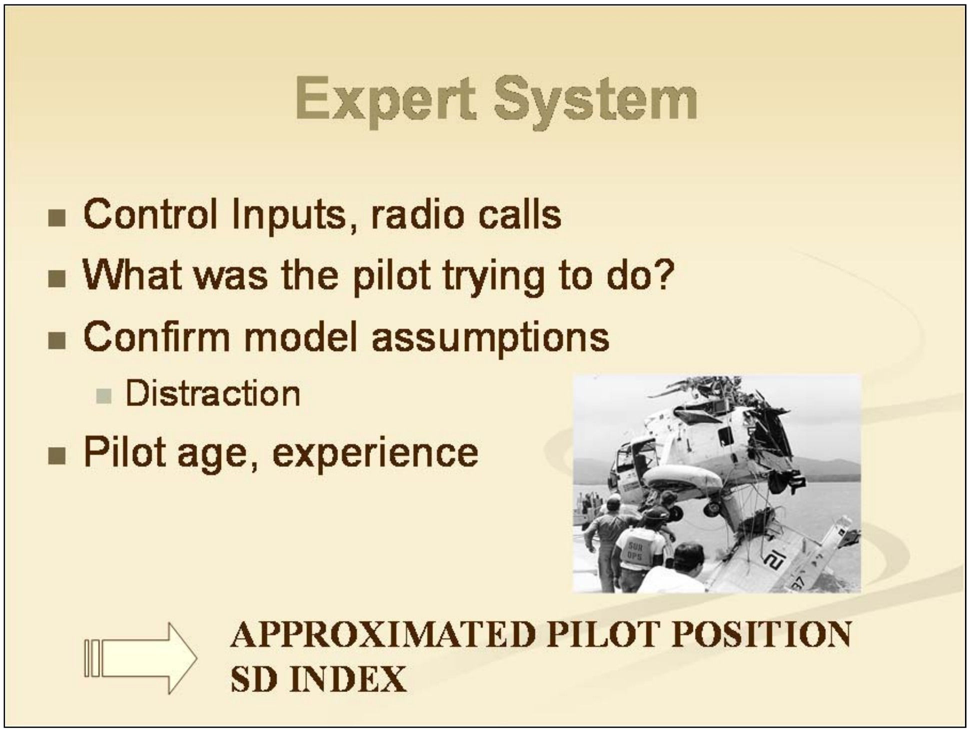
Slide 13

Sensory Models

- Grissett, 1993
  - "Classical Systems Theory", Transfer Function Approach
- Merfeld, 1993
  - "Observer Theory Model"
  - Fixed Gain

⇨ **ESTIMATED PILOT ORIENTATION**

Slide 14

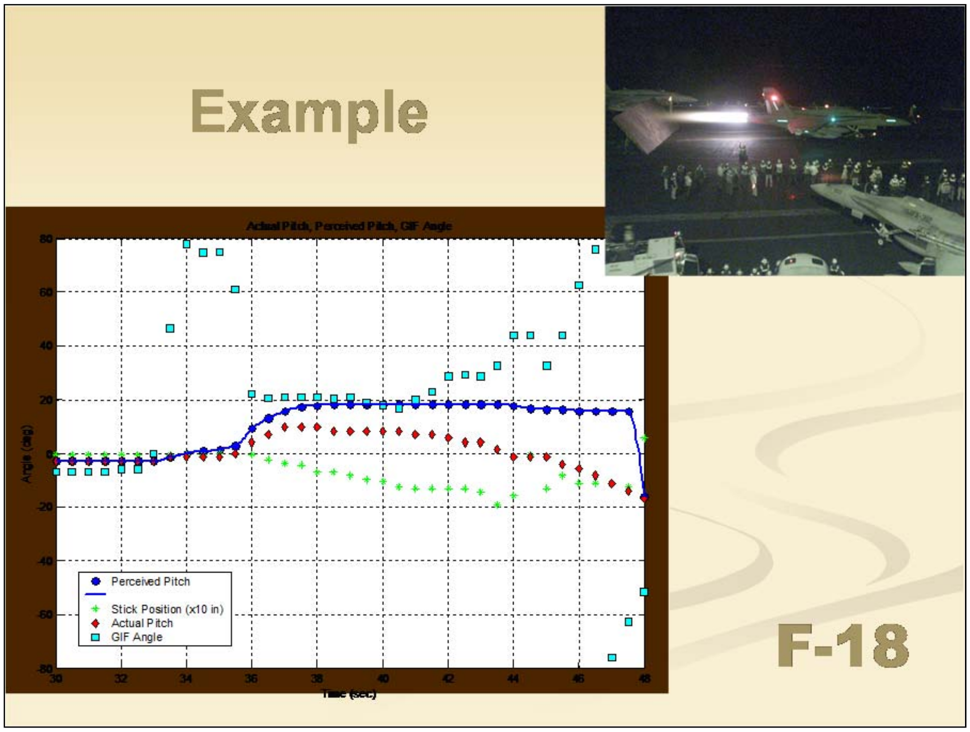


Expert System

- Control Inputs, radio calls
- What was the pilot trying to do?
- Confirm model assumptions
  - Distraction
- Pilot age, experience

APPROXIMATED PILOT POSITION
SD INDEX

Slide 15



Example

F-18

Slide 16

Step 3: Develop Simulation

- 3-D computer simulation of the SD mishap, Vega™ (MultiGen-Paradigm, Inc).
- Permits visualization of a complex problem
- ONYX (1997) -> PC (2001)-> Laptop(2003)

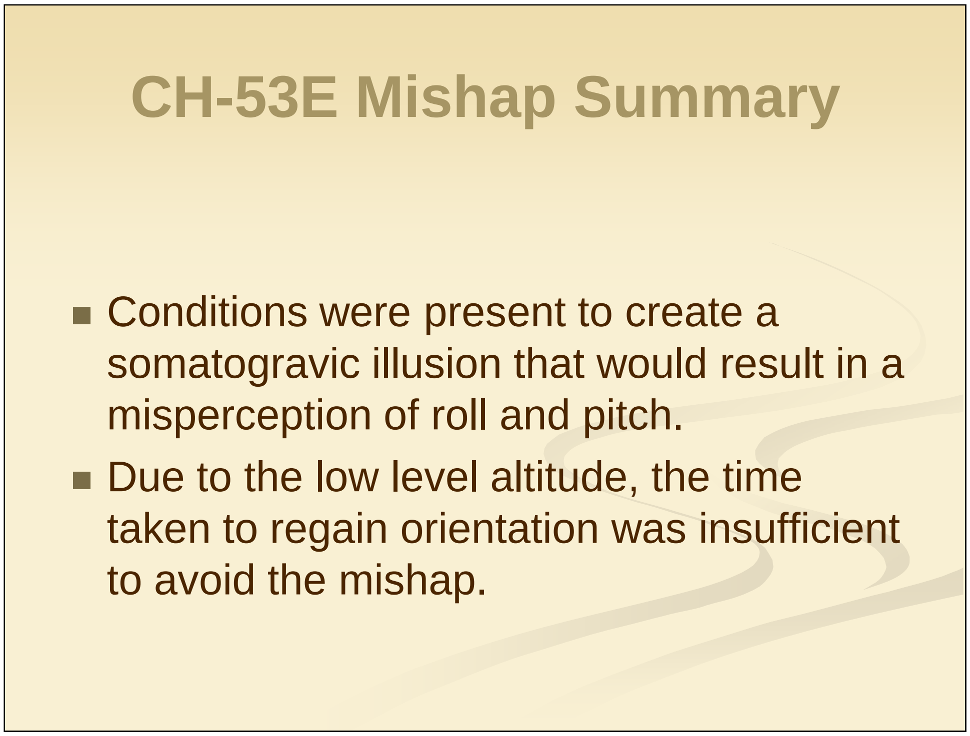
MISHAP SIMULATION

Slide 17

CH-53E Mishap

- 63% (32/51) of all SD mishaps occurred at night.

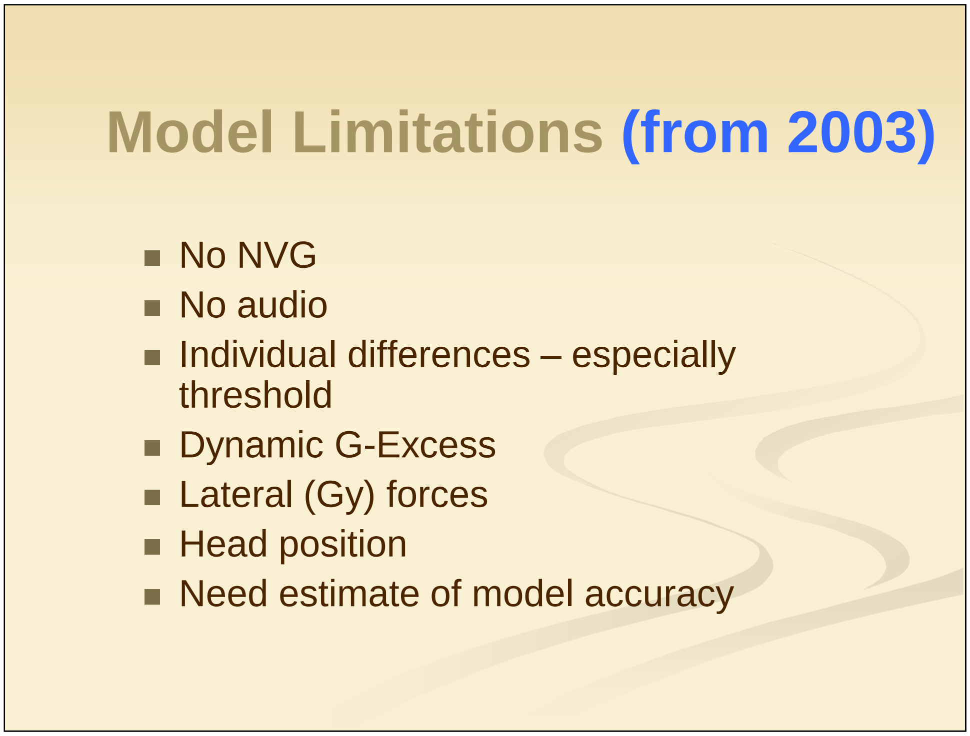
Slide 18



CH-53E Mishap Summary

- Conditions were present to create a somatogravic illusion that would result in a misperception of roll and pitch.
- Due to the low level altitude, the time taken to regain orientation was insufficient to avoid the mishap.

Slide 19



Model Limitations (from 2003)

- No NVG
- No audio
- Individual differences – especially threshold
- Dynamic G-Excess
- Lateral (Gy) forces
- Head position
- Need estimate of model accuracy

Slide 20

Recommendations (from 2003)

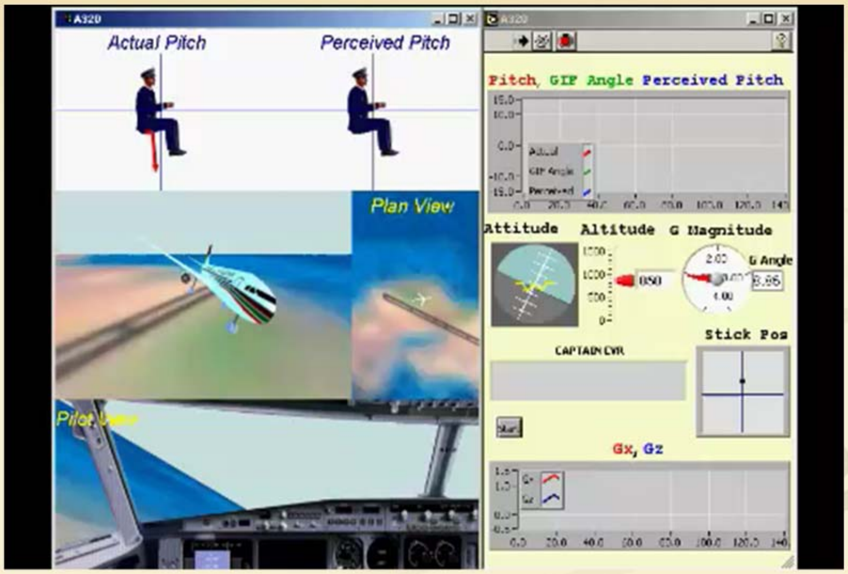
Enhance the SD mishap analysis tool by

- Produce an improved model that overcomes limitations of existing models.
- Refine intelligent, knowledge-based software to quantify the risk and extent of SD.
- Develop advanced computer animation techniques to improve the realism of the simulation.

*Recommendations haven’t changed in 2010

Slide 21

NTSB A320 Mishap



Slide 22

Question and answer session

[No questions recorded.]

Experimental Measurement of Otolith Dynamic Displacement − Wallace Grant

A couple of things I want to say first… Fred [Guedry] earlier was described as [a Tulane baseball player, and] one of his triumphs was [as] a pitcher [in a game] against LSU. Clearly this audience doesn't understand the rivalry there, that's why it's his favorite game. I went to Tulane, as Fred did, and in the state of Louisiana it's open warfare -- you've got to understand that. So, that's why him beating LSU in a baseball game was such a triumph for him; and the other thing you don't ever want to do is get Fred [Guedry] to describe how he throws a fork ball, which is kind of like a knuckle ball, and what all you can get it to do; because it's a detailed description about what you can get that ball to do when you pitch, so it's an interesting conversation.

I have one Fred [Guedry] story I'll tell amongst many. Fred, for about the last 15 years, calls me up on the phone and he wants me to model some kind of simulation. So about 3 or 4 years ago, he wanted me to model a catapult launch off of an aircraft carrier, so he sent me all these equations, and he had five equations and there were three variables that you could adjust in the whole thing. I said, "Fred [Guedry], you can't do this it's way over-specified," and I told him, "I could get anything he wanted out of it but we were going to have to throw some of it away," and I think he gave up on the project at that point because I never heard anymore out of him after that [laughter].

There have been a lot of comments about modeling today, and I'm basically a modeler for those of you who don't know who I am. I think there's a definition or a break point here that people need to recognize, and that is the mechanics or the physics of the problem. There are laws that govern all of that stuff, these are established laws, mostly Newton's Second Law of Motion f = mass x acceleration, people don't argue with those anymore [laughter]. But once you get past that and into the neuro system, we're dealing with hypotheses and theories, and these haven't been developed yet, and that's where a lot of this discretionary work comes along. They're not first principle -- there are some first principles there -- but they haven't really been developed yet. So, I think that's where people need to consider all of this modeling work. The models lead to discovery and that's kind of the key point here that people have talked about today so, I hope everyone appreciates that.

Now the next thing is Ian [Curthoys] told me I had to talk the whole two and a half hours and, well we've already killed an hour [laughter]. I'm off the hook for that, but there's no way in the world I'm going to talk for two and a half hours here, and the second thing is Jan Holly, myself, Ian [Curthoys], and Scott Wood -- I think I've got most of the people mentioned -- have been coming down here for several years now and meeting with Fred [Guedry], and in the spirit of that, in those meetings we've always talked about current research that we were working on, which is what I prepared for, and then I saw the list of people who were coming and as the list grew I said, "Do I really want to talk about this stuff?" I realize I'm loading [i.e., setting] myself up for a lot of criticisms, but maybe I won't get it in the papers this way [laughter]; so keep that in mind as well.

[Slide 1, page 119] I'm going to talk about two experiments we've got going on in the lab. This first one is about experimental measurement of otolith dynamic displacement [Dunlap, Spoon, and Grant, 2012]. This is something we've been working on for about a year [slide 2, page 119] and we haven't quite got it to work yet but we do have some results. We're trying to measure the shear layer stiffness of the utricle otolith organ. In other words, what is the stiffness when the utricle otoconial layer is deflected? We're doing this in an experimental animal, the turtle. [Slide 3, page 120] This is a photograph (or a cartoon really) that one of my graduate students made up that gives a picture of what a turtle utricle looks like here. It does have a curved base, this is the shear layer down here (solid light green band); it has a quite thick otoconial layer (red layer), and this is without any stimulation or any acceleration [indicates the left hand side]. This is when its deflected here [indicates right side] and so we're really trying to measure the stiffness of this layer in here, which includes a gel layer, which is this blue colored layer and the column filament layer which includes all the hair cell bundles in here.

[Goldberg] … I have never seen a turtle diagram. In mammals, I thought that the three layers were roughly of the same dimensions.

[Grant] That's true in mammals. They are, but in this particular animal they are not.

[Goldberg] [unintelligible]

[Grant] No, this is quite thick, I think it's in the neighborhood of -- I'm drawing this out of my memory which is not that good any more -- but I think it's in the neighborhood of a couple hundred microns, and this layer, the shear layer, is about 15 microns, so it's in that ballpark. So it's a quite big otoconial layer, whereas in mammals they're approximately the same thickness, so Jay's [Goldberg] absolutely right here.

[Slide 4, page 120] What we're doing here is we're taking this otoconial layer out of the animal, putting it on a shaker in a microscope stage, moving it back and forth, shaking it in a sine wave and we're tracking the otoconial layer/crystal layer motion with a high speed video. We're measuring the amplitude and phase difference between those two layers to try to map out what the thickness of the layer is by matching that to a mathematical model.

[Goldberg] Can I ask another question?

[Grant] Sure.

[Goldberg] All three layers? You said the otoconial layer…

[Grant] We take the whole utricle out.

[Goldberg]: That's what you're shaking?

[Grant] That's what we're shaking, yes, the endothelial layer. Actually we take quite a bit of tissue on either side of the endothelial layer out of the turtle and put it on this stage [slide 5, page 121]. The advantage of this approach -- first off no one has ever really measured this, there's been some measurements of the gel layer with a glass whisker. Benser, Issa, and Hudspeth [1993] did that some time ago, but nobody's ever done this with a whole utricle, as far as I know. But, it's a natural stimulation, which is the advantage of this. These are [indicates halfway down experimental stimulus slide] what we're able to do right now the amplitude of the motion of the base layer is anywhere from 5 to 15 microns. These are our minimum and maximum values. We can do it at frequency steps, which is what we've used here. These are accelerations which you generate with those frequencies and an amplitude of 15 microns. So, we can get up to almost 1G here in the process. We can't get any faster than this, which I'll talk about later on.

[Slide 6, page 121] Once you get this otolith out of the animal it gets placed on a cover slip stage, it's held in place with dental floss, and then we get it under the microscope. I've got some pictures here that are coming up. [Slide 7, page 122] This is the whole set up, this is the microscope over here, and this is the high-speed video camera. You'll notice this [camera], we had a problem with this; it's suspended from bungee cords because it weighed so much that it was driving the microscope focus downward, so we had to get some of the weight off of this microscope. Here are some pictures of the otolith image coming off the microscope, you can see individual crystals on the stage here. [Slide 8, page 122] This is a picture of the stage we're using on the microscope, this is a piece of electric driven stage we've got embedded into the micromanipulator part of the whole process here; so we actually had to machine a hole out of the stage to get in there to get everything to work, and so the specimen sits right in this area right here. [Slide 9, page 123] This shows that little stage which we've modified many times to get this experiment to work and others, but these are wires in here that you stretch dental floss around to hold it in place. If anybody has any better ideas for how to do that, I'd be glad to listen to them. We tried all sorts of ways to get that to hold the utricle in place. I can tell you that fibrinogen, or any veterinary adhesive, doesn't work, because it completely warps the whole process (or the whole utricle rather) in the process, so this is the only thing we've been able to get to work so far.

[Slide 10, page 123] This is a picture through the dissecting microscope as he's getting it on that stage. This is the top of the utricle, this is the actual otoconaial crystals you can see in here, this is the neuron or nerve coming out of there, and this is a piece of dental floss that crosses over. There's an ampulla (or part of an ampulla) sticking out on either side here, so there's a piece of floss that goes through either one of those and there's one that goes across this side. So there's three pieces of floss that hold it down. This does not hold it directly to the stage which we had to account for; there is some motion of this.

[Slide 11, page 124] This is what we do with the image once we get it. We're taking an image of the otoconial layer with this high speed video. This video camera is capable of 100,000 frames a second, we can't utilize that speed yet because of several problems that I'll get to at the end here. We have a MATLAB® program that analyzes the image that comes off of this, we filter out noise, we improve the contrast, we do a 2-D normalized cross correlation to get displacement out, and then we have a numerical sinusoidal fit to the data points to get the displacement of the otoconial layer, and we get the maximum displacement out of this fit. The data is collected as individual points in lab view so you can't get the exact point when it reaches maximum amplitude, so we have to curve fit that data and extract it from that. Right now we have a spatial resolution of 144 nanometers per pixel in the camera, which is not enough at this point, and we're taking 1500 frames a second out of this video camera, which is about a 0.7 millisecond step every time we take a picture.

[Slide 12, page 124] Displacements -- when we do this, as I said, the base or the endothelial layer does move on the stage, and so we take a reference point which is just outside of the otoconial layer and track that, and then we also take the movement of the otoconial layer so those are the two amplitudes that we measure, the crystal layer and this reference layer, and we compute an amplitude ratio from that. So, that's the data we're getting at various frequencies and amplitudes. [Slide 13, page 125] We've done seven utricles now, that's seven good utricles. I couldn't tell you how many didn't work out here. We're into the hundreds, I think, by now, because I had to up my [amount of] animal care (the number of animals allotted for this project) because we'd gone through so many. But anyway, at these three amplitudes and six different frequencies we can't see any nonlinearities in frequency or displacement. Part of that may be due to our spatial resolution which we're working on trying to solve that problem.

[Slide 14, page 125] This is a schematic of the whole experiment [Grant and Best, 1987]. If you're familiar with how a seismic instrument works, or an accelerometer, we're not operating like that. Generally, in all those, and in the utricle (the otoconial layer), displacement is measured relative to the neuroepithelial base, but we're not doing that. We're actually tracking the otoconial layer relative to the microscope frame, which is an inertial reference frame in this process, and we're tracking this reference layer, as well, and we know how we're moving the shaker stage part of this thing. So, you can write a differential equation to describe this process and it doesn't look like a transfer function for a normal accelerometer or an otolith. This is what you get down here [indicates equation at bottom of slide 14], so this is written in amplitude ratio and frequencies of ω/ω_n and this is the dampening coefficient. This is a simple second-order differential equation that describes the motion of a mass with a spring and damper. We have a term added here that's D_r, that's because this upper layer (the otoconial layer) moves a much larger distance than it would in a utricle. So, we are getting a lot more fluid shear stress up there (or at least that was the thought) so we included it in the model. So far our evidence shows that this is negligible compared to the dampening that you get in the gel layer. So, we've essentially set that term to zero in our simulation here.

[Slide 15, page 126] This is the curve of the fit of the model to the data points. These are the average of the several experiments that we have at different frequency ratios here. This one would be 10, 25, and so forth up to 125, and so you can see we have not crossed over the peak of this model curve (at this point), and the omega over ω/ω_n end point would occur right here so you can figure out what the natural frequency of the system is. [Slide 16, page 126] These are the results from this process; the natural frequency here turned about to be about 350 Hz, and these are standard deviation values over here. The dampening ratio turned out to be 1.44 and let me explain how we got those values.

[Correia] I'm still kind of hung up on this methods thing. Do you have this utricle in a bath?

[Grant] Yes! Oh yeah, it never leaves the solution. Actually, it's a Hanks balance salt solution that we kind of custom fit in our lab. We buy that, and glucose is added to it; it's pH balanced and then we measure the osmolarity of that as well as the pH to make sure it's set…

[Correia] [Unintelligible] … balanced as well?

[Grant] It is, so it's very similar to perilymph, it's high in sodium. Now, we haven't figured out how to -- Jay's [Goldberg] shaking his head back and forth here -- haven't figured out how to get an endolymph layer on there yet, we can't even get the experiment to work well yet, so we're still working on that. Yeah, Larry [Young] you had a question.

[Young] [Unintelligible] …what you'd really like to know is the effective mass of the utricular layer (not the actual mass) because every time it moves it's carrying a certain amount of endolymph with it. I think that's sort of what [unintelligible] was trying to get at, and that's sort of hard to reproduce.

[Grant] Well, the way the model is written, you don't need to do that, that's a long story. If you want to get into it, I can fill up the hour and a half easily with that, but you really don't need to take that into account the way we've got the model written. That's an issue that's been around for a long time. I can't remember who started all that, but there have been people with various predictions of adding that in there, but if you go back to the shear stress that's acting on the otoconial layer, which is what we've done, it's taken care of automatically because of what's going on in the fluids and in the gel layer. That's my explanation for it.

[Young] Are you going to tell us about the elastic component with it?

[Grant] That's what I'm getting down to here.

This is the shear modulus that came out of this. This is calculated from the other variables here and it's about an order of magnitude too small based on other information that people have come up with [Kondrachuk, 2001; Selva, Oman, and Stone, 2009; Davis et al., 2007] which I have no explanation for, other than I'm going to talk about it here in a second, so it's a quite small number in this whole thing. I will comment that the dampening ratio here also is quite low; we thought it would be more like 10 times that amount and we also thought the natural frequency would be 10 times less than this, but this is what we're getting out of the experiment, at this time. [Slide 17, page 127] The natural frequency is higher than we expected and that's just due to the fact that there's low shear stress. We may be damaging this shear layer when we get it out of the turtle and put it on the microscope stage. We've been very careful trying not to do that. It's only slightly over damped (as I said) and the only thing we can figure out as to why this thing would have a low shear modulus and not be very damped is that animals don't move around real fast [laughter]. In fact, we've done some behavior studies that show that even in a feeding strike they only generate about a G of acceleration in their head, so they move around pretty slowly. If you really wanted to up the sensitivity or the lowest value of acceleration that these things could sense, this is what you would do -- you would decrease the dampening and decrease the stiffness of that layer. So that's our speculation at this point; you can attack that all you wish but that's the only thing we've come up with so far.

[Slide 18, page 127] What we need for better resolution is a better spatial resolution in magnification, which we have done. We can increase the camera frame rate, which decreases exposure time as well. When you take a light image and blow it up you decrease the light intensity and when you increase the frame rate on the camera you decrease the amount of time that the light is on the camera, CCD [charge-coupled device] or in this particular camera, it's a CMOS [complementary metal-oxide semiconductor] lens, so that's our limit right now. We can't get any more light through the microscope than we have right now, so that's our problem. We have purchased some very intense LED displays -- they're gang displays -- and we had one, and it was the very low end of what they make and it was not quite enough. We bought the most powerful one they have and have bought heat sinks to mount these on. So, we're in the process of trying to put them under the microscope to illuminate this thing. If we can get that to work, we can also strobe it as well, as far as the camera is concerned. So we're trying to work on all that stuff, as well, to up our frame rate and illumination. I think I'm going to have to buy a new microscope. This is a transmitted light microscope, and it's not capable of being adapted for epi-illumination, which means from above. Microscopes of this sort are very expensive and I haven't chosen to spend that money yet, but I think we might be getting to that pretty quickly. [Slide 19, page 128] To increase the frequency we're going to have to build a custom stage; we've already designed that. We're going to have to get rid of this piezo one that's in there and get one that's driven by a little tiny piezo driver, which we have in place. We just haven't tried it out yet to try and help the frequency [slide 20, page 128].

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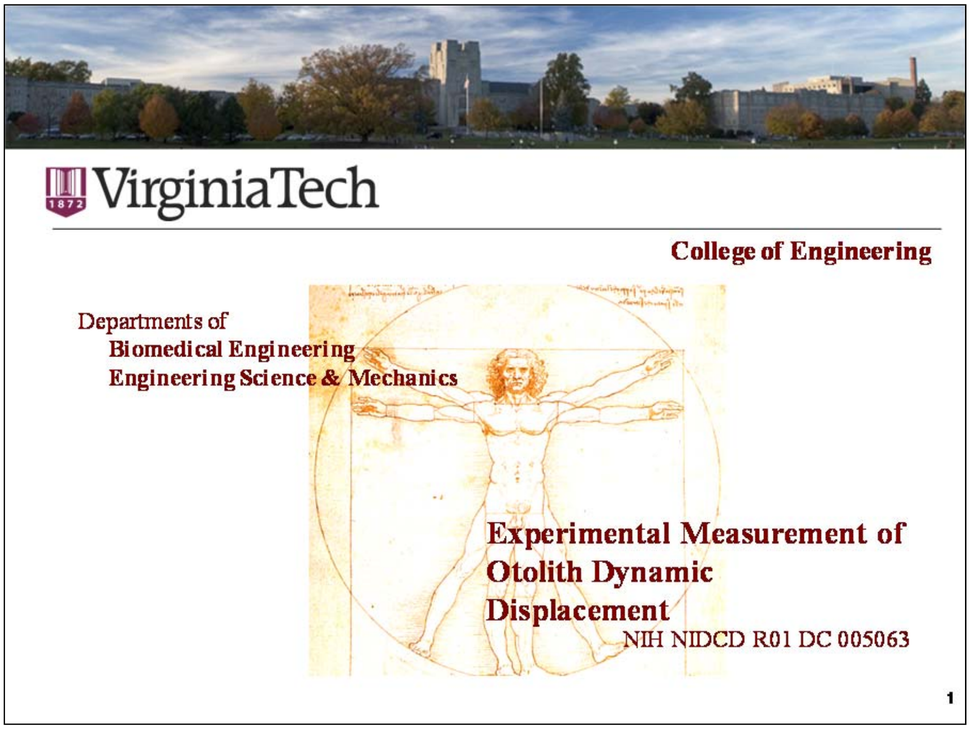


VirginiaTech

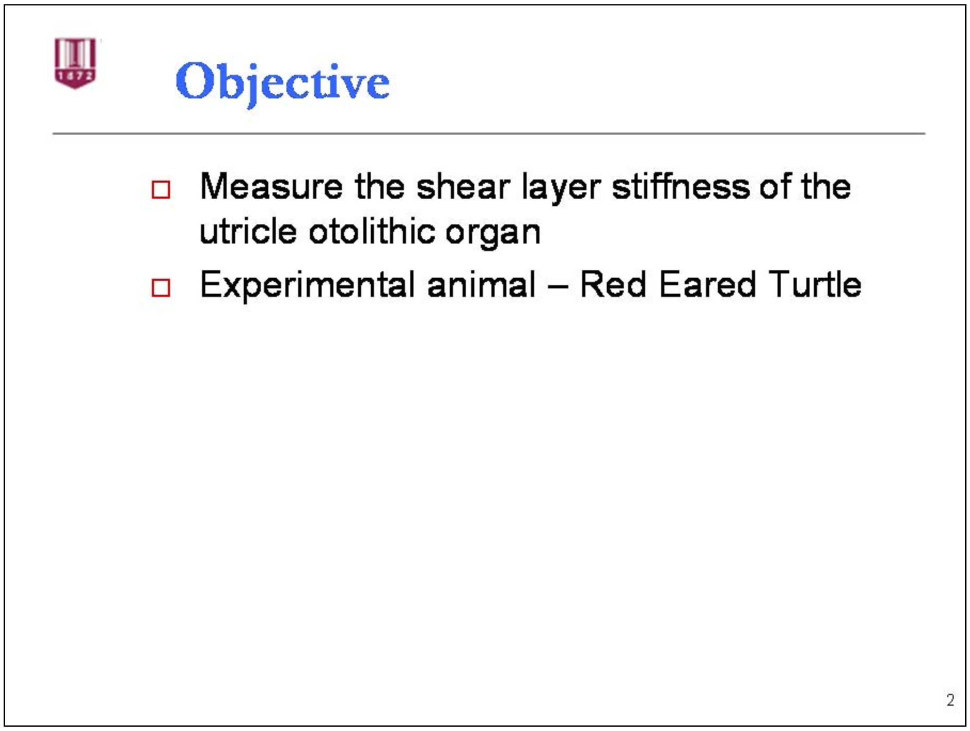
College of Engineering

Departments of
Biomedical Engineering
Engineering Science & Mechanics

Experimental Measurement of Otolith Dynamic Displacement

NIH NIDCD R01 DC 005063

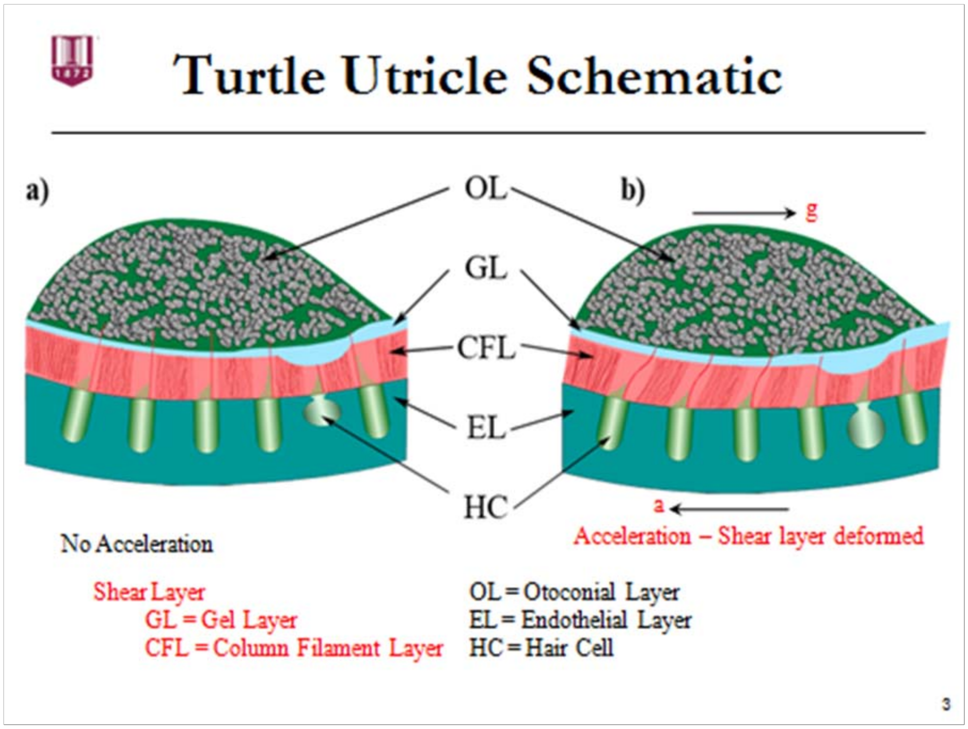
Slide 1



Objective

- Measure the shear layer stiffness of the utricle otolithic organ
- Experimental animal – Red Eared Turtle

Slide 2



Turtle Utricle Schematic

No Acceleration

Acceleration – Shear layer deformed

Shear Layer
GL = Gel Layer
CFL = Column Filament Layer

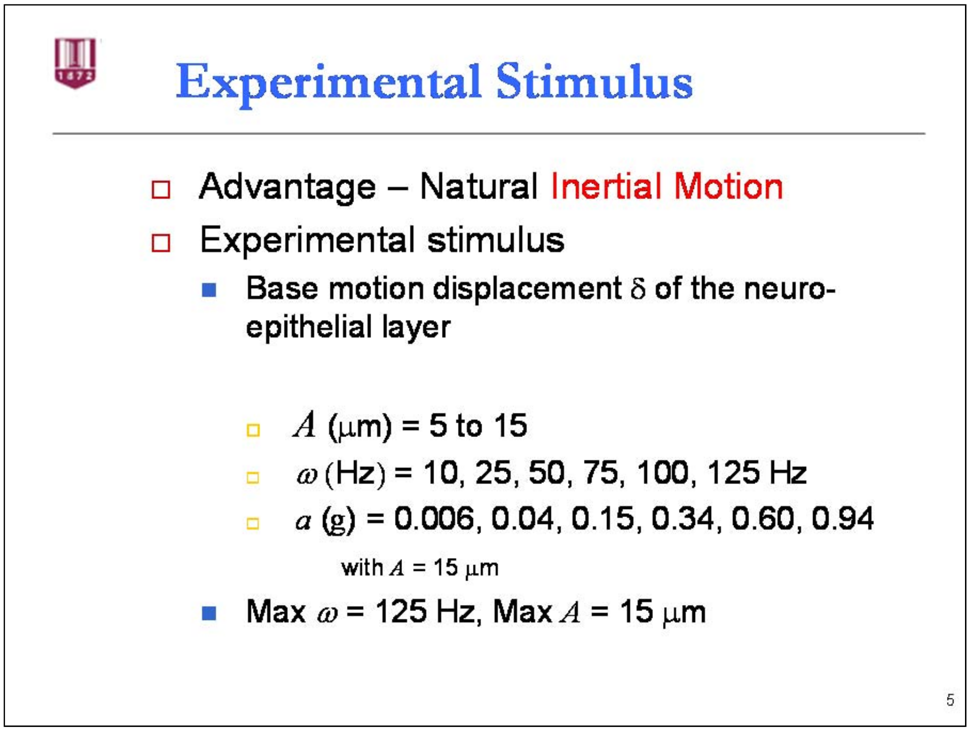
OL = Otoconial Layer
EL = Endothelial Layer
HC = Hair Cell

Slide 3

Approach

- Approach
  - Shake the otolith neuro-epithelial layer (NEL)
    - Piezoelectric driven microscope stage
  - Track the motion of the otoconial crystal layer (OL)
    - Using high speed video
  - Measure
    - Amplitude and/or phase between OL and NEL
    - Match results to model
    - Extract stiffness from model match

Slide 4

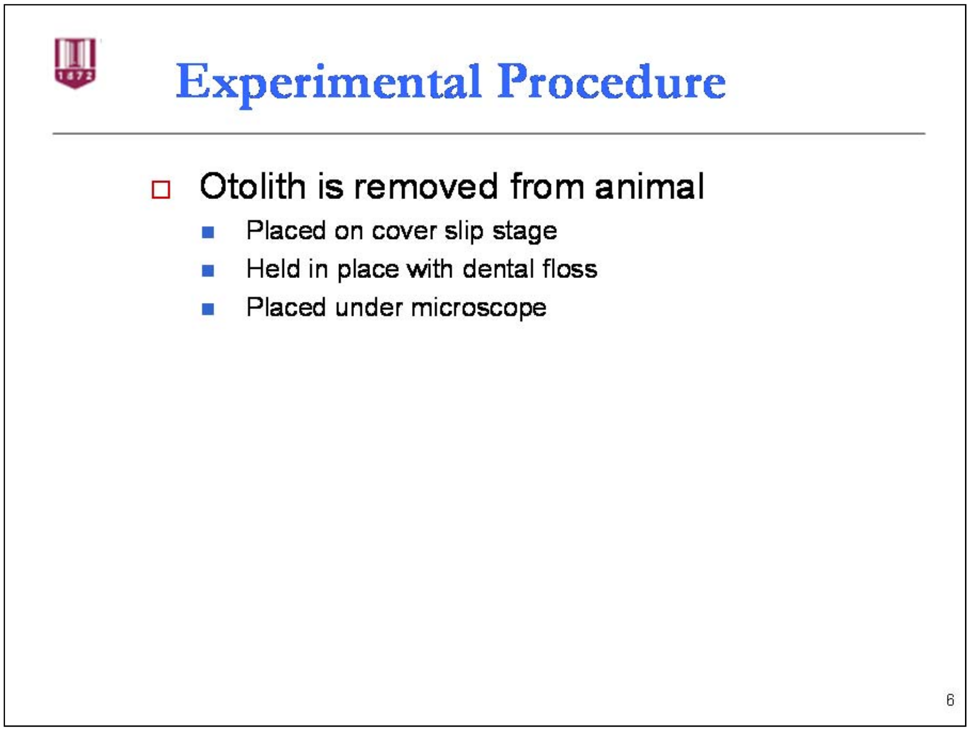


Experimental Stimulus

- Advantage – Natural Inertial Motion
- Experimental stimulus
  - Base motion displacement δ of the neuro-epithelial layer
    - A (μm) = 5 to 15
    - ω (Hz) = 10, 25, 50, 75, 100, 125 Hz
    - a (g) = 0.006, 0.04, 0.15, 0.34, 0.60, 0.94

      with A = 15 μm
  - Max ω = 125 Hz, Max A = 15 μm

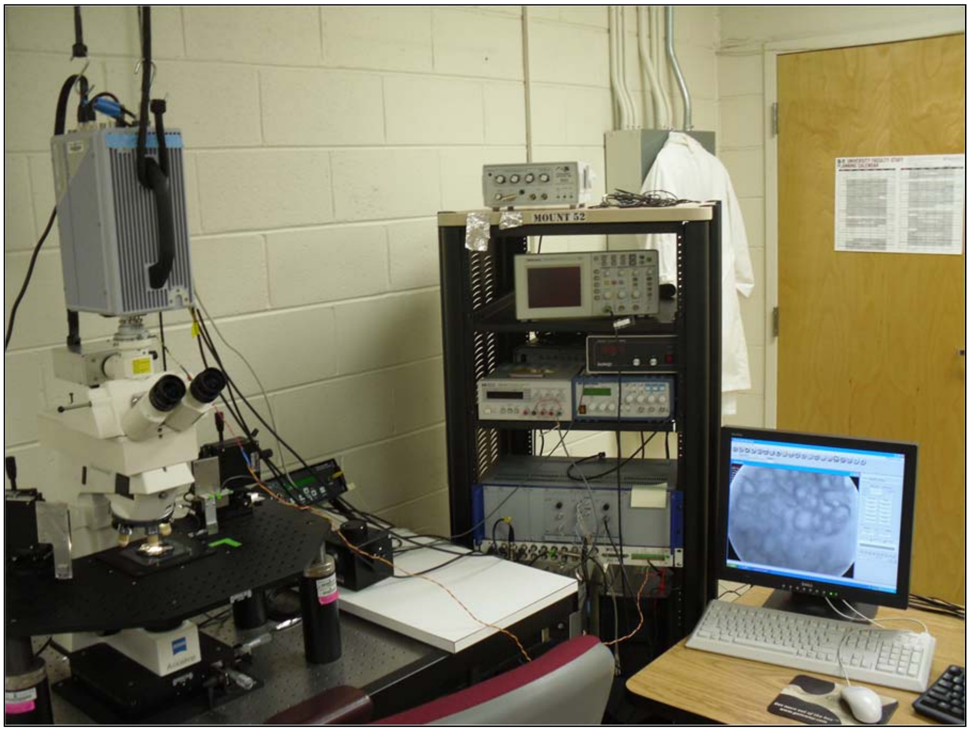
Slide 5



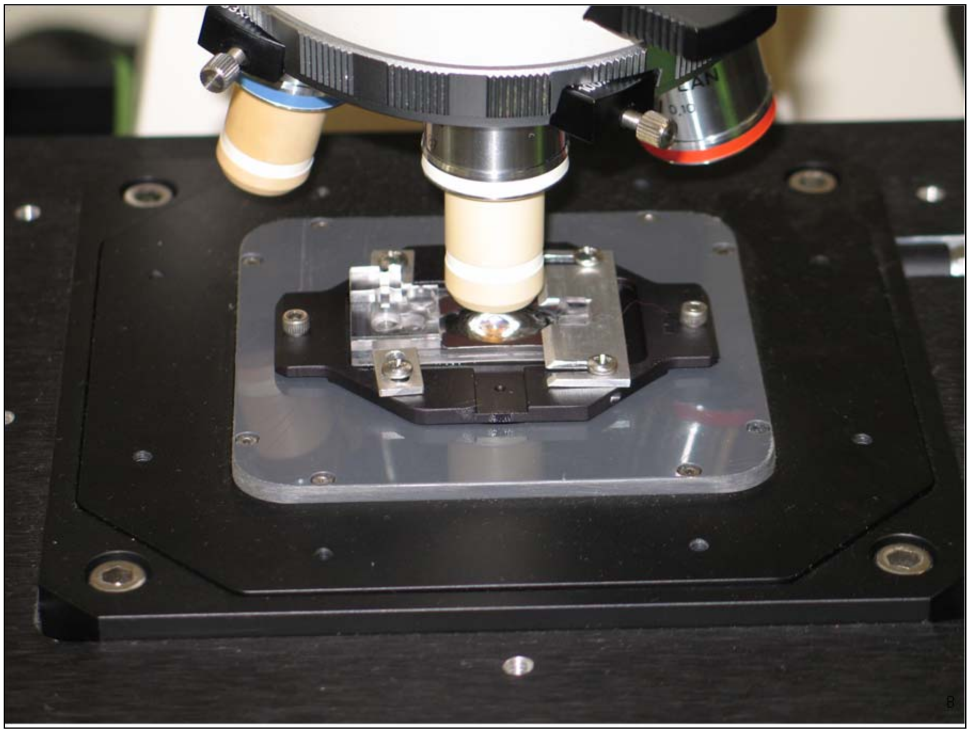
Experimental Procedure

- Otolith is removed from animal
  - Placed on cover slip stage
  - Held in place with dental floss
  - Placed under microscope

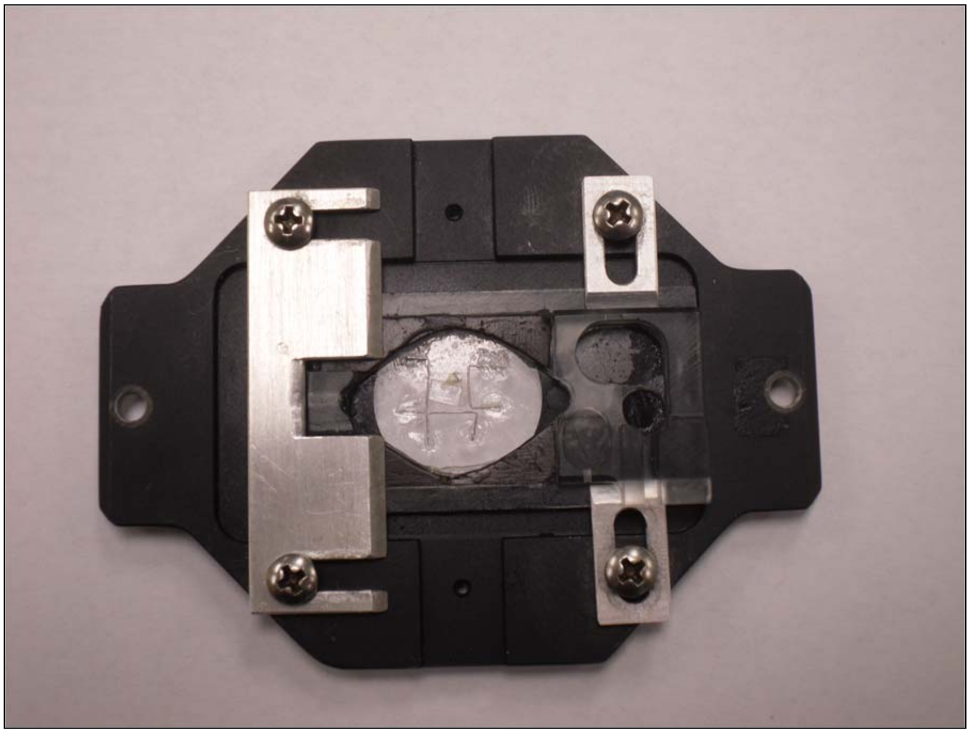
Slide 6



Slide 7



Slide 8



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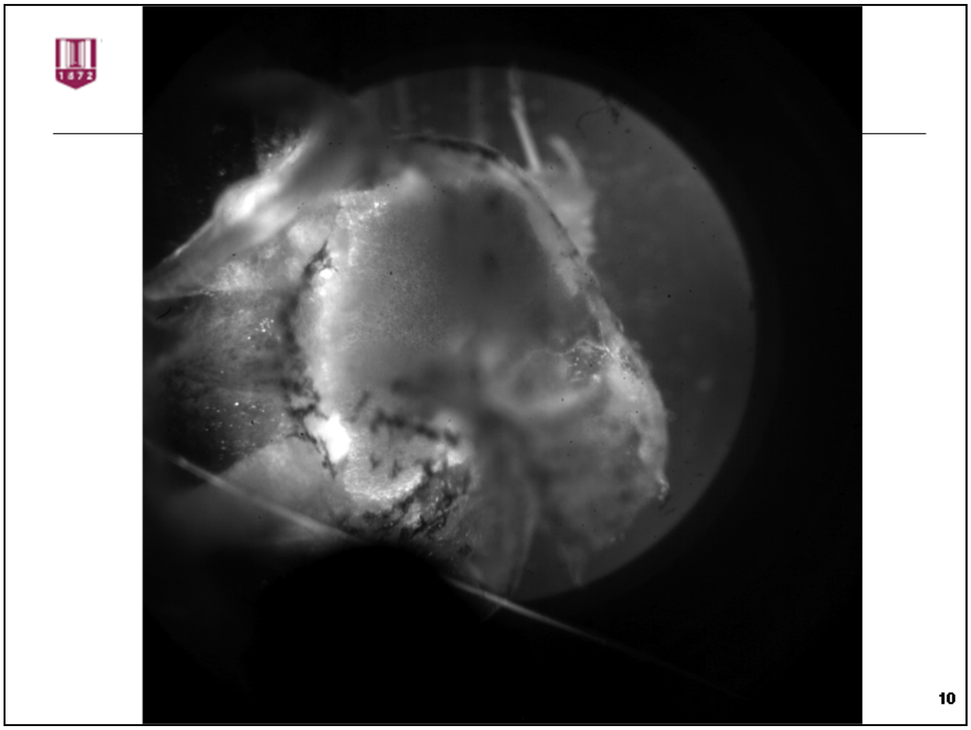
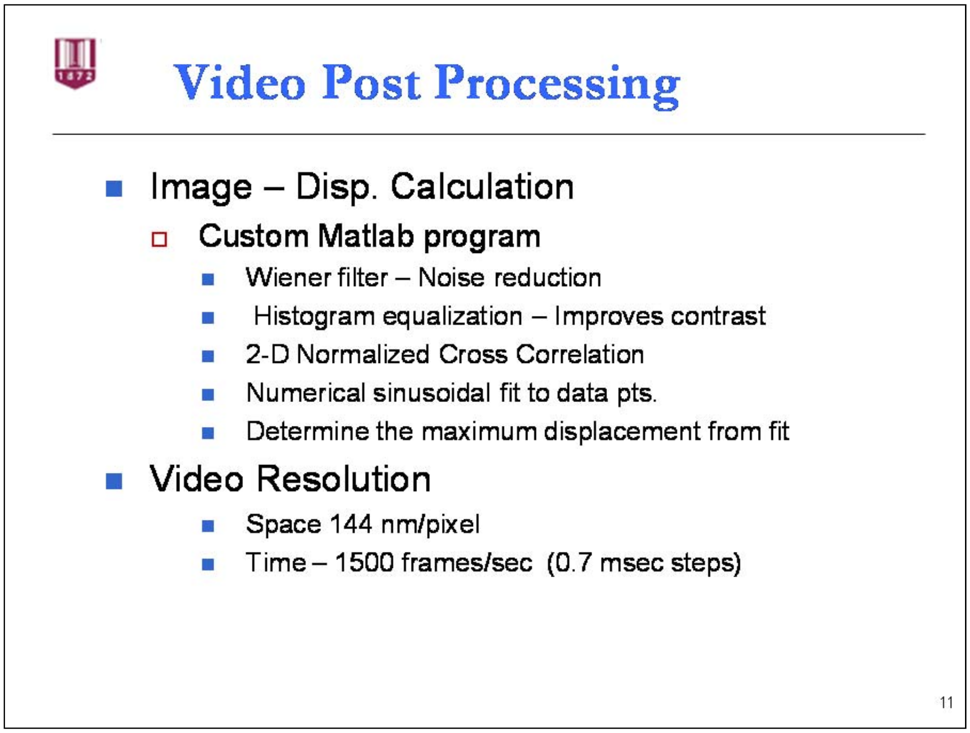


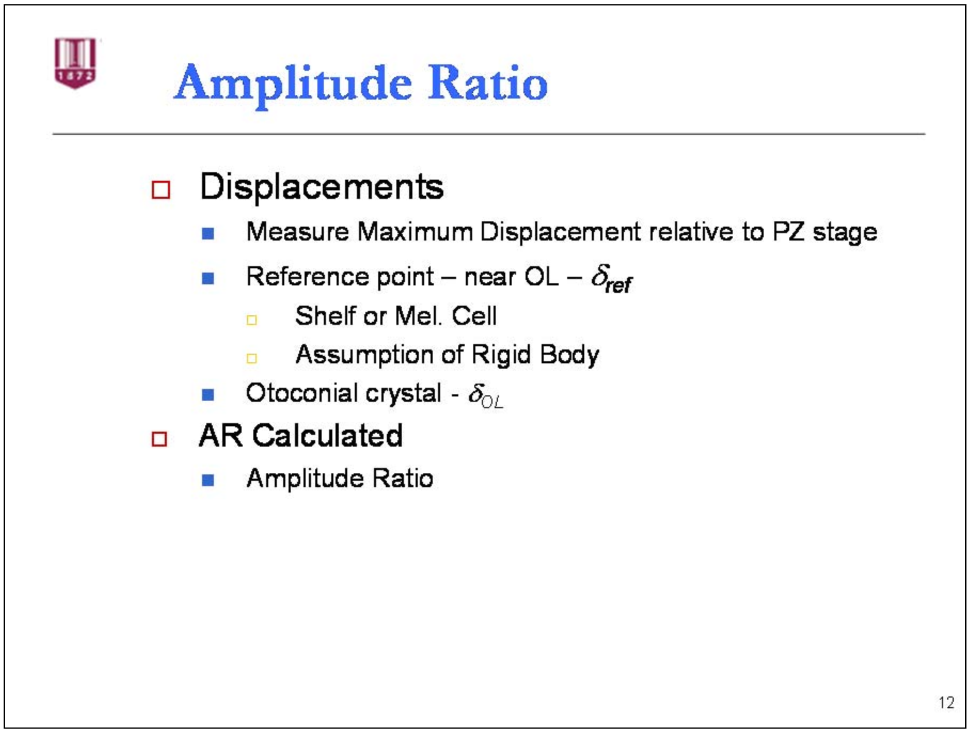
Slide 10



Video Post Processing

- Image – Disp. Calculation
  - Custom Matlab program
    - Wiener filter – Noise reduction
    - Histogram equalization – Improves contrast
    - 2-D Normalized Cross Correlation
    - Numerical sinusoidal fit to data pts.
    - Determine the maximum displacement from fit
- Video Resolution
    - Space 144 nm/pixel
    - Time – 1500 frames/sec (0.7 msec steps)

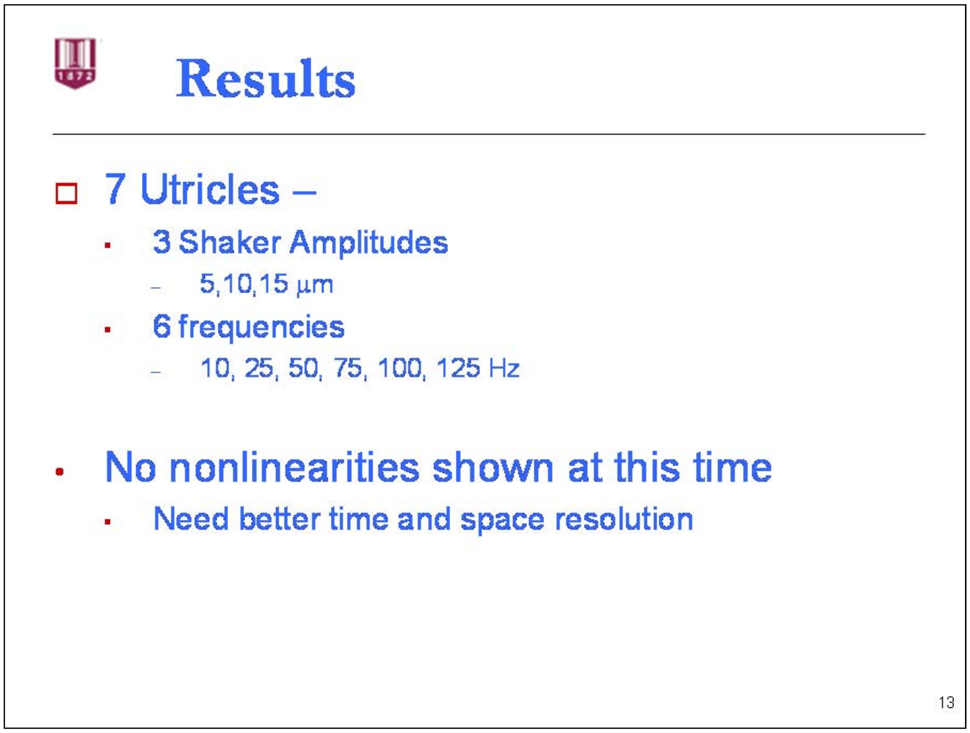
Slide 11



Amplitude Ratio

- Displacements
  - Measure Maximum Displacement relative to PZ stage
  - Reference point – near OL – δ_{ref}
    - Shelf or Mel. Cell
    - Assumption of Rigid Body
  - Otoconial crystal - δ_{OL}
- AR Calculated
  - Amplitude Ratio

Slide 12

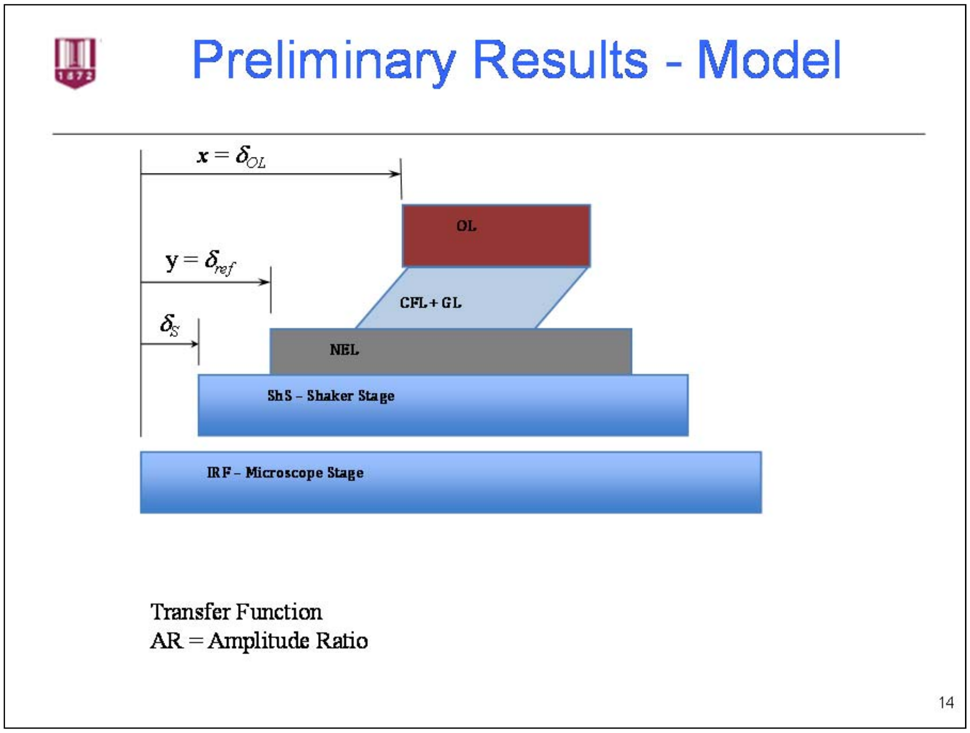


Results

- 7 Utricles –
  - 3 Shaker Amplitudes
    - 5,10,15 µm
  - 6 frequencies
    - 10, 25, 50, 75, 100, 125 Hz

- No nonlinearities shown at this time
  - Need better time and space resolution

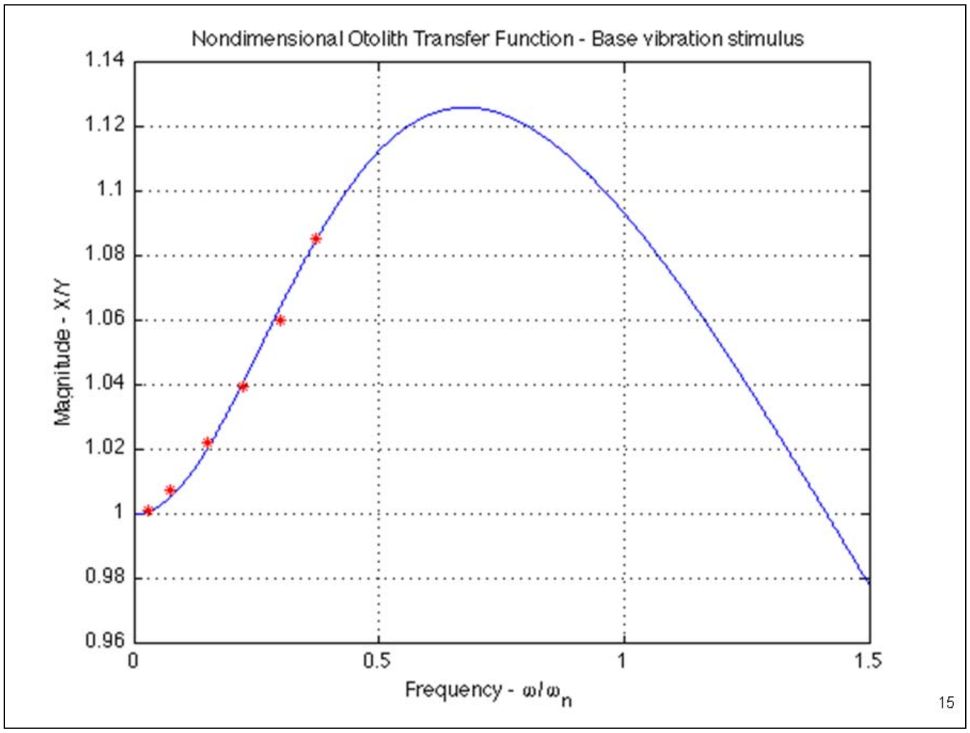
Slide 13



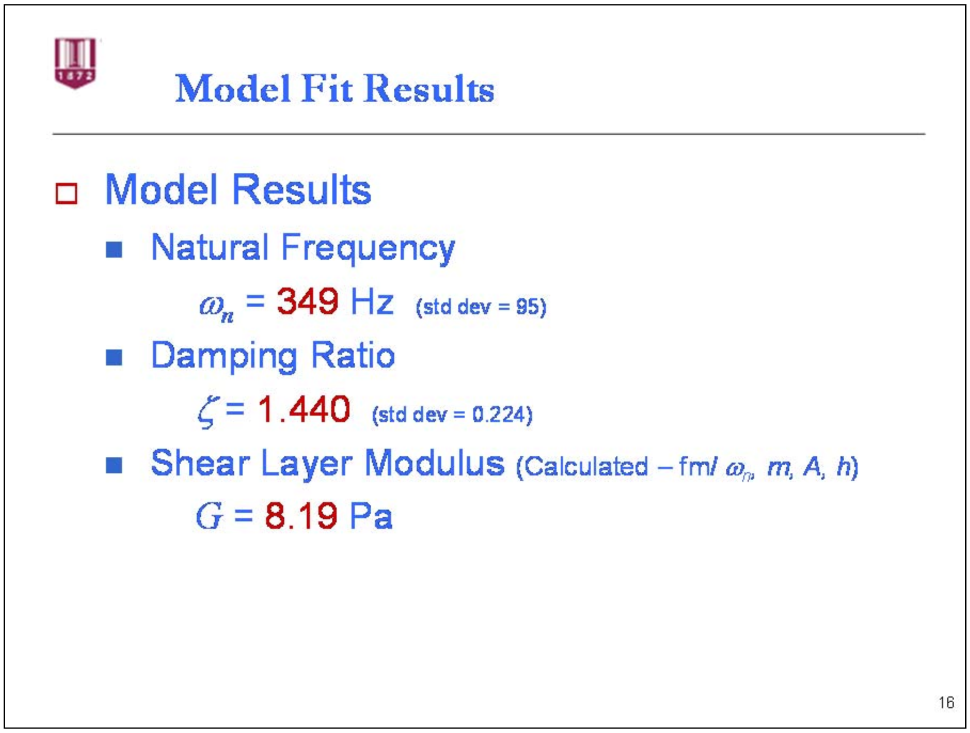
Preliminary Results - Model

Transfer Function
AR = Amplitude Ratio

Slide 14



Slide 15



Model Fit Results

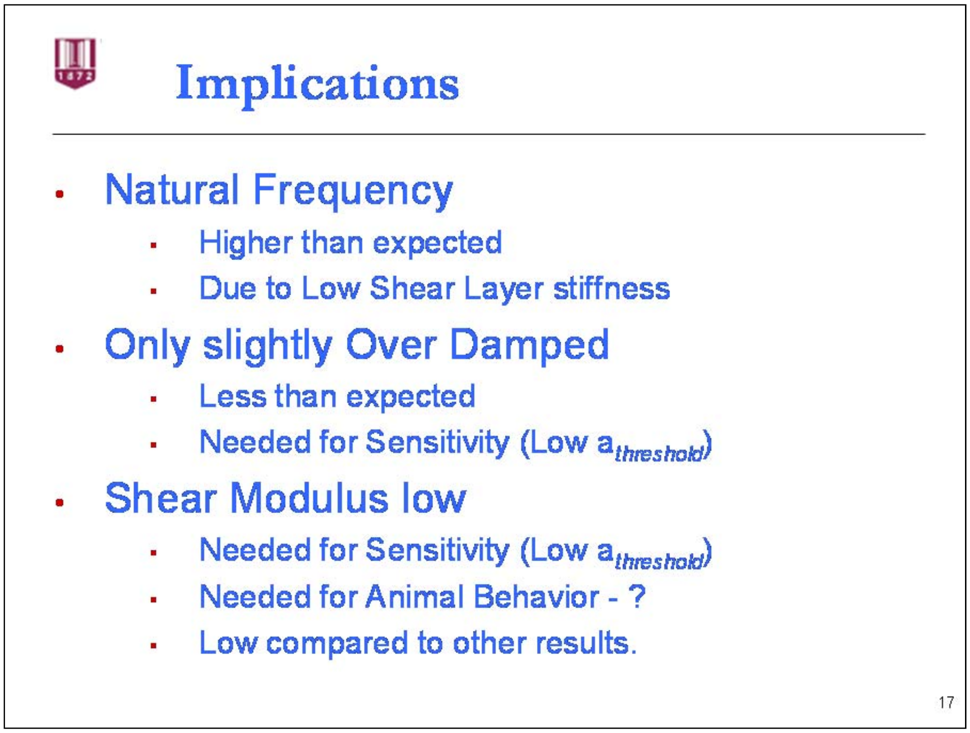
- Model Results
  - Natural Frequency

    ω_n = 349 Hz (std dev = 95)
  - Damping Ratio

    ζ = 1.440 (std dev = 0.224)
  - Shear Layer Modulus (Calculated – fm/ ω_n, *m*, *A*, *h*)

    G = 8.19 Pa

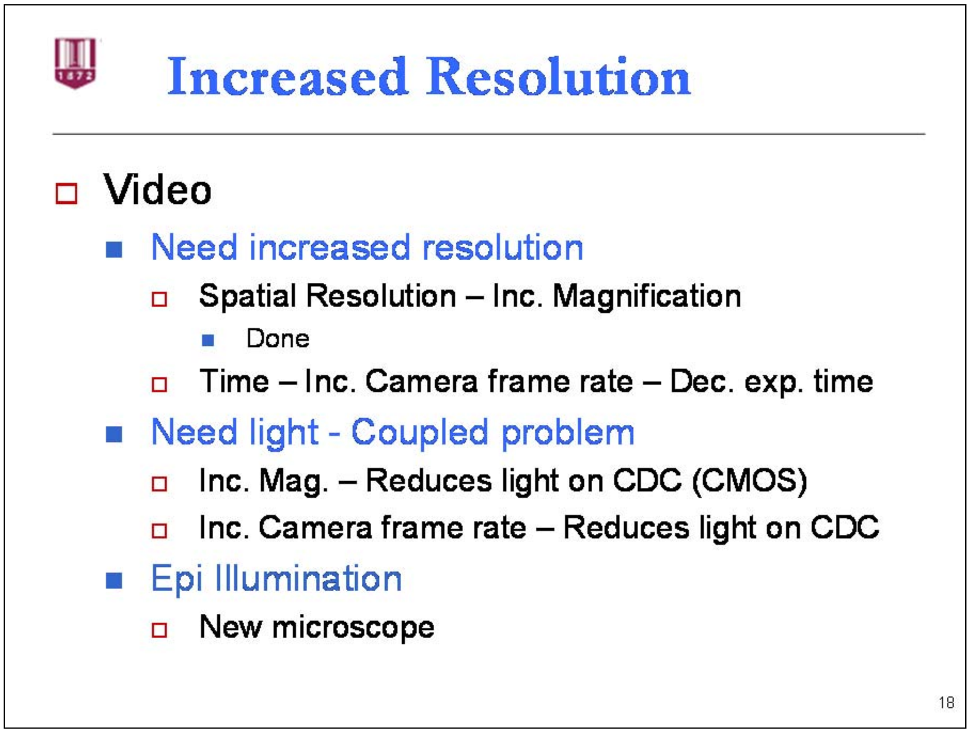
Slide 16



Implications

- Natural Frequency
  - Higher than expected
  - Due to Low Shear Layer stiffness
- Only slightly Over Damped
  - Less than expected
  - Needed for Sensitivity (Low $a_{threshold}$)
- Shear Modulus low
  - Needed for Sensitivity (Low $a_{threshold}$)
  - Needed for Animal Behavior - ?
  - Low compared to other results.

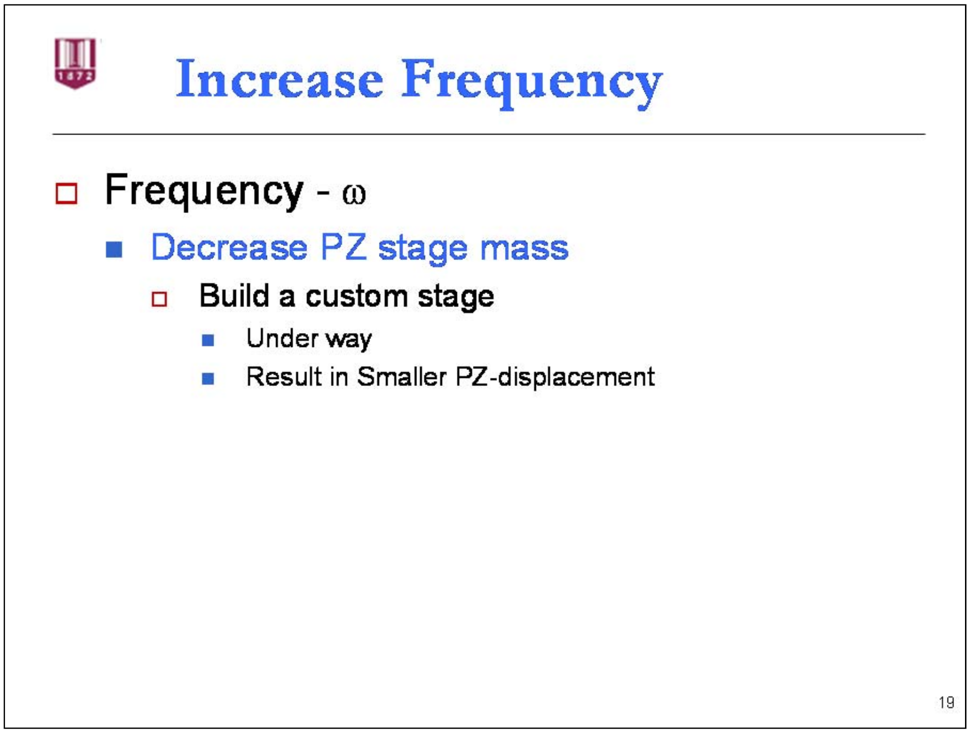
Slide 17



Increased Resolution

- Video
  - Need increased resolution
    - Spatial Resolution – Inc. Magnification
      - Done
    - Time – Inc. Camera frame rate – Dec. exp. time
  - Need light - Coupled problem
    - Inc. Mag. – Reduces light on CDC (CMOS)
    - Inc. Camera frame rate – Reduces light on CDC
  - Epi Illumination
    - New microscope

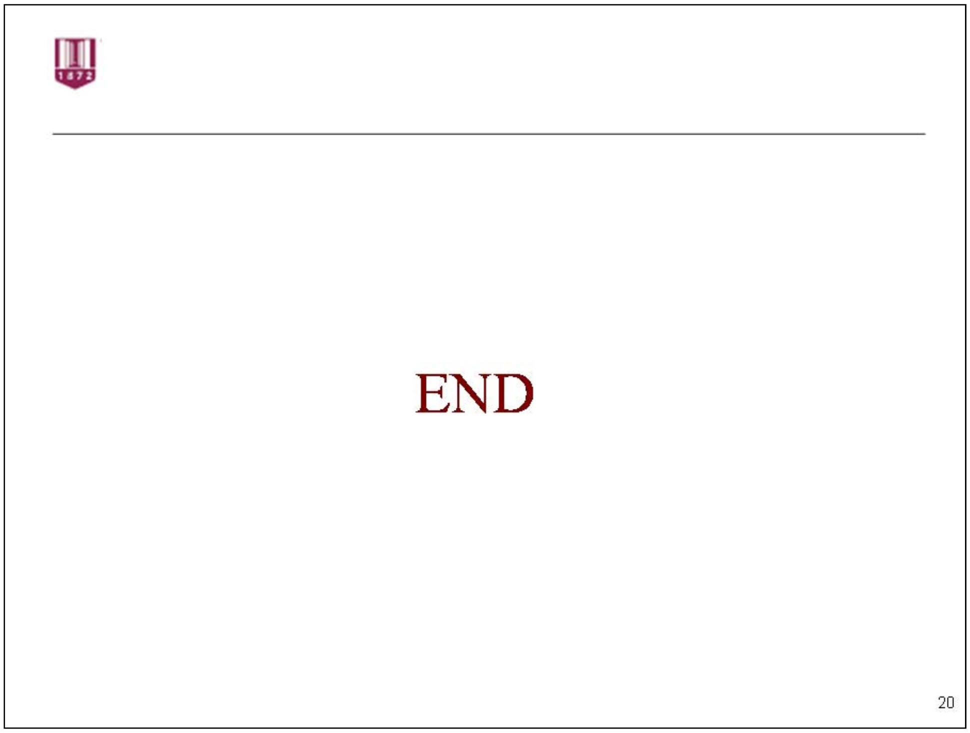
Slide 18



Increase Frequency

- Frequency - ω
  - Decrease PZ stage mass
    - Build a custom stage
      - Under way
      - Result in Smaller PZ-displacement

Slide 19



END

Slide 20

Question and answer session

[Grant] I want to say before Jay [Goldberg] talks: When we first started this, we were getting dampening ratios that were less than one, which means the thing wasn't over-critically damped. I sent Jay an e-mail, because they had done some experimental work on this same animal, and asked him if they had any indication that it was under-damped.

[Goldberg] We did not really study the...

[Grant] Yeah, he didn't. So I wanted to thank you for the comment, but go ahead with your question. Now I've totally gotten you off-track here.

[Goldberg] Well…

[Grant] That was my intention.

[Laughter]

[Goldberg] You're much more facile with these equations than I am. I suspect your results are not compatible with our results in mammals. Is that right?

[Grant] As far as the?

[Goldberg]… the Bode plots.

[Grant] No, they're not.

[Goldberg] Could you, with your finger, draw where, let's say the 45…the first-order…

[Grant] Well, the mechanical part of the system here would probably drop-off with that dampening, somewhere in the neighborhood of 200 Hz. I'm just guessing right now. In other words, our results say right now that Bode plot would be level. The gain would be level out to about that frequency and then it would start to drop.

[Goldberg] Our results were based on afference, and we said that it was a very weak, circumstantial kind of argument. I'm really pleased that somebody has gone ahead and done this. [Considering] the fact that the morphology is clearly different in mammals, I think you are going to have enough trouble with the turtles for a while, but eventually I think you should do it in mammals.

[Grant] Well, if we can get this to work, we may do that.

[Goldberg] Yeah, I think this is really great.

[Grant] Thank you.

[Young] So I thought that with the two parameters, dampening ratio and natural frequency, you have what you need to calculate the three parameters for a second-order differential, right?

[Grant] Yes.

[Young] Which allows you to predict the ratio of mass to…

[Grant] Well, you cannot calculate the mass from that.

[Young] No, but you can calculate the mass to…

[Grant] Yeah, you can calculate the ratio. We have done it. This has been published [Dunlap, Spoon, and Grant, 2012]. We have a finite element model of this exact experimental set-up where we very accurately measured that. Actually, we didn't do it, Ellen Gene Peterson did it. She's a partner in this grant. We then built this model (a finite-element model), of the utricle, and from that we were able to get a very accurate volume of the otoconial layer. We also have a pretty accurate idea of what the density of that is, and so we were able to calculate the mass. In fact, when you do that -- I don't have the numbers handy in my brain right now -- you can actually calculate the mass. You can also get k[10] [otoconial stiffness], and you can get the dampening coefficient out of that.

[Young] Good. So that's what I'm guessing you are trying to get at. So you can calculate that.

[Grant] Yes, you can get all of that. In fact, I have done it.

[Young] So two questions about k. One is, how does this compare with old measurements of k that the Dupré did 50 years ago in fish? Chuck [Oman], do you remember that?

[Oman] Yeah, I was just looking it up here.

[Oman] Dupré backed out a higher Young's modulus. It was up in the thirties.

[Unintelligible mumbling by multiple people]

[Grant] Yeah, this is all quite low. [These are] all quite low numbers. I readily admit that. Now, my personal opinion is that we are damaging this somehow or another before we get it on the stage and take the measurements.

[Young] Okay, so Wally [Grant] -- after you buy your new microscope and you don't care what happens to this one…

[Grant] Okay.

[Young] How about you put the whole thing on a swivel and tilt it?

---

[10] The undamped natural frequency (wn) of the otolith system equals the ratio of stiffness (k) over mass (m), or wn=k/m

[Grant] Yeah, we've thought about that, and that's not a bad idea except, you'd have to build a dam around it to keep the fluid on it. We've actually thought about doing that, and that's probably a pretty good plan for this transmitted microscope if we can get it. Because then, you've got exactly a static 1G force acting on the thing. This is the only really good microscope we have in our lab, and I hate to cut it off and put it on a swivel. I probably have over a hundred thousand dollars in this microscope with everything that's in there.

[Curthoys] Wally [Grant] can I just make a point following up on something I believe you told me last year that might throw some light on these different mechanical properties? And that is, is it the case in the turtle that the utricular macula is, in fact, attached to bone?

[Grant] No, it's not.

[Curthoys] Does it float as in mammals?

[Grant] It is not on bone. That is a fact.

[Curthoys] So, is it floating?

[Grant] It's stretched between. I've got a micro-CT -- if I can find it, I'll show it to you, if you can wait a second here. It is actually stretched between the two sides of the bony inner ear. The nerve comes out of the bottom of this thing embedded in the wall right where the edge of the otoconial layer is.

[Curthoys] Well that's very similar to mammals, and I misunderstood what you said last year.

[Grant] No. Since I have the time to fill here, let me see if I can find it.

[Oman, after having been called on next] I can't do two things at the same time, so I shouldn't ask him to.

[Grant] Go ahead.

[Oman] Okay. I've got one, Wally [Grant]. Do you think that most of the shearing is taking place just below the gel layer? And if so…

[Grant] I think most of it is in the column filament layer.

[Oman] And that has essentially tubes or shadows?

[Grant] There are open holes, and there are little tiny filaments of saccharide gel that connect the area.

[Oman] Okay. So when you're modeling and trying to back out the shear modulus, do you take that into account?

[Grant] That is an effective shear modulus value there. I've already put myself out on a limb here, so my personal opinion is that the hair cells probably add at least as much stiffness to this as does the gel or column filament layer.

[Oman] If they're attached?

[Goldberg] That's why I asked, were the hair cells there? Because that's certainly what [unintelligible] stuff suggests.

[Grant] Oh yeah. They said about 50 percent, I believe. In our particular case, if you do the analysis, it says if we are below 50 percent as far as what the column filament layer adds. In other words, our hair cell bundles provide more stiffness than does the column filament layer.

[Goldberg] I'm wondering whether you could get some idea of how damaged this is because this high frequency could be due to a sort of loss of elasticity or something else.

[Grant] Well…

[Goldberg] Could you fix this thing and look at the electron microscope [EM] and compare it to a normal EM and just see how badly damaged it is, or is that a bad idea?

[Grant] We've tried to figure out how to do that. I'd be glad to listen to suggestions. The problem is that once you take one of these things and put it in an electron microscope, you have to dry it out. So, unless we have created some kind of damage that you can see between the two, I don't think that'd prove much, so that's my opinion. I don't know.

[Goldberg] My opinion would be that it doesn't hurt to look.

[Grant] Yeah.

[Goldberg] Because we do have, at least in mammals, a fairly good description of what, both [unintelligible] and [unintelligible] asked about what it should look like. You know, you would throw it out if you don't think it's interpretive, but I think it should be looked at.

[Grant] We will do that.

[Goldberg] Since Ellen Gene is such a wonderful morphologist.

[Grant] Yeah, I haven't been able to talk her into doing it yet, so bottom line there.

[Goldberg] She's stubborn, but you should just keep leaning on her: Tell her I told you it was a really good idea.

[Grant] Okay [laughter]. I can use that. I am having trouble finding this scanning EM picture here. I apologize for that. Now I've lost everything else.

[Young] I've got a question, Wally -- maybe somebody else already asked. Years ago, we used to talk about the possibility that endolymph was a shear-thinning fluid, it took a certain amount of stress to get it to break down and get viscosity, and that might be attributable somehow to the threshold. I completely dropped out of that. Is there any evidence for it? You said you saw no non-linearities, but…

[Grant] We have not. You've got to understand, we haven't seen any non-linearities with the resolution and timeframe we have right now. I fully expect to see some later on.

[Young] I'm just looking at Måns Magnusson or Jay Goldberg...

[Goldberg] Well, firstly, he needs to [unintelligible] endolymph.

[Grant] That's imperative.

[Young] I know, but I wondered if others...

[Goldberg] It doesn't ring a bell.

[Grant] We have thought about taking endolymph and switching our profusion fluid because the stage is fed with a pump while we're working on it, and you turn it off when you are doing an experiment. We thought about switching it over to endolymph, which would probably kill any hair cells that are in there if we haven't already killed them. But that's a good potential [idea]. I don't know whether we can do that from the time we open up the utricle and get it on the stage, but I think there may be something to that very point. It's not an easy thing to do experimentally, I can tell you.

[Goldberg] I don't know how he did it because I just heard a paper at a meeting by Robert Fettiplace in which I think he just spritzed [sprayed] hair cells with endolymph.

[Grant] Yes, I've talked to him about that.

[Goldberg] So is that a [solution]?

[Grant] That's exactly what we are talking about doing. We have talked about switching the flow source that is profusing the stage, or just putting a micropipette in there [and] just spraying it. We'd be spraying it over the whole utricle.

[Goldberg] Yeah, I would start the sinusoidal motion and then just spritz it.

[Grant] Yeah, and then we can see if there's any changes going on. That's exactly what we've talked about doing. Good idea. That's an excellent idea because we came up with it too.

[Laughter]

[Grant] I'm sorry, go ahead.

[Magnusson] Just a short one, maybe I didn't hear. You took the top of the utricle. Would you assume that if the top had been left on?

[Grant] Yes.

[Magnusson] The space, I mean the space filled with endolymph up to the top of the utricle, could induce some kind of resistance?

[Grant] I'm sorry, say again?

[Magnusson] If you think of it as a physiological specimen (as it is) when it works within the turtle, with the top on… would [having] the top on and possible adherence of the endolymph to that top, so to say, affect the frequencies of the layers? Affect the frequency of the…

[Grant] It could have a minor effect, yeah. We've already made those calculations. In fact, when we started doing this experiment, we were trying to take the whole utricle out intact and put it down there, but we could not get enough light through all of that, and the layer of material over top because we thought that would keep it in endolymph in the process. We may go back to that, especially if we get another microscope. That might help us out there. It might work.

[Magnusson] So, Wally [Grant], when you focus up and down through the specimen, are you seeing the turbulence in the fluid?

[Grant] You can't see.

[Magnusson] Especially at high frequencies.

[Grant] You can't see turbulence. You have to put some kind of special lighting like Schlieren optics on there. We have not done that, and I am not sure we could. But it's an idea. The problem -- and that's the next talk I'm going to give here -- is about a fluid mechanics model of stimulation of hair cell bundles, but the Reynolds number in this (for those people who are engineers and fluid mechanists, at least I've got a couple of them here) for these things are down well below one, so you are way down into the non-turbulent region. So all the flow would be viscous. In fact, I don't know.

[Oman] The shearing, maybe you could talk about...

[Grant] Yeah, but now I'm pretty sure there is no turbulence, but there still might be some kind of fluid motion that could be influencing this. That's been a large argument in our lab about all that stuff, so… I don't know what the answer to that is right now.

[Goldberg] Your original models were quite surprising because many of us thought the viscosity in the system was contributed by the endolymph.

[Grant] Yes.

[Goldberg] But I thought you gave some very compelling answer that it had to be visco-elastic.

[Grant] Yeah, and I still think that. This experiment is beginning to bear that out.

[Goldberg] That's the point I wanted you to make.

[Grant] Yeah, that's true. That's absolutely correct. In fact, it's the viscosity, or the fluid shear stress acting between the otoconial layer and the upper endolymph, or in this particular case the fluid we've got above it. That shear stress even with this large amplitude that we have appears to be negligible compared to what's in the shear layer in the utricle itself. That was what you were getting at, right? Exactly. Yes, somebody else had a question.

[Unknown Speaker] This is pretty much out of my zone, but I just had a quick question. What are the chances that the characteristics of your dental floss have any influence on your data?

[Grant] Well the way you mean it's tied down, or the dental floss itself?

[Unknown Speaker] Well, the dental floss itself, [could you try to] buy three different brands [and compare them], or, you know?

[Grant] Could be, I'll try anything at this point to see if we can get something to change, but I don't think that's it. I think the way the utricle is held down to the stage, I think that can make a difference in the results. We've tried a lot of different ways of holding it down. This is the only one we've been successful with so far, and we actually stole that from somebody else who was using it. So, I can't claim it.

[Goldberg] Well, dental floss is used all the time in brain slice preparations. But, the point is, they are studying mechanics. They are just trying to hold things down.

[Oman] Your measurements are relative, so after you factor that out.

[Grant] What, the shear?

[Oman] You are measuring the motion of the layer relative to the…

[Grant] Yeah, we are actually measuring the motion of the layer, which takes out any slippage or shear of that layer. We're actually measuring the motion right on the other side of the otoconial layer. So, we are looking at how the base endothelial layer is moving. That's what we're really measuring in there. Correct.

Computational Fluid Dynamics Model of Endolymph Flow around Hair Cell Bundle − Wallace Grant

[Slide 1, page 139] This is a modeling process where we are trying to model endolymph flow around hair cell bundles and I thought for a long time (we published a couple of papers on this) about fluid stimulation of hair cell bundles, and I really think it's as important as the kinocilium being attached to the otoconial layer [slide 2, page 139]. That's my own personal opinion, but I haven't been able to prove that yet. This study incorporates computational fluid dynamics [CFD] modeling of endolymph fluid flow and its interaction with finite element models of utricle hair cell bundles. Initially non-deformable bundles were studied and this was extended to deformable bundles. Striolar and extra-striolar hair cell bundle morphologies were studied that represented those found in regions of the turtle utricle [Rowe and Peterson, 2006; Xue and Peterson, 2006]. There have been a variety of attempts to model the behavior of hair cell bundles, but never has a detailed model of a vestibular hair cell under fluid loading been attempted. Bundles in fluid stimulation have previously been modeled by Freeman and Weiss [1988] as hinged planes, and by Shatz [2000] as half-ellipsoids.

Again, we are using red-eared turtles (their hair cell bundles) as models [slide 3, page 140]. This is the same cartoon we had before where these hair cells sit in little holes that are in fact filled up with endolymph. These filaments over here represent the column filament layer; so when [it] gets sheared, the fluid is actually forced to flow around the bundles, and so it's that process we are trying to model here [slide 4, page 140]. We are doing this with ANSYS®-Fluent. Fluent seems to be okay but ANSYS® is not working so well here. ANSYS® is the finite element part of this thing and Fluent is the fluid modeling part of this thing. I don't want to get into that too deeply but I have innate suspicions of packaged elements like this, especially when they are designed, to actually model aircraft. I shouldn't say that in front of [an] aircraft audience here [laughter], but this thing is not working that well. Ultimately, we have usually gone in [the direction with] all this modeling stuff [i.e., efforts] to writing our own code and I think we're going to head that way pretty soon, but anyway these results were done with that [program]. The volume we are modeling is about a is 10 by 10 by 10.5 micron size; we have a shear flow in here and the size of the volume match what the wall will be doing as far as displacement is concerned here.

[Slide 5, page 141] This is the velocity profile, it's essentially a shear flow linear, with height. This is the otoconial layer height, this is about the height of the tallest stereocilia in some of the bundles we are looking at and we have a maximum velocity here that runs anywhere from 1 to 10 microns/milisecond here for velocity [slide 6, page 141]. The bundle types come out of a red-eared turtle again, we look at the striolar and an extra-striolar bundle.

We have several different models here. I'm going to talk about the first we looked at; Non-deformable bundles and the fluid flowing around them to get this to work, and we have results for that. We are now looking at deformable bundles and without any cilia interconnections, no lateral links, no tip links, we can get that to work. Once we interconnect these things, we have an awful time getting this to run, and we have got some results lately. These are overnight runs on a computer -- they are not fast solutions. I can get into all the details of that if you are really interested, and we have a computer that we custom-built for this. I forget what the processor is, but it's the fastest one they make at the present time, then we have juiced it up with the same technique that gamers use to speed up the clock in a computer, until you start getting storage problems, so we have gotten it as fast as we can go right now.

[Slide 7, page 142] So these are non-deformable results. I've got pressure distribution and shear stress distribution. [Slide 8, page 142] So this is the striolar bundle that we put together, this is the kinocilium, and this will give you the pressures over here, and these little lines you see around here stream blinds and you can get velocities from them. You can see that pressures here are quite high at the upper part of the kinocilium in this particular case.

[Slide 9, page 143] This is an extra-striolar bundle in this particular animal and this is what it looks like. It's quite low in stereocilia, in number and height and they are elongated like this, as well, so the fluid-flow streamlines that you can see around these things are in that fashion.

[Slide 10, page 143] This is a top view of striolar bundle, right above the endothelial layer. This was the first time that we came to the conclusion that there is virtually zero flow through the middle of the bundle -- all the flow is around these guys, it's such a viscously dominated environment. Fluid does not flow through there, so you can see these streamlines go around there. These are quite fine if you can make these things finer, it just takes longer run time to do it, but with this thing you can see there are no streamlines that really go through there, these on top of the bundle are really above these lower shorter sterocillia and [slide 11, page 144] here is a top view showing all the flow profile around it. This is a side view [slide 12, page 144]. This was a lower profile you saw, and you can see these ones that you saw going over the top, actually flow up and over the top of this thing, and this was the upper profile. There is an intermediate I didn't put in here [slide 13, page 145]. This is a result we didn't expect from this; there is a significant pressure on the rear of these things, and when this fluid flows around them they get not only pushed by the flow coming in, they are sucked by the fluid flowing around them as well, and that was a result we didn't really expect. In fact, the negative pressure on the back adds almost as much -- if you looked at the overall force on this -- as does the flow coming in the front of these things.

[Slide 14, page 145] This is the wall shear stress. Those were pressure forces, these are shear stresses and again, shear stresses out here on the periphery are the highest because that's where the fluid is flowing. Interestingly enough, this shear stress on these outer periphery bundles or stereocilia produce a moment on these things and they actually get torqued and it gives you an abnormal deflection in the process. I'm beginning to think this is one reason why lateral links are so prominent in this area -- to keep those things from being torqued too much [slide 15, page 146]. Here is a no link same velocity profile picture [slide 16, page 146]. You can see (that's not a very good [picture]) but here's a side view [slide 17, page 147] so you can see these upper ones, which is where most of the force is applied, are being pulled away from the main part of the bundle. As soon as we start connecting these things up (which we have done) that does prevent this but our results are rather inconclusive at this time [slide 18, page 147]. I'm not going to be presenting any of that, so I'm done. Questions?

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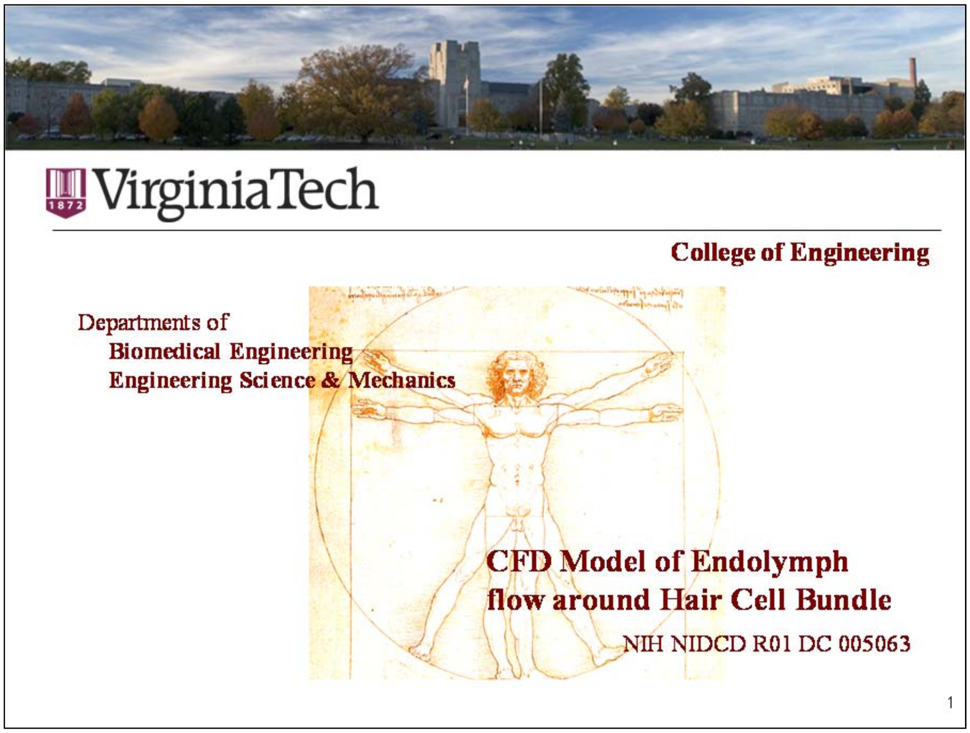


VirginiaTech

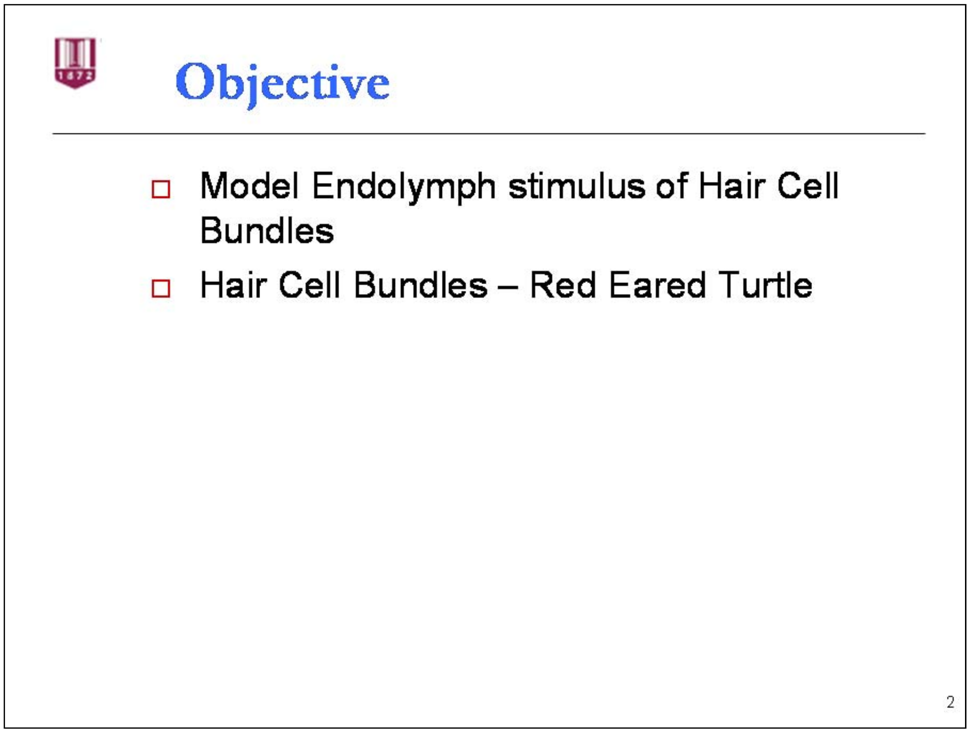
College of Engineering

Departments of
Biomedical Engineering
Engineering Science & Mechanics

CFD Model of Endolymph flow around Hair Cell Bundle

NIH NIDCD R01 DC 005063

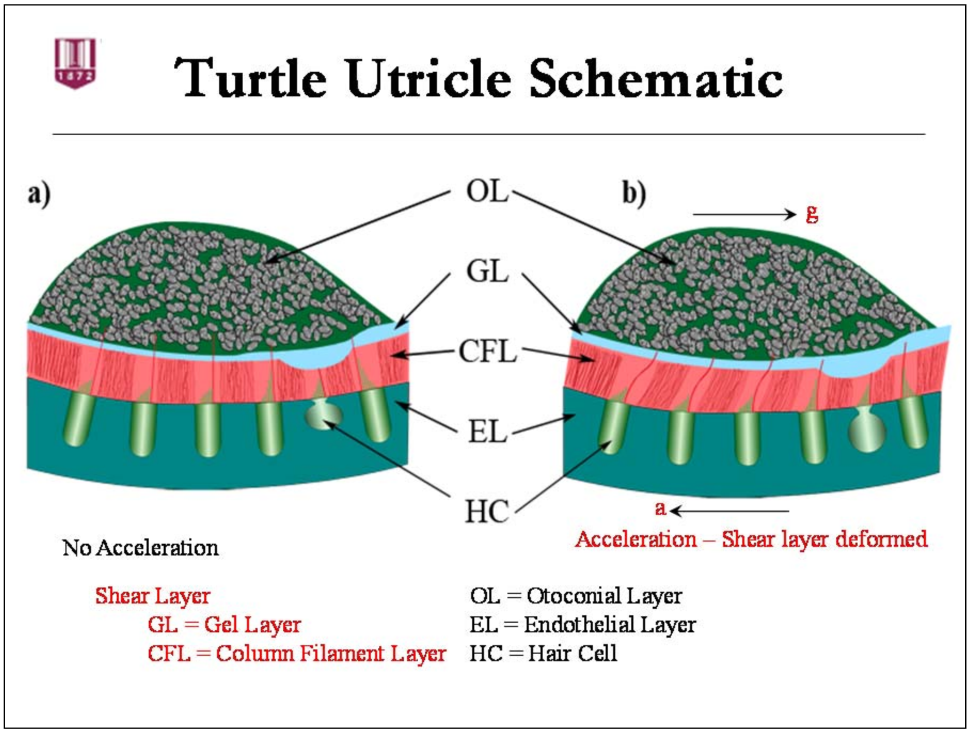
Slide 1



Objective

- ☐ Model Endolymph stimulus of Hair Cell Bundles
- ☐ Hair Cell Bundles – Red Eared Turtle

Slide 2



Turtle Utricle Schematic

No Acceleration

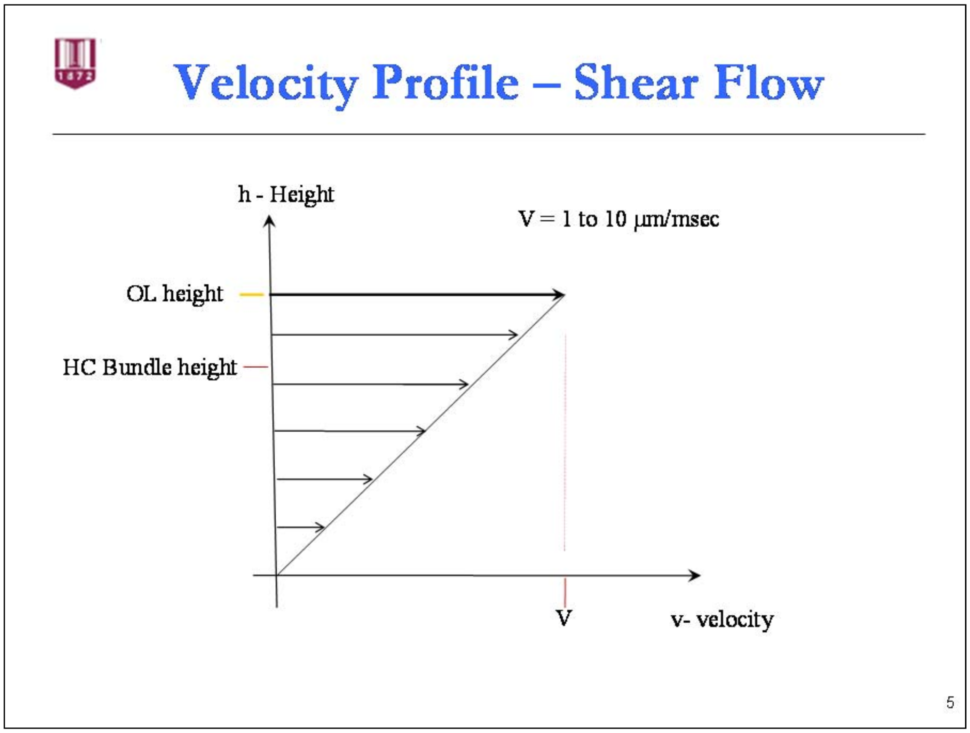
Acceleration – Shear layer deformed

Shear Layer
GL = Gel Layer
CFL = Column Filament Layer

OL = Otoconial Layer
EL = Endothelial Layer
HC = Hair Cell

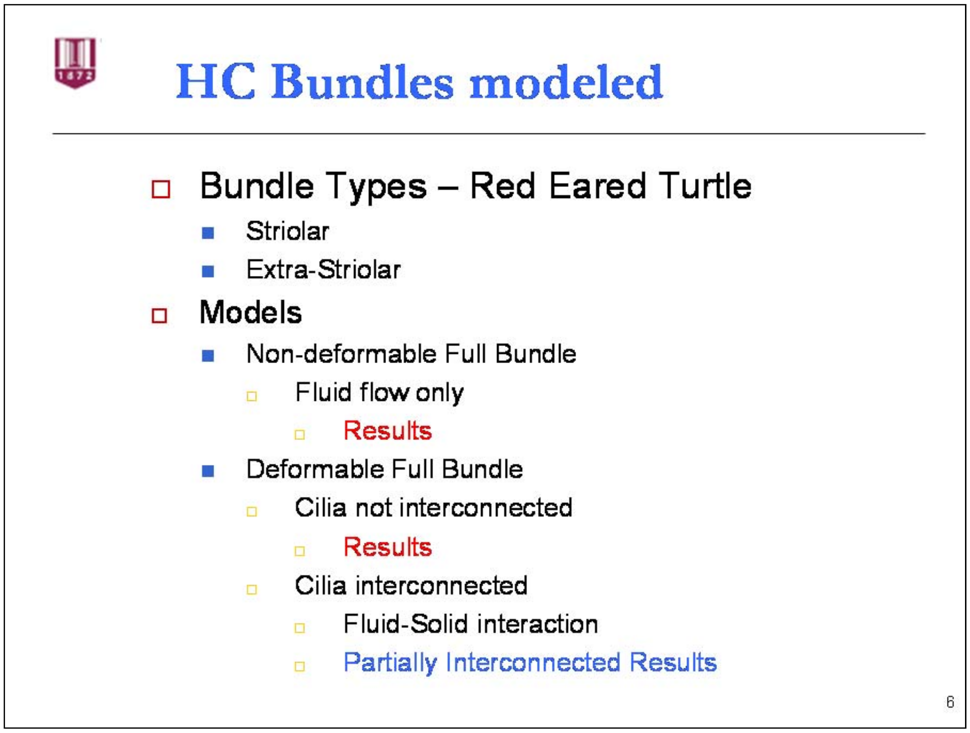
CFC Model

- ☐ ANSYS-Fluent
- ☐ Volume Modeled
  - Size in μm – 10 x 10 x 10.5 high
  - Velocity Profile – Shear flow
  - Sides of Volume follow bulk shear flow



Velocity Profile – Shear Flow

Slide 5



HC Bundles modeled

- Bundle Types – Red Eared Turtle
  - Striolar
  - Extra-Striolar
- Models
  - Non-deformable Full Bundle
    - Fluid flow only
      - Results
  - Deformable Full Bundle
    - Cilia not interconnected
      - Results
    - Cilia interconnected
      - Fluid-Solid interaction
      - Partially Interconnected Results

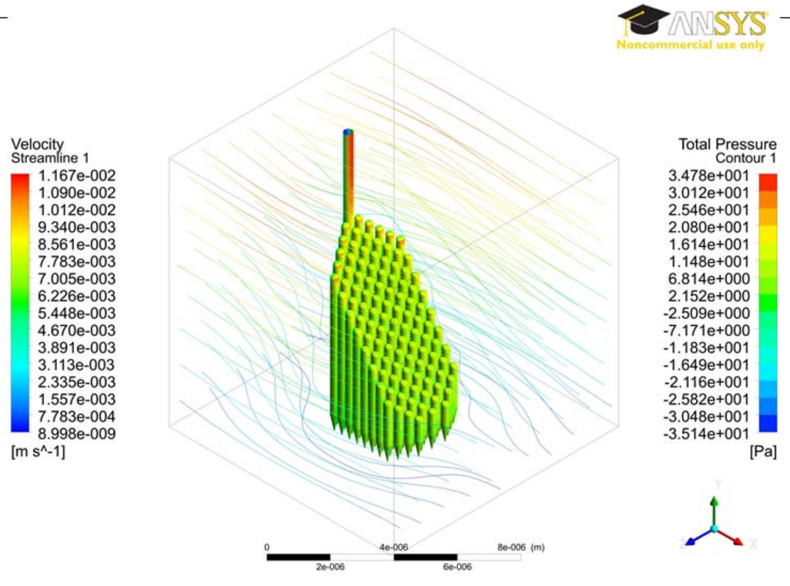
Slide 6

Non-Deformable Bundle

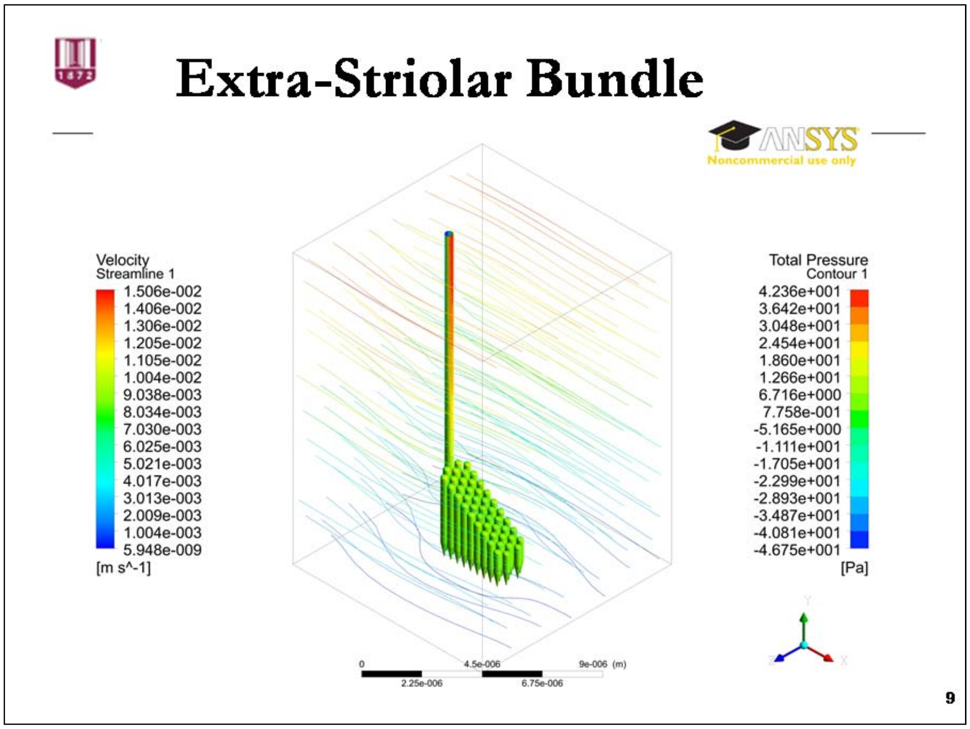
- Fluid flow
- Pressure distribution
- Shear Stress distribution

Slide 7

Striolar Bundle

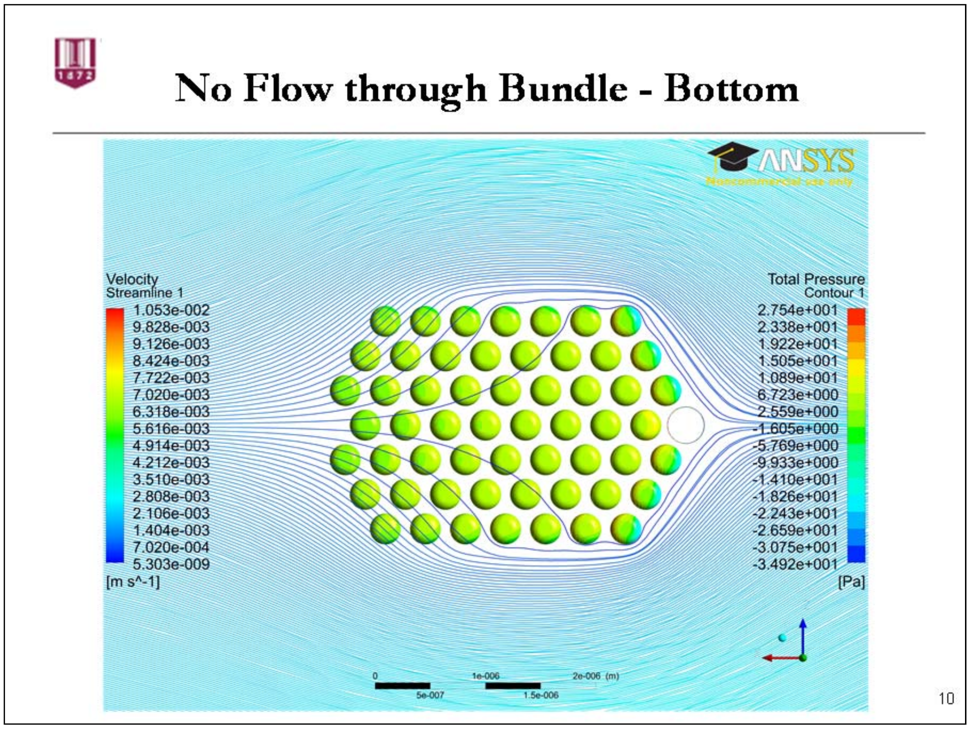


Slide 8



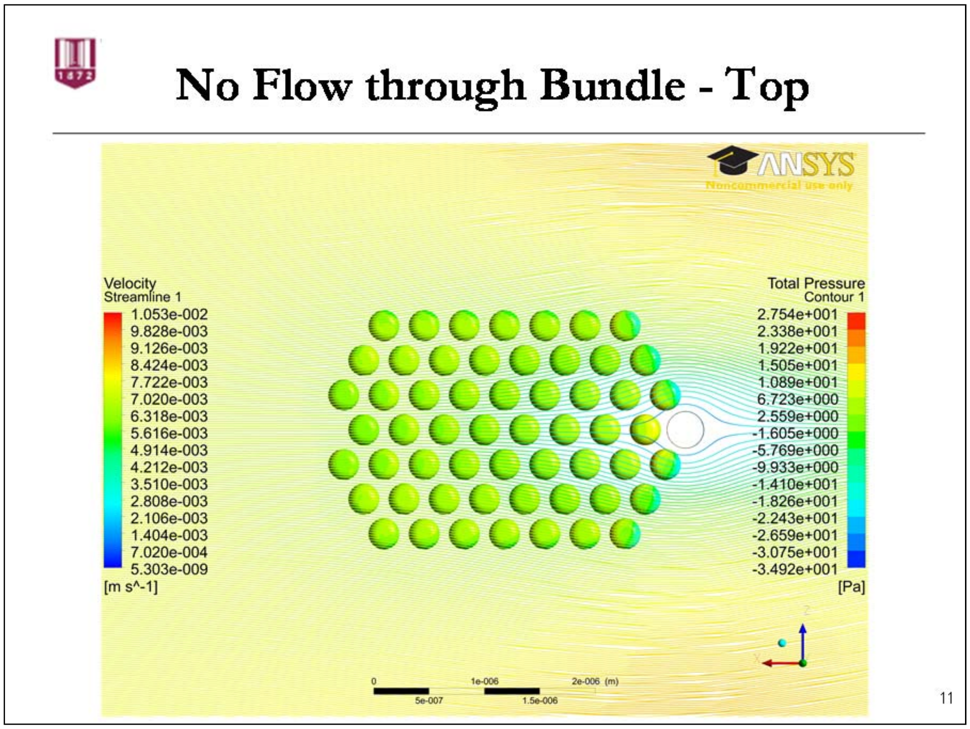
Extra-Striolar Bundle

Slide 9



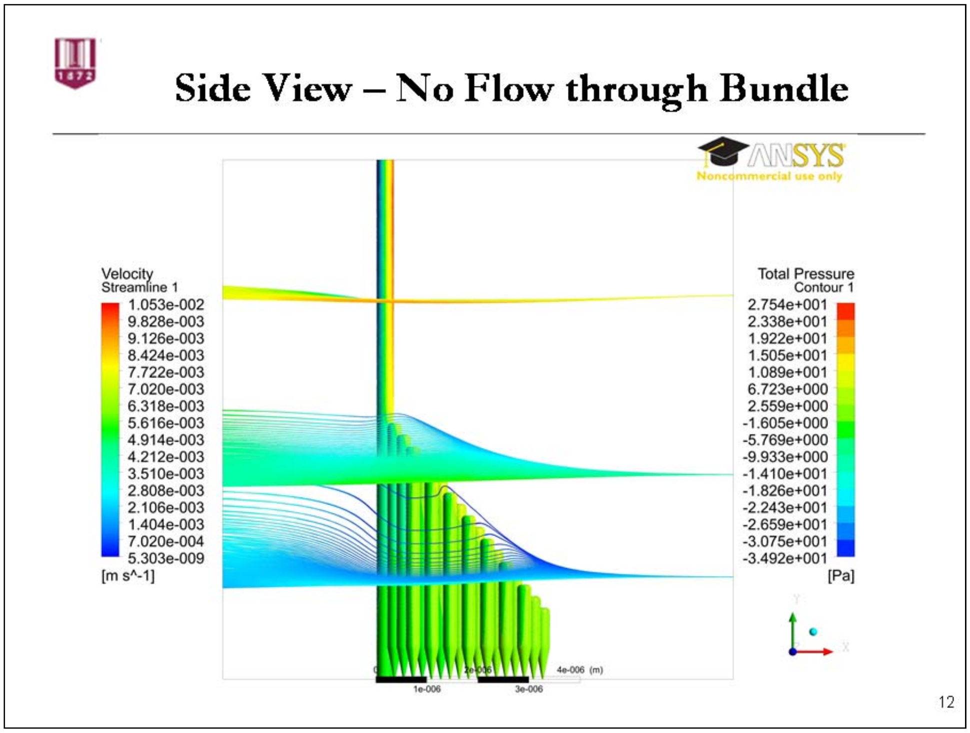
No Flow through Bundle - Bottom

Slide 10



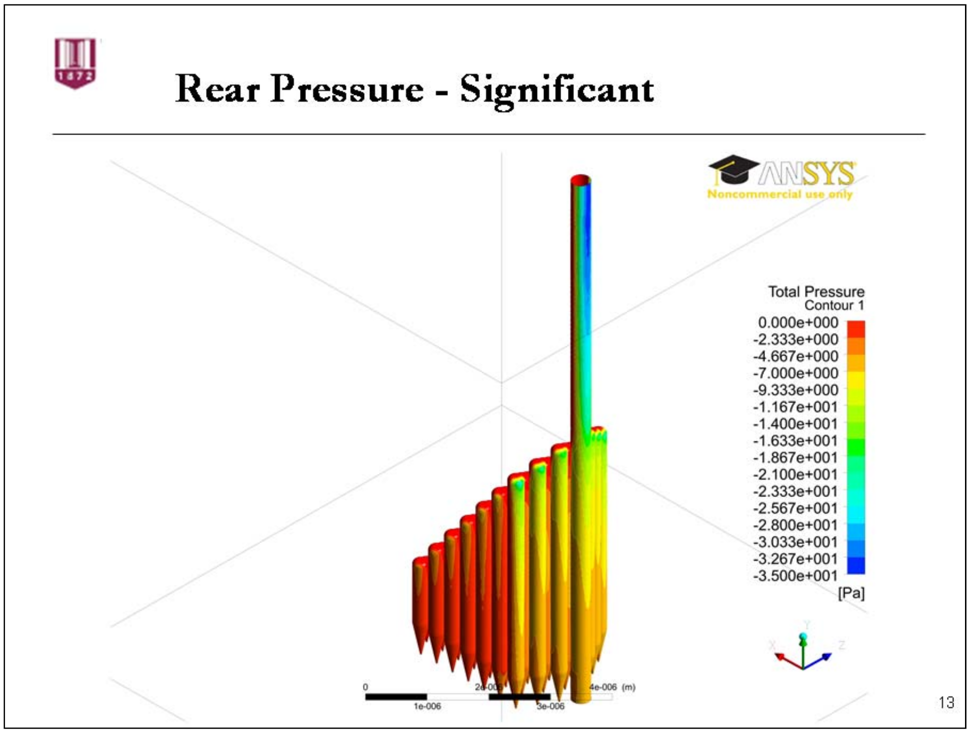
No Flow through Bundle - Top

Slide 11



Side View – No Flow through Bundle

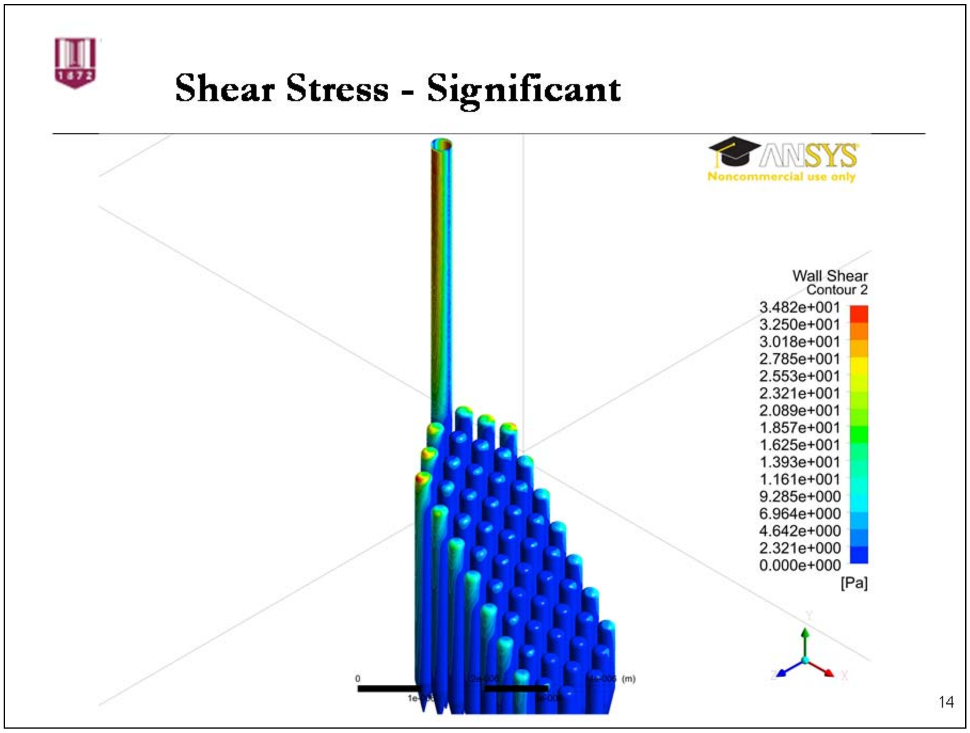
Slide 12



Rear Pressure - Significant

13

Slide 13



Shear Stress - Significant

14

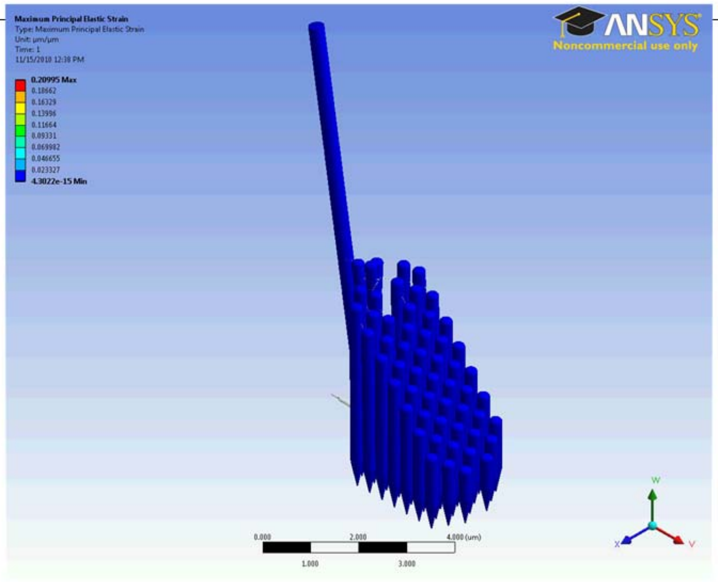
Slide 14

Deformable Bundle

- No links
- Same velocity profile

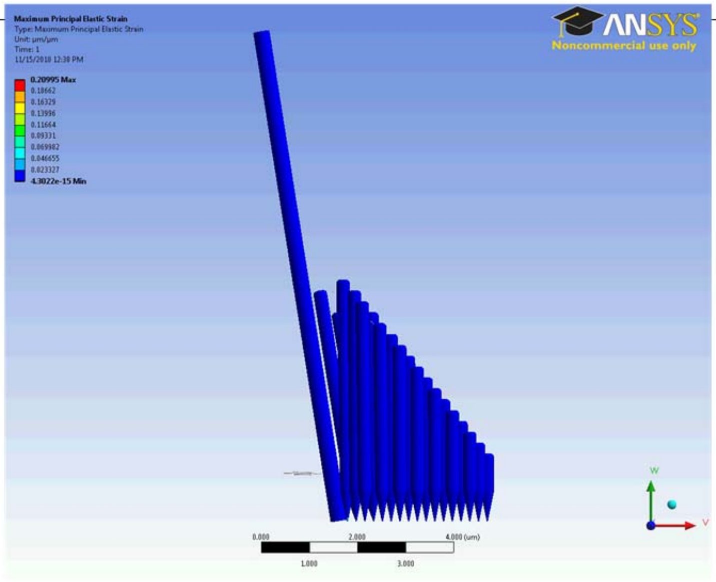
Slide 15

Deformable Bundle



Slide 16

Deformable Bundle



Slide 17

END

Slide 18

Question and answer session

[McGrath] When I was with Ian Curthoys we looked at doing the cupula deformation, and the thing we found is that with all the commercial codes, because the Reynolds number is so low in this, none of the commercial codes really worked.

[Grant] This one does. That is one of the reasons that this is a quite expensive piece of software.

[McGrath] The fluid part of it?

[Grant] Yes, the academic license is $20,000 a year, and my share of that is $2,000 a year, which is another incentive for us to start writing our own code to solve these things. Besides, I think our code would work better than theirs does.

[McGrath] Yeah, we came to the same conclusion.

[Grant] Yeah, but now, the Fluent part works nicely. What it doesn't do is interact with the finite-element part, the solid motion part of this. There is a solid deformation part of the program that does not work well at all. This code was really developed to design aircraft wings and structures, where it's not a… you've got a compressible fluid and the numerical solutions of Navier-Stokes equations are much simpler for a compressible fluid than for an incompressible fluid, and so, the interaction of that on an aircraft wing is pretty straightforward. Alright. So, all the aircraft you flew here on were designed using the same code, I'm sure. It doesn't work very well on hair cells though. Yes?

[Goldberg] Well, granted the way I understood it, this is a work in progress.

[Grant] Yes, it is, very much so.

[Goldberg] So, what is your intuitive appeal? You said you started out with a working hypothesis that the fluid motion would be a stronger coupling for the bundle, as for example [i.e., versus] the conventional motion that is largely being transmitted through the kinocillium, or essentially being attached to the wall.

[Grant] We have done nothing to make me believe otherwise so far.

[Goldberg] That's all I really asked.

[Grant] I think in fact that it may be more significant than the mechanical attachment part of this, especially in a high-speed situation. I really think that, -- I will go out on a limb again and say -- I think these bundles that are in the striolar region are really jerk sensors or startle sensors, however you want to look at it. I think this is designed so that you get a very rapid deflection, and the central nervous system interprets that as an initiation of an acceleration. I still think that's true. I think that's what's going on here. In fact, our… I shouldn't have said that -- I can tell right now.

[Laughter]

[Goldberg] Yeah, I was going to say… our [work] in mammals does not suggest that. Is that because we are not high enough in frequency?

[Grant] Could be. I would think so. Very much so.

[Goldberg] You know the turtle ear does have a jerk sensor. It's called the papilla neglecta.

[Grant] Yeah, I do know that, but we have enough trouble with the utricle right now.

[Goldberg] Oh yeah, I know.

[Grant] But that's a good suggestion and we have thought about that. That is a very good suggestion.

Update from Sydney − Ian Curthoys

[Slide 1, page 162] I have never worked with Fred [Guedry], but about 6 or 7 years ago I came up to Neuroscience in New Orleans [LA] and Angus Rupert came over, saw my poster and said, “Why don’t you come over and say good day to Fred?” Since I had come about 10,000 miles or something to get to New Orleans, I thought, “Why not?” So, in fact, he [Angus] flew me over [to Pensacola] in his little plane and we landed in an orchard. I will never forget that, my heart was in my mouth [laughter]. He simply tied [the plane] up to a tree, I could not believe it. Anyway, we came over and I had a good visit with Fred, in which I talked about the kind of stuff we were doing then in Sydney [AUS], and brought him up to speed. I come up here to Neuroscience most years, but I have done that [visit with Guedry] every year since. Two or three of us, Jan [Holly], then Wally [Grant] came[11], and this year a great number of people are here and I am very pleased to see you all. However, I do want to emphasize that the way this began was kind of an Australian way. Have you heard about an Australian 10 minutes before [in a previous talk]? Well, an Australian lecture or Australian talk is very informal. We kind of like telling you things that are going on; so, you have to take what I am telling you in that sense because it is not all published. It is not all nailed down, and there are a lot of unknown things in it.

What I want to do today is tell you a little bit about the anatomical work we have been doing, a little bit about the eye movement work we have been doing, and then some about our new clinical test. Unlike the work that most of you do in this room, the work that I do is focused on quick clinical testing of dizzy patients, and coming up with physiological basis for these new clinical tests. Of course, it all goes back to basic anatomy and some old stuff. So, that is what I am going to talk about.

[Slide 2, page 162] I have to draw your attention [to this] [slide 3, page 163]. Some of you in this room probably know I am very lucky to work with some excellent people in Sydney; Hamish McDougal and Andrew Bradshaw. Names that you may well know, or you certainly will know. This is the latest story in semicircular canal anatomy, as far as I am concerned, because Andrew Bradshaw is an engineering student who wrote algorithms for fitting surfaces to standard CT [computed tomography] scans. So, he has taken standard CT scans from our CT scanner and validated them against micro-CT. All these algorithms are not just hand-waving things; they are beautiful illustrations. They are comparing micro-CT at the one temporal bone and standard CT at the one temporal bone, demonstrating that these algorithms do a fantastic job, and then applying them to a whole lot of human data [Bradshaw et al., 2009]. These [animations] look dreadfully phony [speaker opens animations of labyrinths], but I point out to you [that] these are in fact reconstructions of the living human being’s labyrinth reconstructed from these CTs, and I draw your attention to the falsity of some of the simplifications that we made in the past.

We have also developed methods for identifying the membranous labyrinth in fixed temporal bones, both of guinea pigs and of humans. These are data from 34 individuals superimposed so that you can see how similar their labyrinths are [video shows graphic not in slides]. Again, these are streamlines fit to the center of the canal, but I just wanted you to see the systematic curvature

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[11] Others who were included in some of these yearly Guedry visits were: Scott Wood, Anil Raj, Angus Rupert, and Ben Lawson.

of the anterior canal. For example, the horizontal canal is not a flat simple plane as Chuck [Oman] and I assumed -- well, we did not really assume, but you can certainly follow this. This is to show you what the inner ear of a guinea pig looks like [video plays here]. This is a high-resolution axial scan through the temporal bone of the guinea pig, which has been stained with osmium so that you can see the membranous labyrinth. Over here is the common crus and you are moving up through the temporal bone of this guinea pig. That is the utricular macula floating in space very close to the stapes right here and just below it is the sacular macula. Down here is the hook of the sacular macula. Now, here is the long arm of the sacular macula and the nerve from it emerging to join the eighth nerve.

Yes, that white stripe. Yes, the otoconia of the striola really pick up that osmium, as do the nerve fibers and the foot plate of the stapes. You can see right there around the foot plate of the stapes, but that is the utricular macula. It is attached to bone over here, but as you can see most of it is floating on this membrane of limitants which is a very flexible membrane. That is endolymph on this side and perilymph on that side, and those nerves are coming out just as Wally [Grant] described earlier. But there has been a lot of talk about modeling and I just thought it might be kind of nice to see…

[Oman] Any sign of canal otolith clumps?

[Curthoys] Canal otolith clumps?

[Oman] What is the resolution?

[Curthoys] This one is about five microns. This is micro-CT. They have just installed, in Sydney, a device which is a nano-CT. It has the resolution of nanometers and we are just starting to use that with very interesting results that I am not going to talk about at all and do not ask me.

[Goldberg] Have you drawn any different qualitative conclusions about what is called the Curthoys-Oman Model [Curthoys and Oman, 1987]?

[Curthoys] There are implications in the work that Andrew Bradshaw has done about those differences [Bradshaw et al., 2009]. Andrew Bradshaw has written them out using Fourier terms. He can describe the labyrinth by Fourier series and, personally, I just have a lot of trouble getting my brain around that, let alone that he was able to do it. Now at this stage, I do not have any direct predictions about this result occurring, but I do find great satisfaction about being able to describe the labyrinth with the kind of accuracy that we now can do. It is up to people with skills apart from mine that have used that data to follow through. I am not a modeler.

[Oman] What do you think about the ellipticity of the canals. Does it match what we thought?

[Curthoys] Ellipticity?

[Oman] The flattening of the duct, the canals.

[Curthoys] Well, in the guinea pig the actual duct is fairly circular. It is only modestly elliptical, whereas in the human that is not the case; although the implications of that are beyond us. Anyway, I had to show you that.

One little spin off from this has been this [slide 4, page 163] which I had not expected and that is that because we have this micro-CT process that shows the membranous labyrinth, and we are able to visualize the utricular macula and the saccular macula. This surgeon came to me doing a project. She wanted to identify exactly the optimum place to put in a piston through the stapes so that there is minimal chance of damaging the utricular macula. We just had a paper published based on micro-CT (it is in the process of being published) that shows exactly the optimum place, which is anterior, inferior in the stapes, and it is just an amazing spin-off from that kind of study.

[Grant] The bird also has a very curved duct. I had always thought that was to fit his head because it goes right along the skull to fit it, but I was interested to see that in humans, where you do not have that problem, there is also that curvature. My question is, have you measured the percent of the canal that is out of plane?

[Curthoys] In that paper, there are numbers which qualify what I call nonplanarity, but don't ask me what they are. I have a question for you, though: how curved is the frog's anterior canal?

[Grant] I do not know.

[Goldberg] I am not terribly impressed with that and let me explain why. Certainly the plane of the canal is something we have all thought was important. However, as Rick Rabbit [University of Utah] pointed out, because you have two openings into the ventricular sac, there may not be an exact correspondence; there could be a qualitative correspondence between the physiological plane and the anatomical plane. Do you agree with that?

[Curthoys] I agree with Manning [Correia], it is just a bit bizarre that everyone has this very unified curvature in their anterior canal. I do not know why. I do not know the functional reason and it may be trivial, as Jay [Goldberg] is implying.

[Goldberg] Well I did not mean trivial, just trivial in terms of the way we think about canal planes as determining the physiological, anatomical planes. It is probably off by 10 degrees because of lots of things.

[Holly] We are all looking for a functional significance of the curvature, but given like what Rick Rabbit and some other modelers are saying, it really does not matter, and maybe the curvatures… I mean why is the liver the shape it is? What do you think? Do you think it may just be because that is how it [i.e., the anterior canal] happens to fit into the head?

[Curthoys] I do not think that is the case. I do not think so.

[Holly] So, you think it is functional?

[Curthoys] I do believe so.

[Slide 5, page 164] Well, that was the anatomy. I want to talk now about some behavior because I want to talk about this head impulse test (the so-called "Halmagyi-Curthoys test") [Halmagyi and Curthoys, 1988] for horizontal canals that we developed and published back in about 1987 actually. It is a very simple stimulus for testing horizontal canal function. Simply turn the head abruptly, unpredictably, through a small angle only about 10 or 20 degrees. It is not this huge rotation that people mistakenly use. In an impulse like that -- the peak head velocity gets up around 200 to 400 degrees a second, and the accelerations are very high. It is a good test because we know that patients with no vestibular function can generate null eye movements during the first hundred milliseconds or so. What happens in patients like that and unilateral patients? This is the kind of standard figure that we use to explain it before, during, and after [slide 6, page 164]. Up here is the healthy subject and down here is the patient. Just look at the eyes; the person's eyes are exactly on target on the physician's nose the whole time. Down here the patient's eyes are on target simply because they have an inadequate VOR [vestibulo-ocular reflex] -- their eyes go with their head. That is what an inadequate VOR means: they do not compensate for head movement. So at the end of movement, they have to make a corrective saccade back again and that is their hidden pulse sign. So a deficit causes the eyes to go with the head and that little saccade is what clinicians have been looking at for a long time. Of course, we measured that and showed that the eye matches the head extremely well in healthy individuals but in patients with vestibular loss, it is very poor [slides 7-9, pages 165-166].

For a number of years, people (Owen Black is one of them) have said to us, "Look, I know this patient has got no canal function on one side, but I cannot see that response. I cannot see that saccade." We usually implied that people who made comments like that should read the manual. Of course, Owen [Black] had read the manual and what we now realize, thanks to some search coil measurements, is that some patients can learn to make a very small saccade during the head rotation. If they make a saccade during the head rotation, there is no need to make a saccade at the end. So these are the saccades that we measured and this is our new 3-D way of representing data. [Slides 10-11, pages 166-167] This is an increasing series of head velocities. This is the eye velocity response [from] very low peak head velocity impulses to very high peak head velocity impulses. This is a normal healthy person and this is the eye movement response which you can see is excellent. These little things out here, these little stalagmites are saccades.

Of the people who have gotten the inadequate VOR, you can see the peaks are down here [slide 12, page 167]. These patients make these saccades after the end of the head impulse and they are easily seen, and these are the overt saccades which really are our hidden pulse sign. What we discovered, thanks to Konrad Weber [Weber et al., 2004] and others who did detail measurements with search coils during head impulses is that these people make these saccades actually during the head impulse stimulus itself. Now this person does make some extra saccades at the end, but if he or she made one during the head impulse, then there is no need to make one afterward. So we call these saccades covert saccades because they are hidden and clinicians do not see them. If they just go by [i.e., ignore] that [covert] saccade then they are going to be wrong. The position we came to is if you see that corrective saccade, you know there has to be a problem. If you do not see it, you cannot conclude anything. The patient might be normal and the patient might have a unilateral loss in generating these saccades [slides 13-14, page 168].

[Black] One thing that we did notice is that even though we could not see the saccades, often if you ask the patient to fix on a target, usually a tumbling E-target, they will still describe the displacement of the E. So, it is clear that the optic load stabilization is not occurring. We have not recorded the saccades. So, my question is: do you think that might be still a good differential test just using the perception?

[Curthoys] That is an extremely good point because if a saccade occurs there has to be saccadic suppression occurring and you are going to get perceptual consequences to it -- if you have patients that are good enough observers to report something like that. The way we have been going, though, is to try to come up with a way measuring the eye actually during head impulse, and that is what I want to talk about because now we have done that and have a system.

Search coils are wickedly expensive as you probably know [slide 15, page 169]. They are hugely complex. There are very few research labs in the world that have them so we are fortunate that we have them. So we wanted to come up with a system for measuring eye movement during head movement that was clinically realistic and this is it. This little firewire camera weighs 60 grams. This is mounted on a very lightweight frame here which very tightly fits the orbit -- tight strap back here -- because we have to minimize the amount of slip that occurs between the camera and the head during head rotation. If you look carefully here, you can see this face happens to belong to Hamish MacDougall -- the guy who came up with this whole system I might point out -- illuminated by a little infrared light here. He is wearing a search coil as well because the first step in this was to validate this technique.

Does this video method actually give the same answers as search coils? The bottom line of course is that it does and there is a blown up illustration in case you cannot see it. These things are now $800 each, Australian [slide 16, page 169]. They are wickedly expensive and, as I say, they are just absolutely clinically unreal. [Slide 17, page 170] The other little system is not. We have a little sensor on the goggles to measure head velocity. This is our head velocity record [slides 18-19, pages 170-171] and that is a normal subject's eye velocity from this little lightweight camera mounted on the person's head during it; and we conducted a study that was published in *Neurology* last year that demonstrated how very closely coils and video matched the data [slide 20, page 171]. The concordance correlations were extremely close. There was no significant difference. Obviously, in particular cases there will be situations where these do not work. People are going to blink; some people have problems with blinking. Blinking is a particularly difficult problem and of course if the cameras are not put on tightly then you are going to get artifacts. One thing that this new system does is allow us to measure the VOR, the normal natural head accelerations, not the 10 degrees or 100 degrees-per-second that people have been talking about today. I am talking about accelerations 2 or 3 thousand degrees-per-second squared which is your normal head acceleration as I do this [speaker makes a rapid head movement]. It is a different ballpark than what a lot of people were talking about today, but that is what we want to measure and we want to do it quickly and this test does it in about 10 minutes.

I gave a set of these glasses to my colleague and friend in Cassino, Italy (who I am on my way to visit after this) -- Leonardo Manzari. He is a very unusual guy. I met him at the Bάrάny meeting. The aim of the Bάrάny meeting is to bring scientists and clinicians together. We did [get together]. We met and it has been a remarkably successful collaboration since because he tests every patient himself, very unusual, and he tests them with these goggles. Being Italian, he calls these goggles "mi mi" because they sing to him, and boy they sing beautiful songs. Let me show you some of the stuff (as in the value of them) because they allow you with a patient with neuritis [slide 21, page 172], you can see all these overt saccades when a person is measured on video shortly after. You can see all these saccades here and then when they are recovered, you can see there are not any of these overt saccades. This person's vestibular function has returned.

It is not that they just learned new strategies, they in fact have recovered [slides 22-23, pages 172-173].

[Young] What is the difference between the open and filled circles [on slide 23]?

[Curthoys] These [open circles] are the acute stage of vestibular neuritis, and these [filled circles] are after recovery.

[Slide 24, page 173] Well, we have now put these into Leonardo's [Manzari] clinic and I want to show you some of the data that we get from it. These are normal healthy people superimposed with traces of about 20 impulses each side, to the left and to the right [slide 25, page 174]. The red traces are head velocity; the black traces are eye velocity and you can see normal healthy people as this one is superimposed. It is almost exact. You can see the gains up here which I point out, even during the tests, are very high up around 0.8. This is a person with a unilateral loss [slide 26, page 174]. You see here all of these saccades which occurred during the head velocity. So, they are covert saccades meaning they are going to be hard for the clinician to detect. This person's inadequacy is easily detected by this video system over here, the gains from the two directions. This is from a bilateral patient [slide 27, page 175] and you can see their gains are way down from both directions of rotation as shown here.

What I want to show you is the application that we have performed taking this particular probe [slides 28-29, pages 175-176]. I look at "mi mi" as a way of testing, or rather probing, into the vestibular system which is going to give us new insights and it is; but I must admit to you, I do not understand some of the songs that "mi mi" is singing to me. I want to show you some of the data here. This is the kind of stuff Leonardo [Manzari] sends over to me. He calls me "Saint Thomas" (doubting Thomas) because I do not believe a word of what he says and after a year, I am gradually coming around to believing him. This is data from healthy people [graphic from video not provided in slides] and I have 95 of them like that; you can see all of them lined up. These are real data and these are not models. This is the way data really looks with all the warts on it and all. You can see right off that they are remarkably good. Now, let me show you what he sent me and what is coming out from this.

He [Manzari] has tested patients with early Meniere's Disease (MD) during the first few attacks. Their data is very different. These are data obtained even from patients during quiescence. So when they come in and they have had an attack, he measures their VOR. Then, they come back actually during an attack because he works in a country town in Italy and these people trust their clinicians there like God Almighty. So if he says, "Come back during an attack," they come back during an attack and he measures their data. Let me show the results. These enhanced gains are like this [graphic from video not provided in slides]. Some of these gains are around two and three. My first thought is these have to be saccades. We have looked at these data for a year and we have put it under a microscope. They are not saccades and that is one of the most puzzling aspects. Many of these patients with unilateral loss show this kind of pattern bilaterally for both directions of rotation. I do not know the answer to that. The one thing we do know is that if you test the same patient repeatedly, you find fluctuations in VOR performance particularly around the time of the attack. In other words, the VOR is changing just the same way as cochlear function is changing in these Meniere's patients at the time of attack.

I think everyone in this room knows Meniere's -- that dreadful disease with awful vestibular and auditory symptoms. We are working on this and that is one of my tasks when I go to Cassino (Italy), to sit down and go through this and see where we are going. I wanted you here, though, to see that [i.e., the preliminary findings] because I think this is giving us insight into a disease that has been just about intractable up to now. Whether it is good insight, I do not know but the data just bears out. I have 108 PDF's there. If you want me to go through all of them, I will, but most of them are remarkably similar.

Enhanced canal function in Meniere's disease, what could be causing it? It might be changes right out in the periphery [slide 30, page 176]. Alan Bridger and others have recently been looking at animal models of MD by injecting fluids into the labyrinth and recording from primary afferent response to that. One of the things that appears to be happening is that in all the models that have been around for so long, it has been assumed these walls are pretty inflexible. That is not what he is finding. It looks like the cupula is getting stretched. If the cupula is getting stretched, then some hair cells are going to get bent even before a stimulus is delivered. So, I guess one of the things I am saying to you is be alert to some of the assumptions that are there [i.e., commonly held]. For awhile I thought the utricular macula was causing some of the effects that we have seen on centrifuges because it was dragging on the base of the crista. That does not appear to be correct, though it may be that it is causing effects because it is dragging on the apex of the ampulla right up here and therefore deforming the cupula. These are ideas. That is simply what I want to put on the table for you to think about.

Now I want to switch gears and talk about testing otolith function because, as I said, I want to come up with ways of looking at simple tests of vestibular function in the clinic. These are some of the ways that do not work in the clinic because they are so huge and so expensive [slide 31, page 177]. This is our centrifuge in Sydney, sleds, big rotators and this huge sled. We wanted a way of delivering linear accelerations that was going to be reasonable. The way we came up with was very simple: a tap on the forehead [slide 32, page 177]. I built a sled. I used it for awhile. It does not work because people's bodies slush around so much on it. So I made a head sled, that is my term, biting on dental bite bar and moving people's heads, but that was potentially dangerous to the neck. Then I realized the very simplest way of delivering a linear acceleration is a tap. If you tap someone's head right here [indicates forehead] lightly with a tendon hammer, and measure their linear accelerations at the mastoids, you find that there are XYZ components of linear acceleration at the mastoids. In fact, tapping there causes both mastoids to move outwards, not very much, but it is a linear acceleration and that is what I am after.

We looked at how bone conduction by something like this activates primary vestibular afference and I want to show you that [Curthoys et al., 2006] [slide 33, page 178]. If you have to come up with [a] clinical evaluation, you have to have a firm scientific foundation and that is what I have been after. So, we recorded from many primary afferents in anesthetized guinea pigs --extracellular recording [slide 34, page 178]. What I have done in the guinea pig using Ketamine, etc. is very fortunate because in the guinea pig, recording primary afferents is not easy [slide 35, page 179]. However, it is not nearly as difficult as it is in the monkey because in part, in the guinea pig, the various divisions of the eighth nerve emerge through different apertures in the bone, superior nerve here, inferior nerve here, and cochlear down there. I am right up here recording mainly in the superior nerve, occasionally down here in the inferior nerve (that is the facial nerve right there). So it is like the whole Scarpa's ganglion [vestibular nerve ganglion] is laid out ready for direct attack rather than being buried in bone as in humans and in some monkeys [slide 36, page 179]. This was the stimulator we used to deliver vibrations to the skull of the guinea pig [slide 37, page 180] because what I wanted to do was to verify I was recording from vestibular neurons by the placement and verify that I was doing it by natural stimulation -- tilting the animal or giving angular accelerations, then delivering this vibration to the animal's skull by the standard little bone oscillator, it is a B-71. It is used in clinics and this is a very simple arrangement, it is a bit difficult to see but this is where the guinea pigs skull is, and I can tilt and rotate this animal any which way at all [slide 38, page 180].

Well sadly, most of the neurons that we recorded with our stimuli are like this [slide 39, page 181].You can deliver the vibration, which in our case so far has been 500 Hz. It is a long duration stimulus. Here it is here. We have also delivered air-conducted sound. I guess, and I hesitate to use numbers because people misread, somewhere around 80 percent or more of cells are exactly like this. You deliver the stimulus and there is absolutely no change at all. Nothing happens both for regular neurons like this and irregular [canal] neurons like this [slide 40, page 181]. You can see if there is a change, it is very minor. A very small percentage of neurons, though, are very strongly activated. This is how insensitive these neurons are, increasing the stimulus strength from nought [zero] up to 2G peak-to-peak [slide 41, page 182]. Here you can see an otolith irregular neuron and you can see the huge difference [slide 42, page 182]. Now deliver a very weak stimulus and you can see that increase far into bone-conducted vibration and also air-conducted sound. Let me make this point here. Utricular neurons respond to air-conducted sound. Saccular neurons also respond to air-conducted sound. Utricular neurons respond to vibration. Saccular neurons respond to vibration. In the clinical literature it has been a great confusion about this partly, I must confess, generated by myself. I am very sorry about that, but if you keep doing experiments I guess you might eventually get the right answer. When we first demonstrated air-conducted sound activated saccular neurons, people instantly thought air was a very specific stimulus just for the saccule. Our work now shows that is not true. Otolith irregular neurons from the utricular macula are also activated by air, probably not all of them. It looks like there is going to be a differential proportion of them to air and bone, but it is certainly the case that utricular afferents are activated by air.

[Grant] What is the frequency of the stimulus here?

[Curthoys] 500 Hz. There was a point earlier about the high frequency. In fact, some of these bone-conducted neurons go up higher than that. We have activation not on every spike, not on every cycle, but they are activated above 700 Hz and they roll off rather sharply after that. You get very few that activate up into kilohertz. This is another otolith neuron [slide 43, page 183]. This is the kind of sensitivity function of these irregular otolith neurons [slide 44, page 183]. You see some of them are activated down around stimuli which are just barely being presented and they have this really steep increase in sensitivity in firing rate as you increase the intensity. That is the contrast [slide 45, page 184]. These are the regular neurons, these are the irregular neurons and that is what I mean by activation -- I mean taking right off. These cells are extremely sensitive. If you want numbers for sensitivity -- somewhere around 2000 percent increase in firing per G versus nought [zero] [slide 46, page 184]. That is my kind of number. I like that number. Also, they lock onto the stimulus as you can see here in the cycle by cycle which [Larry Young and] Jay [Goldberg] showed many years ago [Young, Fernández, and Goldberg 1977] [slide 47, page 185].

This is from our earlier data showing that otolith irregular neurons are the ones preferentially activated by this [slides 48-49, pages 185-186]. They are also activated by air-conducted sound [slide 50, page 186], this is with respect to ABR [auditory brainstem response] threshold [slide 51, page 187]. ABR is this brain stem response, and you can use that as a reference level rather than SPL [sound pressure level] if you wish to use a number that is relevant for the particular guinea pig because some guinea pigs have conductive hearing loss. As you can see, these cells are activated irregular neurons very close to ABR threshold. Whereas these here are ABR threshold for air-conducted sound [slide 52, page 187], and the absolute magnitude where those irregular neurons start taking off and start increasing their firing is up around about 115 dB SPL which is about 60 dB above ABR threshold. I happen to be a subject in many of these experiments and let me tell you, I prefer receiving bone-conducted vibration (bzzzz bzzz bzzz) on my forehead much more than these high intensity air-conducted sounds which are used for clinical evaluation of VEMPs [vestibular evoked myogenic potential]. I think that air-conducted sound is probably going to be on the way out, but bone-conducted vibration is a very effective stimulus and you can see that contrast right there [slide 53, page 188]. Does that answer your question?

[Goldberg] It answers my question, but I thought this morning you said that…both otolith organs were sensitive to airborne sound.

[Curthoys] They are.

[Goldberg] They are not, [unintelligible] is not sensitive.

[Curthoys] Oh okay, well I should rephrase it then. They respond to air-conducted sound.

[Goldberg] They most certainly do.

[Curthoys] I agree with that. Absolutely.

Otolith irregular neurons -- let me take you from this physiology to get towards a clinical test [slide 54, page 188], take you through the way my brain worked to establish this. Jay [Goldberg] is showing that otolith irregular neurons originate mainly from the type 1 receptors around the striola and these are sensitive to changes in linear acceleration to jerk. I think that 500 Hz is why bone-conducted vibration is so effective. It is 500 changes in acceleration per second. It just so happens these receptors also (I happen to think) are the very ones that you wish to test clinically because it is these receptors that other data suggest are particularly the most vulnerable receptors to ototoxic antibiotics. We have disagreed with Jay [Goldberg] because there are just so many differences between the data that he published in 1977, the squirrel monkey data, and the data that I have just told you about. [Slides 55-56, page 189] I happen to think my guinea pigs are a better model, believe it or not, for human work than the squirrel monkey. I do so because the guinea pigs have much larger, thicker skulls than the squirrel monkeys that I have seen. In fact, you (or perhaps it was Caesar [Fernandez]) sent me many years ago squirrel monkey's skulls, (we used them for measuring as well). Allowing for that difference [slide 57, page 190], I think I will not go there any further.

Follow my logic: If we say bone-conducted vibration is a selective stimulus for these otolith irregular neurons [slide 58, page 190], what kind of responses can we get from otolithic stimuli? We know that there are many spinal responses, but one of my favorite studies of all in vestibular literature is the study by Suzuki [Suzuki, Thokumasu an d Goto,1969] [slide 59, page 191], which showed that the electrical stimulation of the utricular nerve in cats gave torsion, gave verticality, and it gave horizontal components. Notice here electrical stimulation of the left utricular nerve activated the right inferior oblique and the right inferior rectus [eye muscles]. It did not activate the inferior rectus and the inferior oblique on the ipsilateral side [slide 60, page 191]. There is asymmetry between those two which I shall come back to. I think that probably works (although the circuitry is very poorly understood) through projections from the utricular and saccular maculae [to] the vestibular nucleus up to crossing over and going to inferior oblique [slide 61, page 192]. I reasoned if bone-conducted vibration really does activate utricular neurons, then I should be able to get a good eye movement response to bone-conducted vibration [slide 62, page 192]. What we did was to set up alert guinea pigs with 3-D search coils, acute search coils and with head-free (head was absolutely free). These animals were wearing one of those little B-71s on their head and we measured their eye movements. Here is the bone-conducted vibration stimulus [slide 63, page 193], 7ms, and these are the eye movement components measured by search coils in these guinea pigs.

Bone-conducted vibration does elicit eye movements in guinea pigs [slide 64, page 193]. Does it in humans? Yes, it does [slide 65, page 194]. What we did was put those B-71s on the mastoid and used a video technique to measure eye movements of healthy human subjects and their response to it [i.e., vibration]. Each line here is one trial. As you can see, all of these presentations elicit a very small, very reliable horizontal component, vertical component, and torsional component of this subject's eye movements. That is for one side, the right mastoid. That is for the left mastoid [slide 66, page 194]. Opposite directions mainly, put them together [slide 67, page 195], and horizontals cancel. Stimulate both sides together, and horizontals cancel… torsion cancels. The vertical sum because both mastoids generate the vertical component. Well these are very small eye movements. They are only about less than half a degree big. It is only by means of our very sensitive video methods we are able even to record them [slides 68-69, pages 195-196]. What we wanted to do was to use a stimulus that allowed us to get at this without having to actually measure the eye movement itself [slide 70, page 196]. So, what we do is use this vibration device here, B-71, which looks enormous but in fact is not that heavy. It is simply placed on the person's head delivering 500 Hz, 7 ms vibration here using these electrodes on the skin beneath the eyes as the person looks up, which is absolutely critical. The patient lying horizontally simply just has to look up, [then we] deliver this and average the responses. The test takes about 20 seconds [slide 71, page 197]. Let me say that again -- 20 seconds. We have tested people in this and Leonardo Manzari has tested over a thousand people on "mi mi". He has tested over a thousand with this as well. It is a very innocuous test taking about 20 seconds. Actually, for those people who need to measure vestibular function in children, you can increase the repetition rate. So instead of 3 per second, you can make it 20 per second and you can answer about vestibular function in a child in 3 seconds -- 3 seconds. I happen to think that is remarkable.

Anyway, this is what you see, a very small response to this vibration applied to Fz [slide 72, page 197]. Fz right there, the midline of the forehead right at the hairline is a special location because it stimulates both ears about equally. If you apply at different places, you get different answers. That is coming out very clearly, but this whole record, this whole response that is picked up in response to 50 repetitions of that stimulus is called an oVEMP [ocular vestibular-evoked myogenic potential]. We are just interested in this first component that has very short latency about 10 ms to peak. It is very small, only about 5 microvolts, so you have to be careful. However, it is negative. It is an excitatory potential that I think is reflecting the activity of afferent volleys coming over onto the inferior oblique and inferior rectus eye muscles [slides 73-74, page 198]. Of course we have done the controls: these are 67 healthy subjects [slide 75, page 199]. All of them show these small responses, these small n10s [small short-latency negative potential that is the first component of the oVEMP response]. These are five patients with bilateral loss thanks to Gentamicin who still can move their eyes, who can still hear the stimulus very well, and who still have facial function. They just happen to have no n10s [n10 response] at all.

This is a vestibular test [slide 76, page 199]. Of course the question is what happens to patients with complete unilateral loss? Well, that happens [slide 77, page 200]. On the side opposite the healthy ear, there is a standard n10. On the side opposite the affected ear, there is just about nothing. So that affected ear [slide 78, page 200] (we think) is generating nothing because that pathway is getting wiped out. Over here this pathway is still intact. So you get this asymmetrical n10 [slide 79, page 201], and we calculated that kind of an asymmetry ratio much like a canal paresis score [slide 80, page 201]. These are all the normal healthy subjects down here; these are all the unilateral patients up here. Forty percent divides them, simple as that. Can we be more specific [slide 81, page 202]? Can we zero in even further? Which part of the otoliths is generating this? Well, we can because there is a disease called superior vestibular neuritis which affects just the superior division of the vestibular nerve carrying all the afferents from the utricular macula and some of the afferents from the saccular macula (as opposed to inferior neuritis). We reasoned, "If someone has superior vestibular neuritis what happens to their oVEMPs?" The simple answer is here [slide 82, page 202]; all the utricular macula afferents that are causing the patients to have superior neuritis are gone. [Slide 83, page 203] You say, "Well, they're just five patients." There are 133 from Leonardo's [Manzari] patient group down there [on slide 83]. The asymmetry ratio is very large indeed. These are healthy subjects. This is Australia and Japan; this is Italy. You can see the superior neuritis is very similar to the people with complete unilateral loss.

I should just point out that those patients with superior neuritis do have intact cVEMPs [cervical vestibular evoked myogenic potential] [slide 84, page 203]. These myogenic potentials can also be picked up on the neck. I have been talking about these guys [i.e., findings] under the eyes which are reflecting utricular function. The ones on tense neck muscles are reflecting saccular function, not because it [the stimulus] is air, but because the saccule largely projects down to SCM [sternocleidomastoid muscle]. The patients I just showed you, all 133 of them, and the others from Australia all have normal cVEMPs but absent oVEMPs -- almost perfect dissociation. So, what we have been doing now is apply[ing] this to ask questions about what happens to these measures in early Meniere's patients testing the same person at quiescence [slide 85, page 204]. Is their n10 wave of the VEMP [i.e., the evoked response] in the Meniere's patient meeting the standard criteria? Is their n10 about equal when they are quiescent? Here it is during attack [slide 86, page 204]. You can see there is a great enhancement in that n10 when they are measured actually during an attack. We have interpreted that and the cVEMPs, as you can see here, are hardly affected during an attack versus during quiescence. We have fifteen Meniere's patients [slide 87, page 205] and just about all of them show this increase in the magnitude of that n10 during an attack compared to normals or compared to what happens to their cVEMP function. We interpret this as showing that the utricular function is enhanced when these patients are having a Meniere's attack [slide 88, page 205].

Lastly, I want to show you just one other patient group that we have looked at [slides 89-90, page 206]. You have heard about them and read about them, these patients with dehiscence of the semicircular canal. This is a superior semicircular canal, not a very good image I am sorry, but this superior semicircular canal should be covered by bone. That white should go all the way around and you can see it does not. So the really interesting question is, "What happens to these patients when you test their oVEMPs?" The answer is they [the oVEMP responses] are huge -- to bone-conducted vibration [slide 91, page 207]. Here is a normal healthy person's Fz, you see the size of the n10 is about equal. This is one of these SCD [superior canal dehiscence] patients. You can see this huge response opposite their affected ear. The other side is just about normal. One of the things we latched onto, thanks to Lee McGarvy (and I mentioned earlier), is if you deliver this stimulation at a different location you change the response. If instead of tapping right there which is called Fz, you tap the top of the head… in most normals you get just about nothing. This is the same person. Instead of tapping at Fz, you just move the vibrator to the top of the head -- here you get nothing. In this SCD patient you can see there is still an enhancement. I think this goes back to the work of Tullio [Tullio, 1929] who opened the labyrinth and demonstrated enhanced movement of the utricular membrane. I think that is what is contributing here. I have no doubt the superior canal does contribute to this as Lloyd Minor [Minor, 2000] has made so clear in so many of his papers. I also want to make the point that I think SCD has otolithic components too. It has a strong otolithic contribution to it as well, and that is what I am looking at in guinea pigs at the moment, doing recording from primary afferents after artificial dehiscences. That is what we've been doing in Sydney. Thank you [Speaker does not use slides 92-95, pages 207-209, but they are included for reference].

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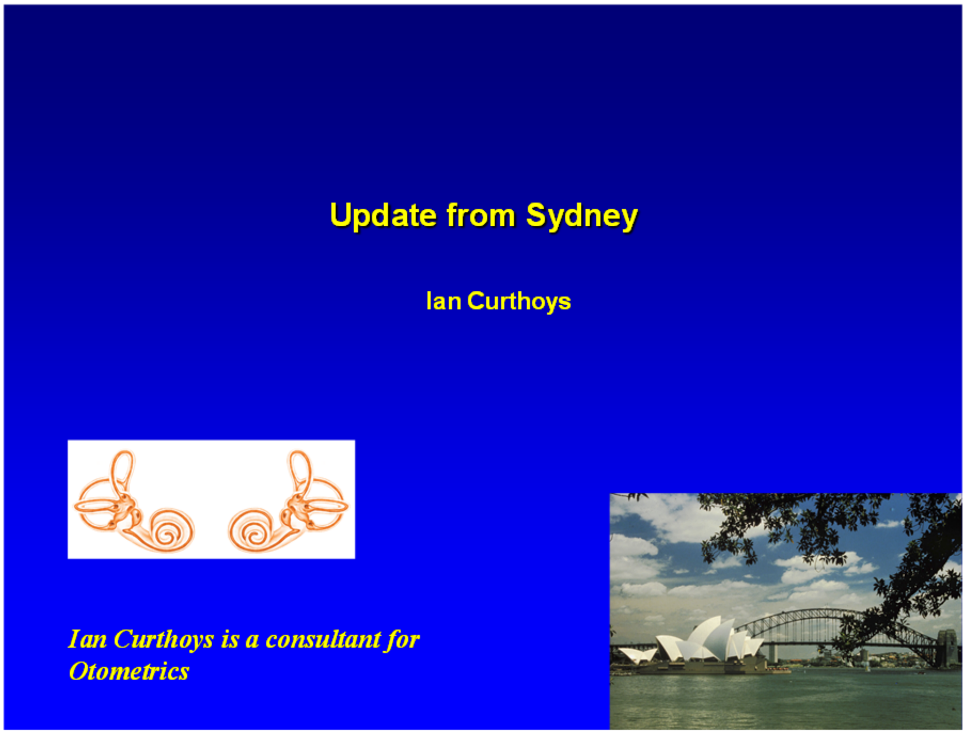
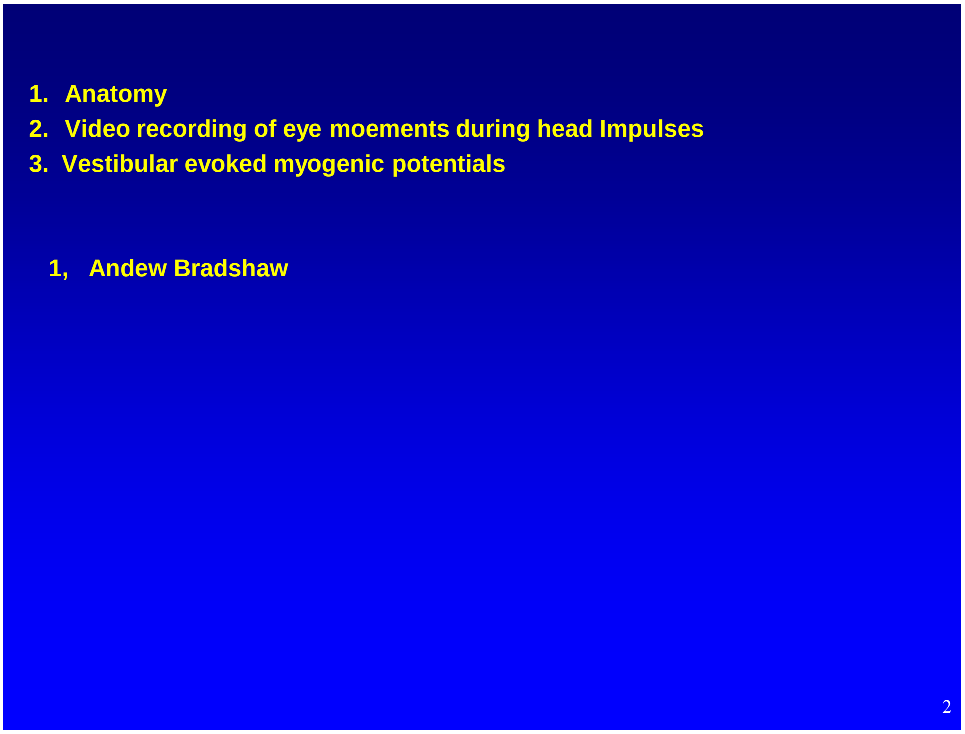


Update from Sydney

Ian Curthoys

Ian Curthoys is a consultant for Otometrics

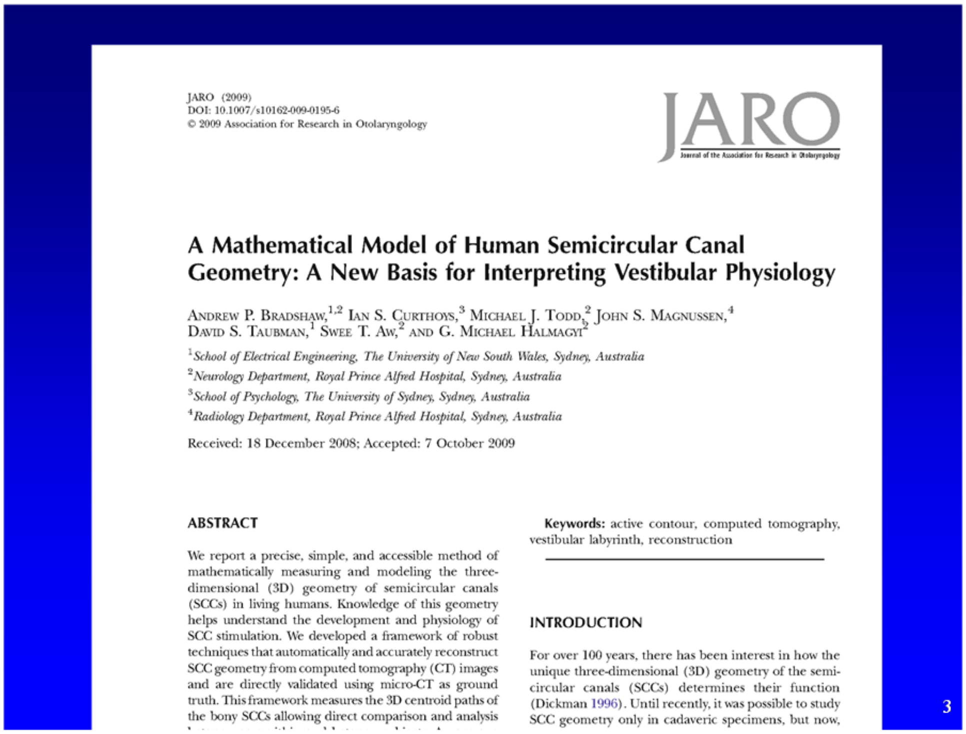
Slide 1



1. **Anatomy**
2. **Video recording of eye moements during head Impulses**
3. **Vestibular evoked myogenic potentials**

1, Andew Bradshaw

Slide 2



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A Mathematical Model of Human Semicircular Canal Geometry: A New Basis for Interpreting Vestibular Physiology

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ABSTRACT

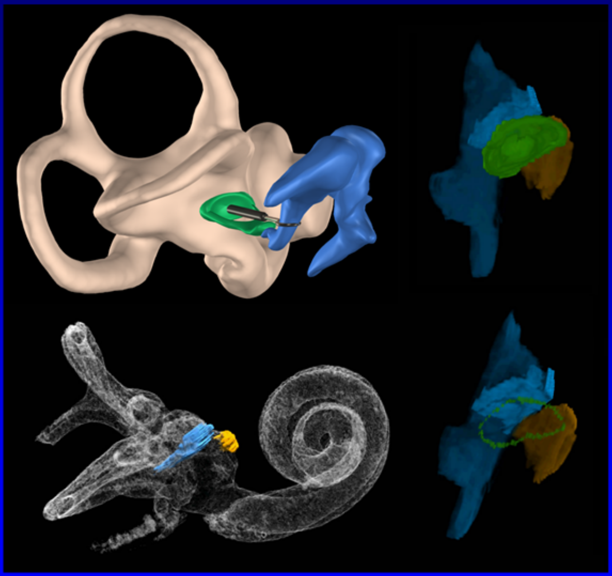
We report a precise, simple, and accessible method of mathematically measuring and modeling the three-dimensional (3D) geometry of semicircular canals (SCCs) in living humans. Knowledge of this geometry helps understand the development and physiology of SCC stimulation. We developed a framework of robust techniques that automatically and accurately reconstruct SCC geometry from computed tomography (CT) images and are directly validated using micro-CT as ground truth. This framework measures the 3D centroid paths of the bony SCCs allowing direct comparison and analysis

Keywords: active contour, computed tomography, vestibular labyrinth, reconstruction

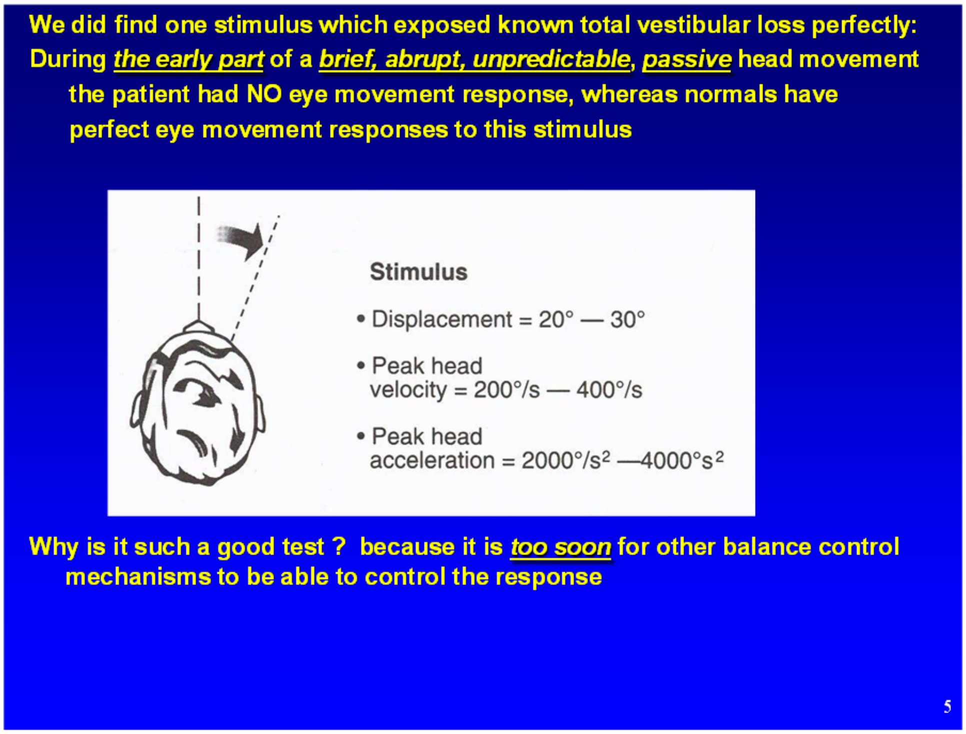
INTRODUCTION

For over 100 years, there has been interest in how the unique three-dimensional (3D) geometry of the semicircular canals (SCCs) determines their function (Dickman 1996). Until recently, it was possible to study SCC geometry only in cadaveric specimens, but now,

Slide 3



Slide 4



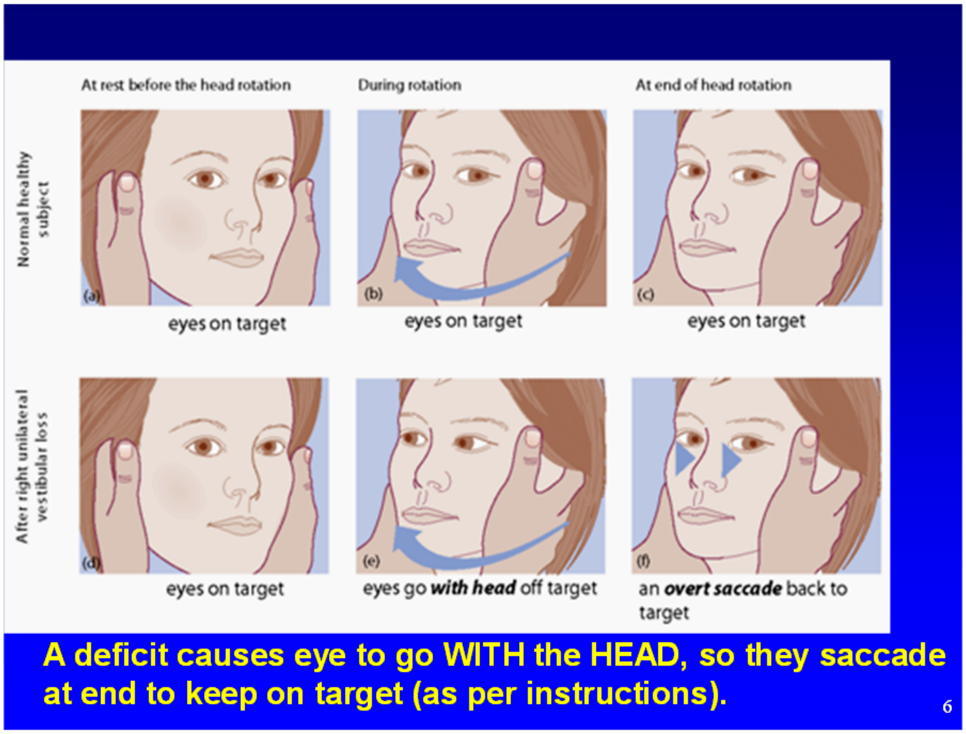
We did find one stimulus which exposed known total vestibular loss perfectly: During *the early part* of a *brief, abrupt, unpredictable*, *passive* head movement the patient had NO eye movement response, whereas normals have perfect eye movement responses to this stimulus

Stimulus

- Displacement = 20° — 30°
- Peak head velocity = 200°/s — 400°/s
- Peak head acceleration = 2000°/s^2 —4000°s^2

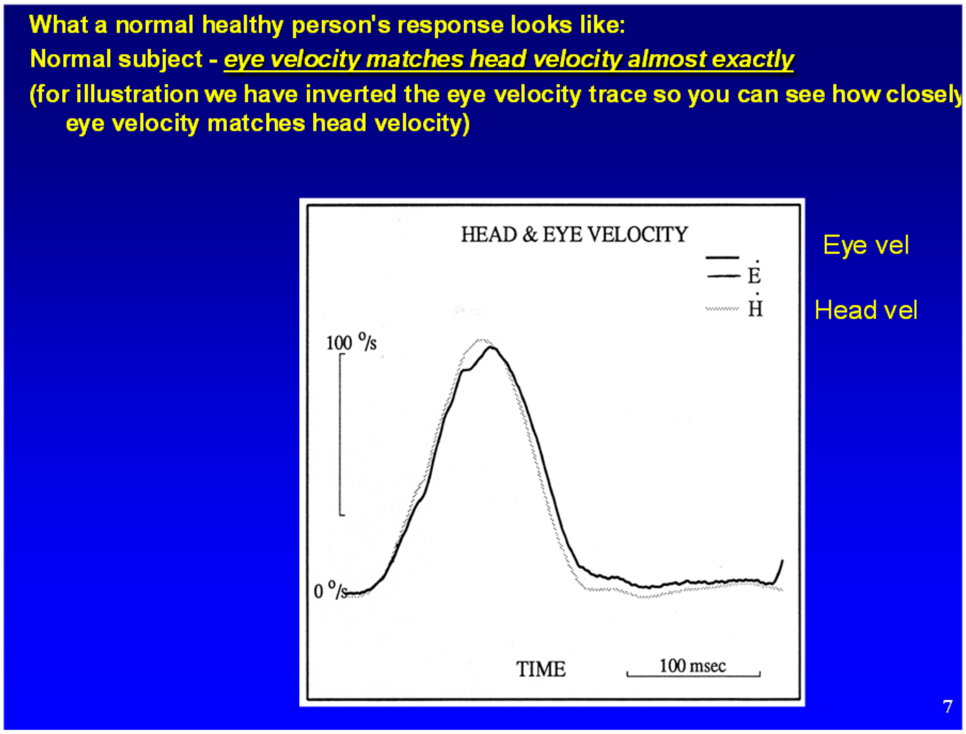
Why is it such a good test ? because it is *too soon* for other balance control mechanisms to be able to control the response

Slide 5



A deficit causes eye to go WITH the HEAD, so they saccade at end to keep on target (as per instructions).

Slide 6



What a normal healthy person's response looks like:

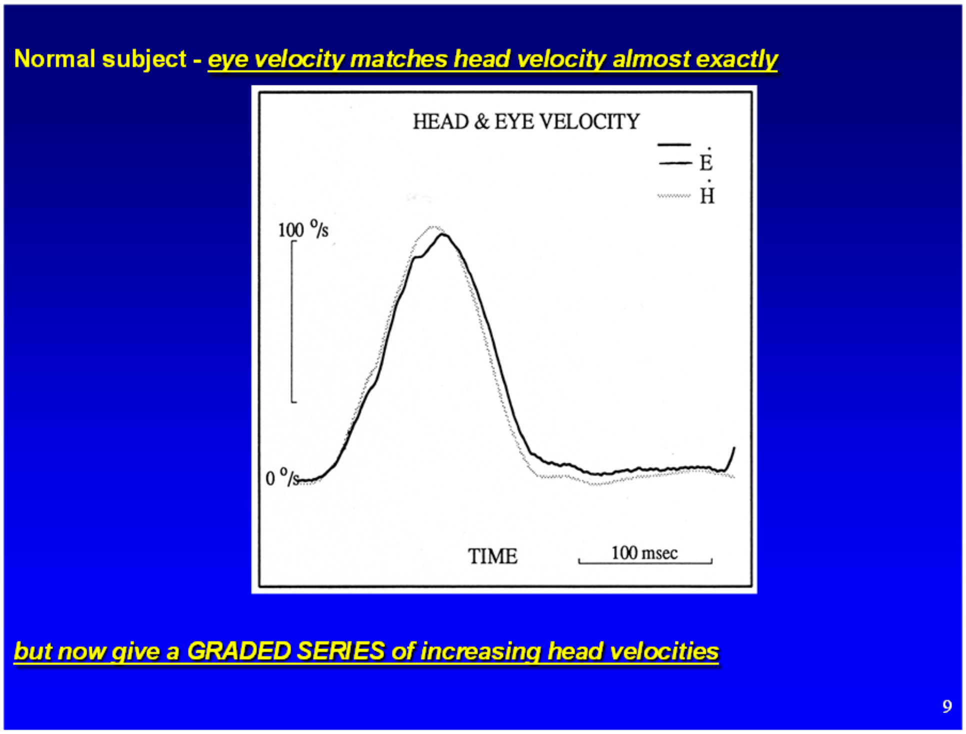
Normal subject - ***eye velocity matches head velocity almost exactly***

(for illustration we have inverted the eye velocity trace so you can see how closely eye velocity matches head velocity)

Slide 7

Head impulse **movies**

Slide 8



Normal subject - ***eye velocity matches head velocity almost exactly***

but now give a GRADED SERIES of increasing head velocities

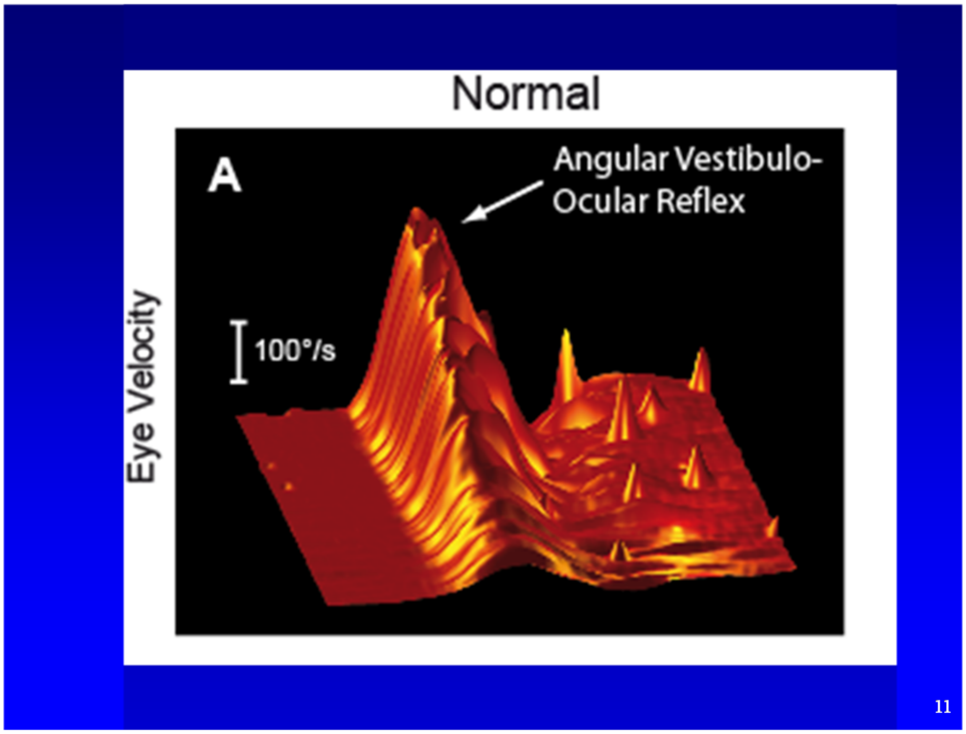
Slide 9

With Konrad Weber we have introduced a new version of this stimulus which gives

GRADUALLY increasing velocities - increasing velocities. so we call it the ***gHIT*** test

- still direction is unpredictable but the velocity gets faster and faster (higher and higher head accelerations)

Slide 10



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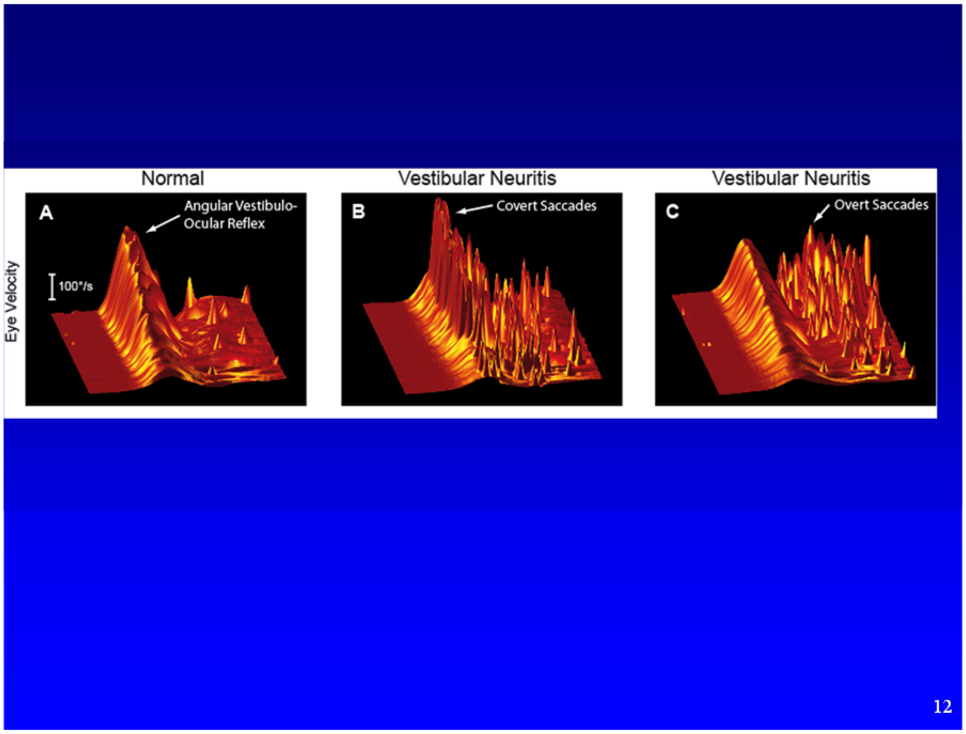

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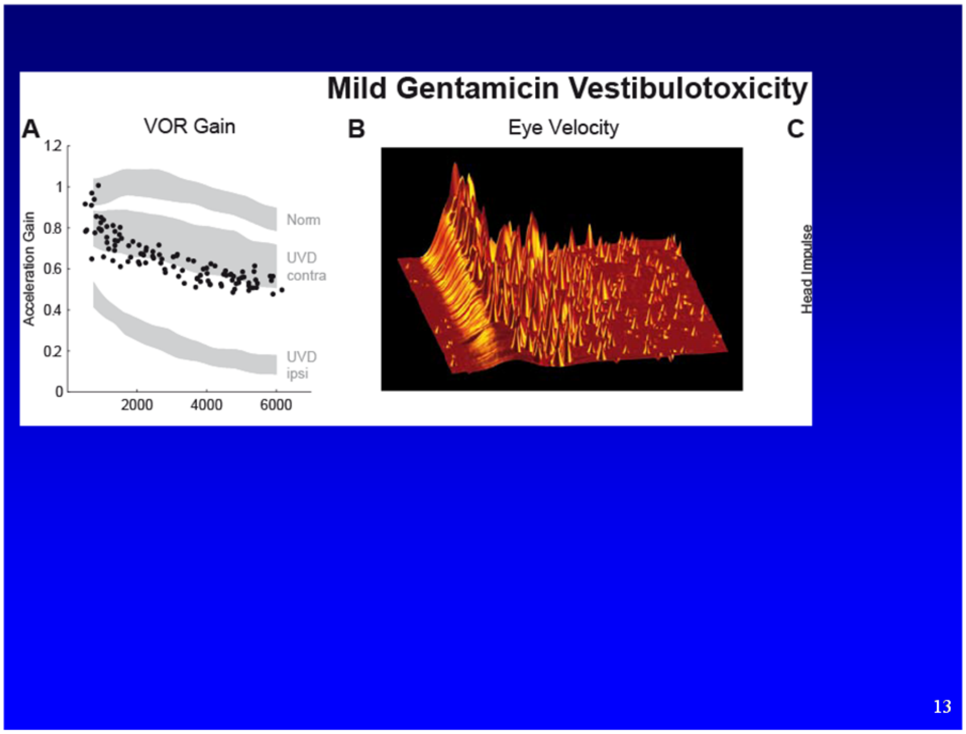
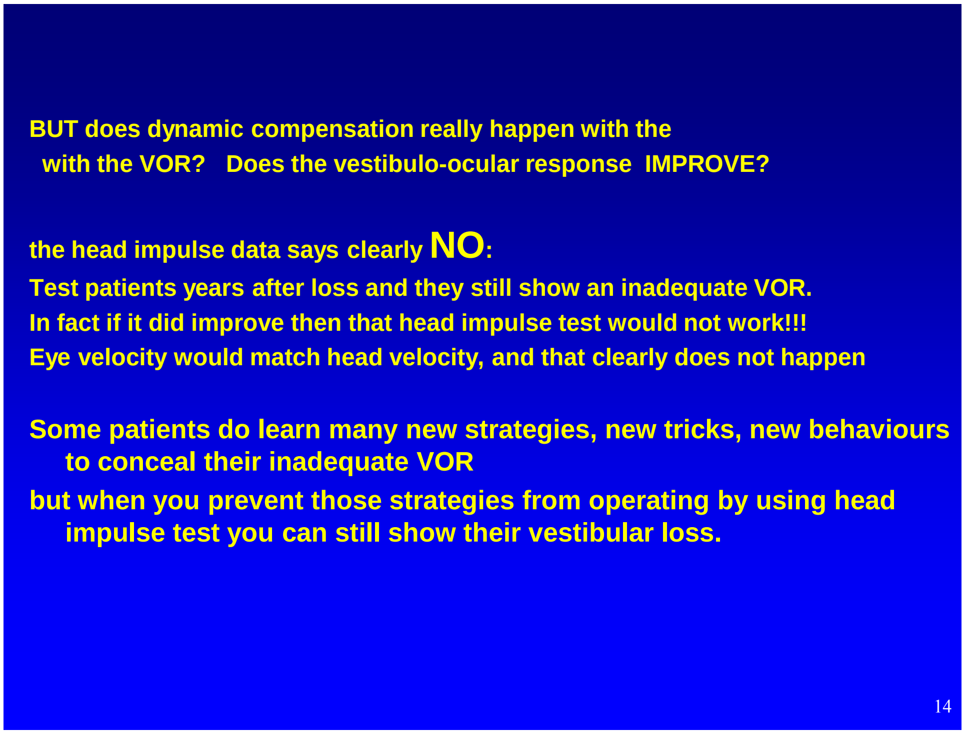


Mild Gentamicin Vestibulotoxicity

Slide 13



BUT does dynamic compensation really happen with the with the VOR? Does the vestibulo-ocular response IMPROVE?

the head impulse data says clearly **NO**:

Test patients years after loss and they still show an inadequate VOR.

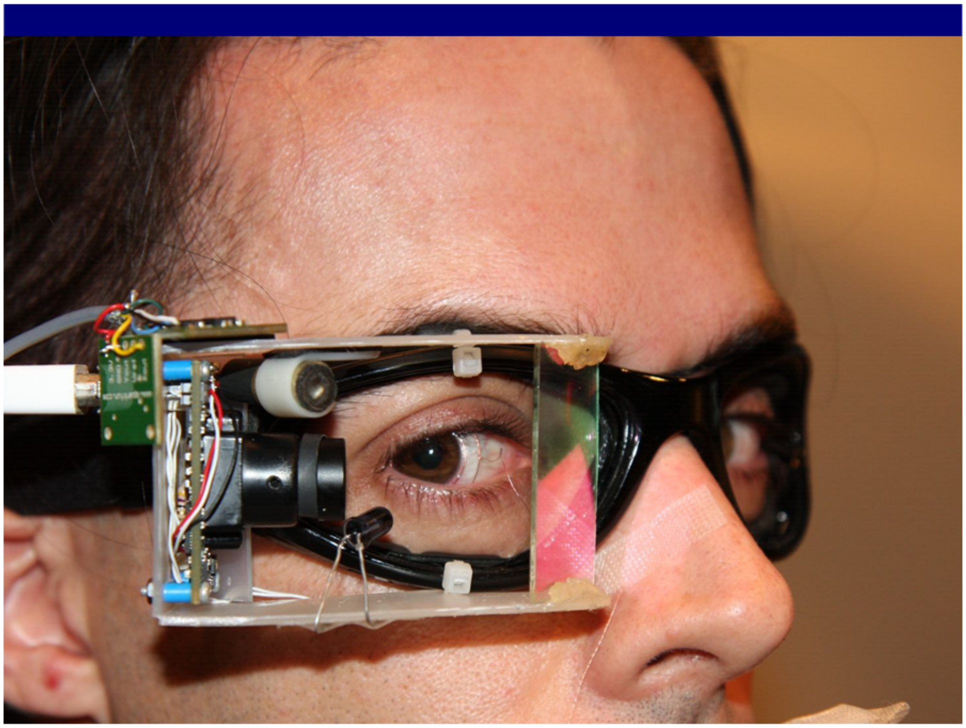
In fact if it did improve then that head impulse test would not work!!!

Eye velocity would match head velocity, and that clearly does not happen

Some patients do learn many new strategies, new tricks, new behaviours to conceal their inadequate VOR

but when you prevent those strategies from operating by using head impulse test you can still show their vestibular loss.

Slide 14



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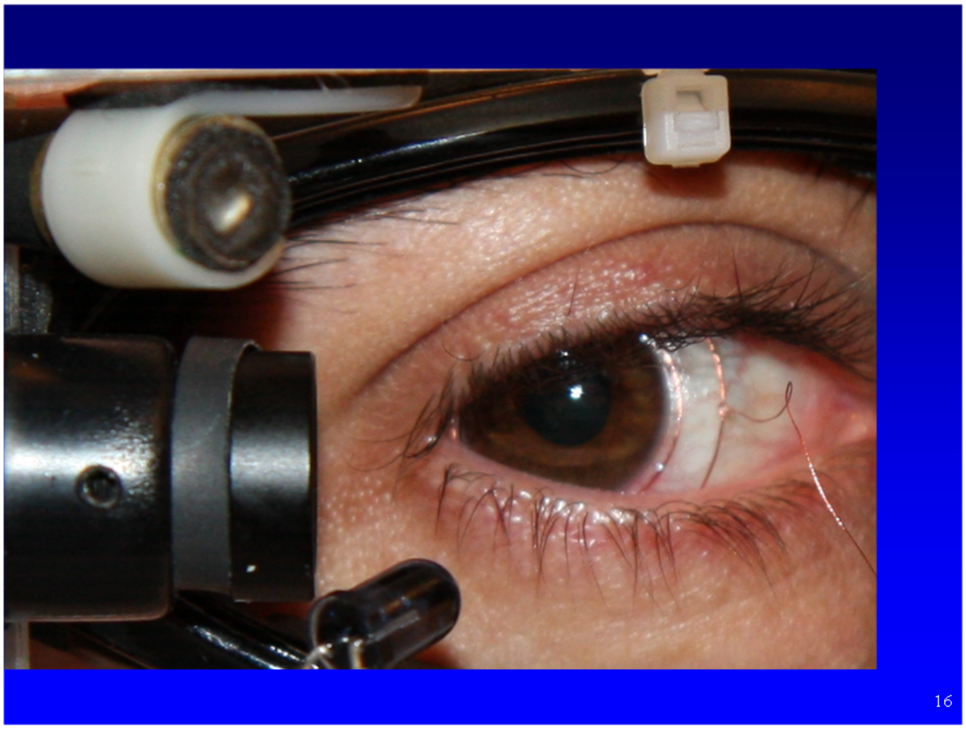


Slide 16

For measuring eye movements

This is the *gold standard* - a search coil - two coils of very fine wire wound in a silicone contact lens.

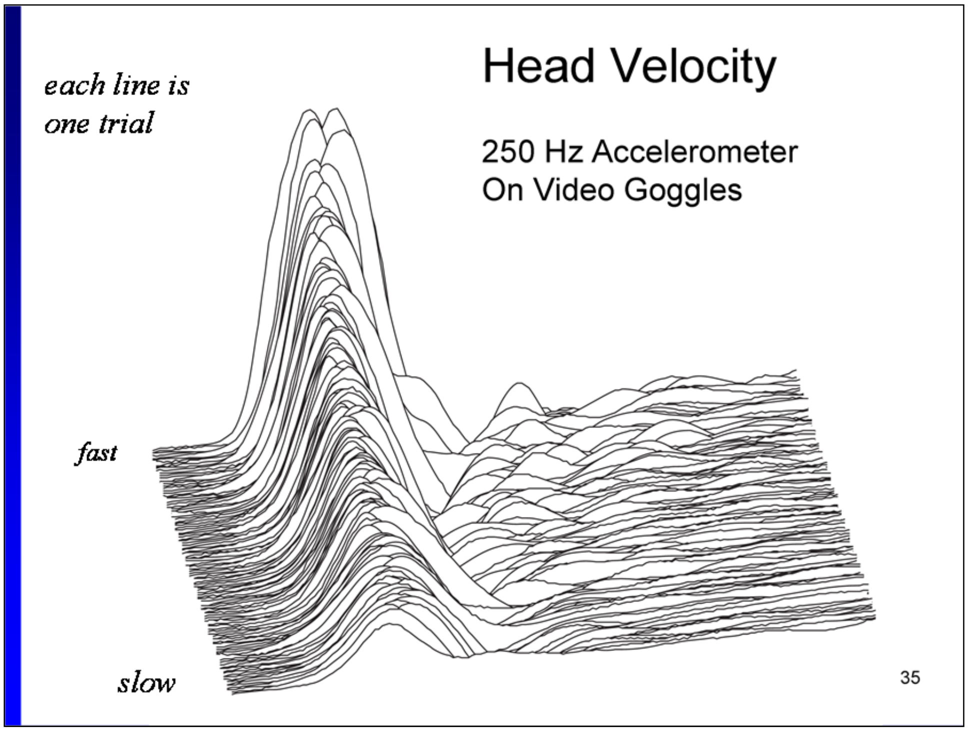
The person sits inside a transmitting field and as their eye moves with respect to that transmitter field, the eye coil signal changes.

(very like the way a transistor radio is very directional.)

Extremely fast, extremely accurate, but relatively invasive and very very expensive!! - each contact lens costs $700. Rayleigh's dictum?

Now video

Slide 17



Head Velocity

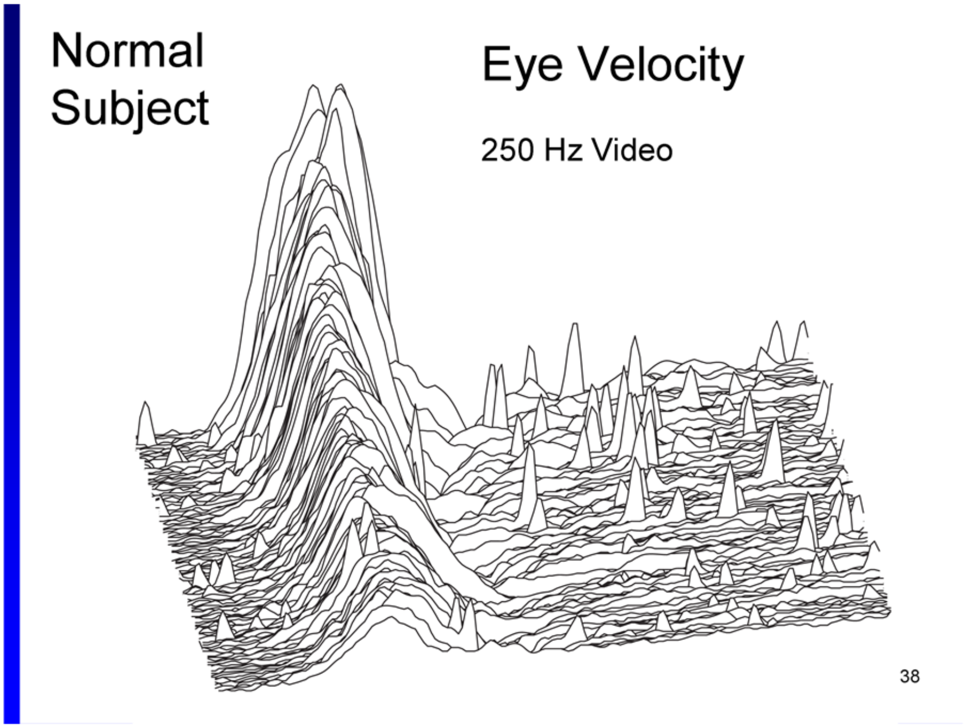
250 Hz Accelerometer
On Video Goggles

each line is one trial

fast

slow

Slide 18

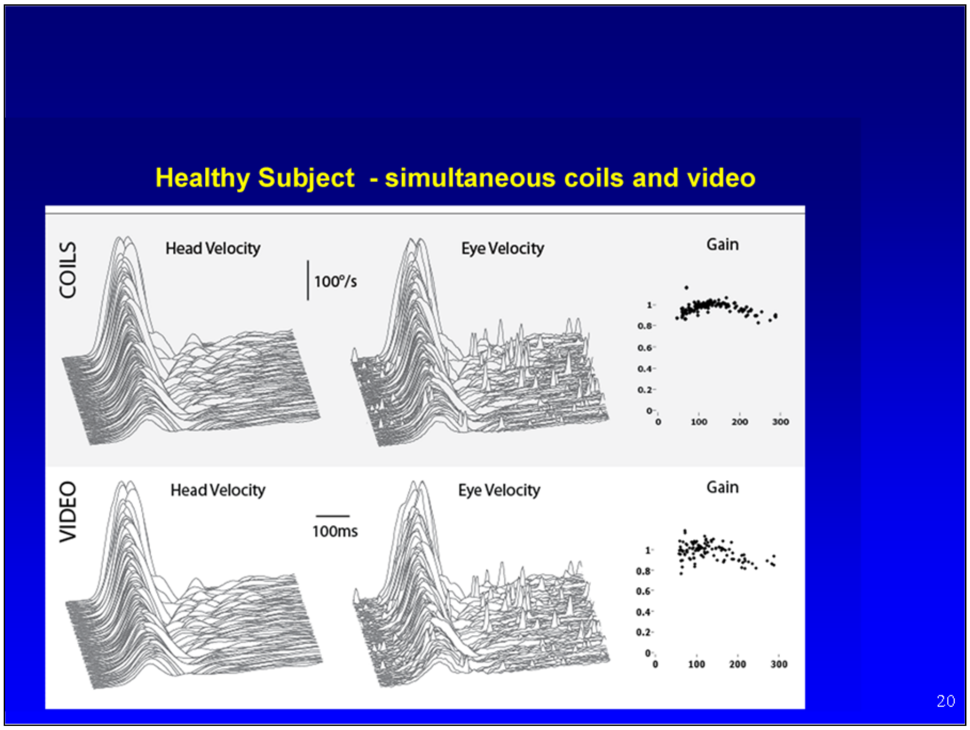


Normal Subject

Eye Velocity

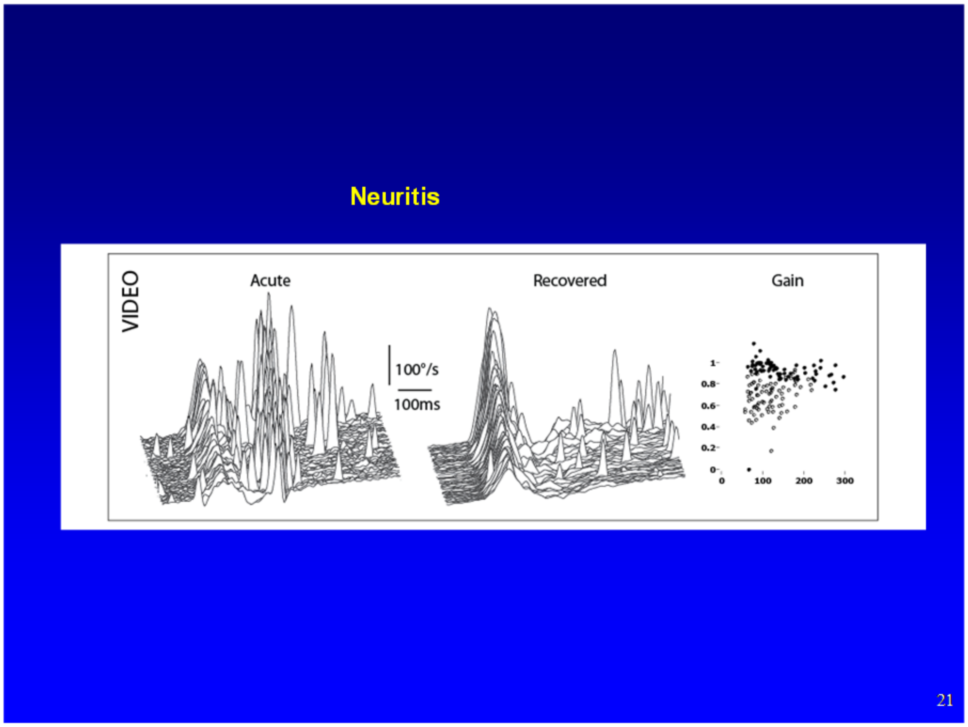
250 Hz Video

Slide 19



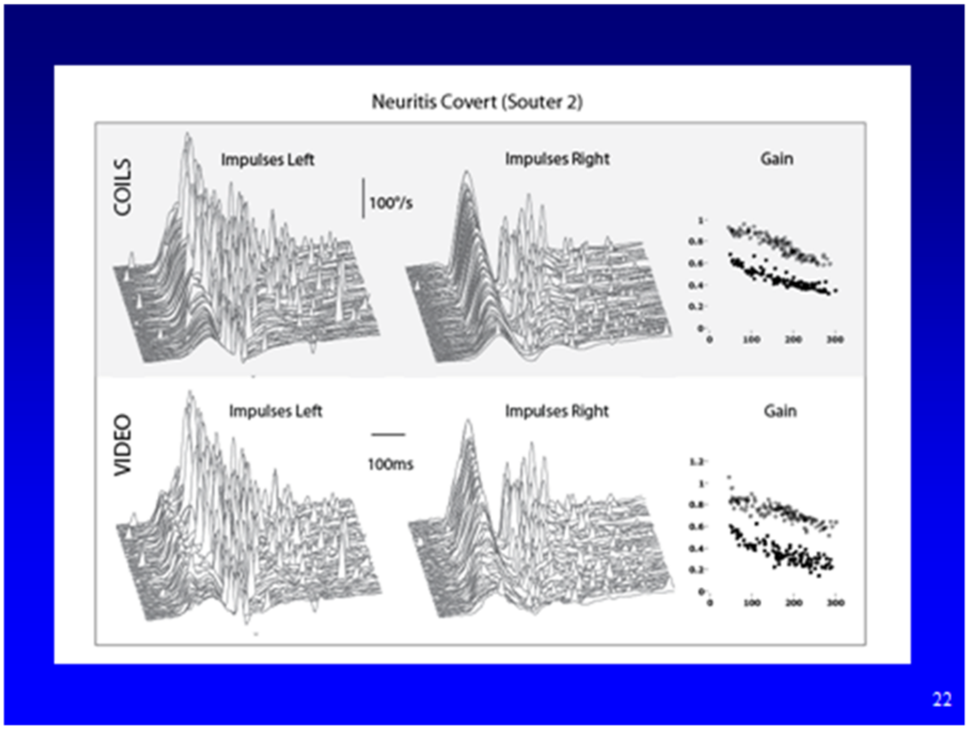
Healthy Subject - simultaneous coils and video

Slide 20



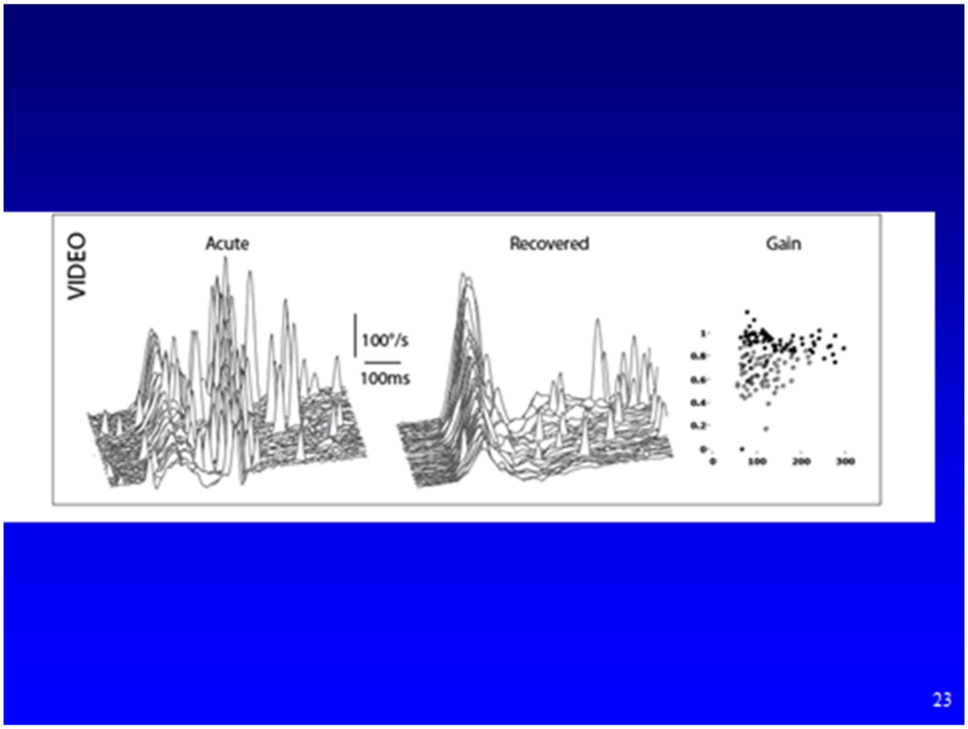
Neuritis

Slide 21



Neuritis Covert (Souter 2)

Slide 22



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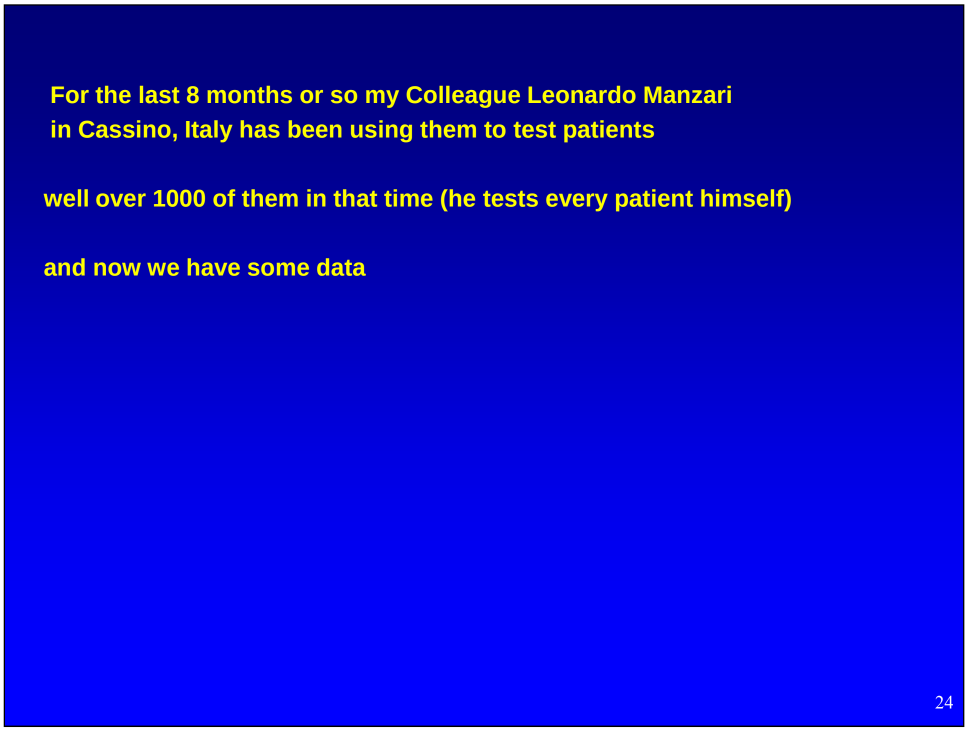
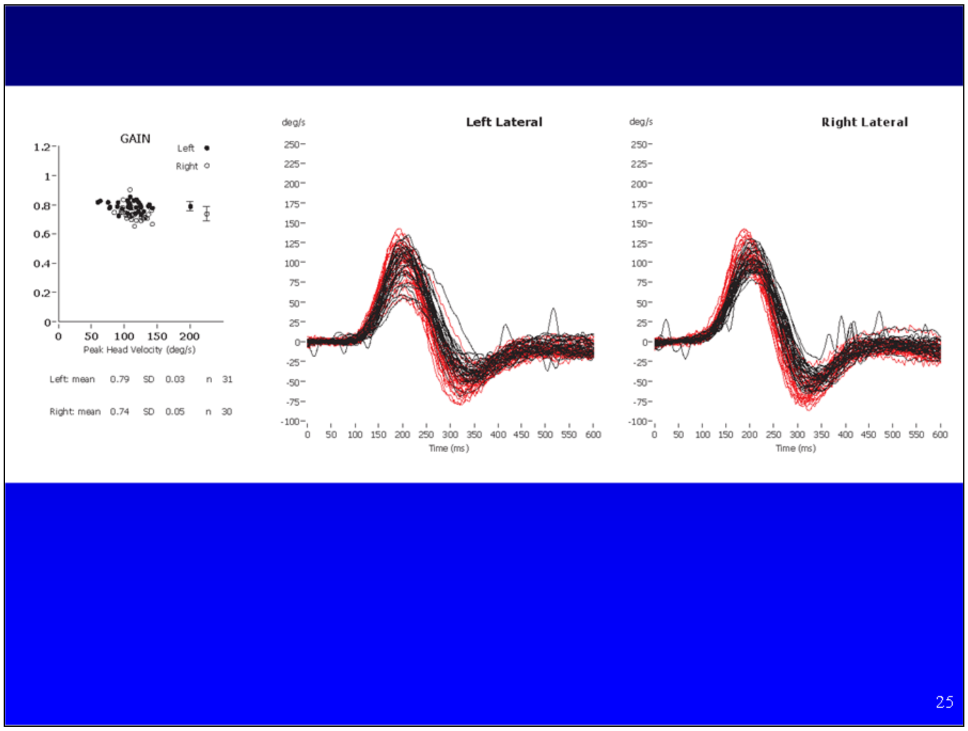


For the last 8 months or so my Colleague Leonardo Manzari in Cassino, Italy has been using them to test patients

well over 1000 of them in that time (he tests every patient himself)

and now we have some data

Slide 24



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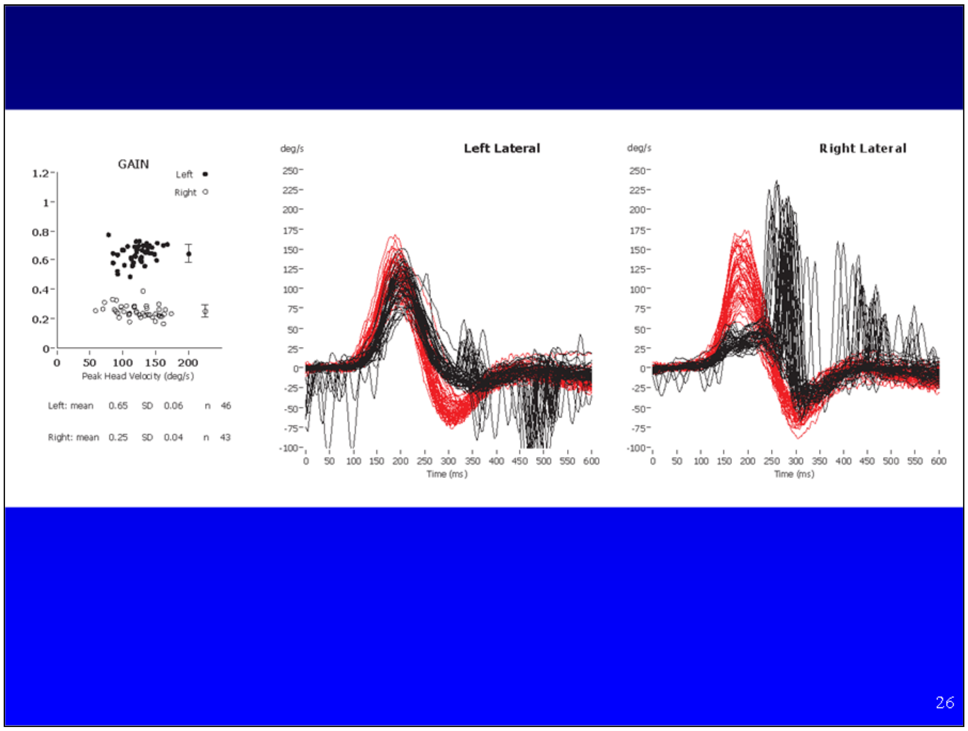

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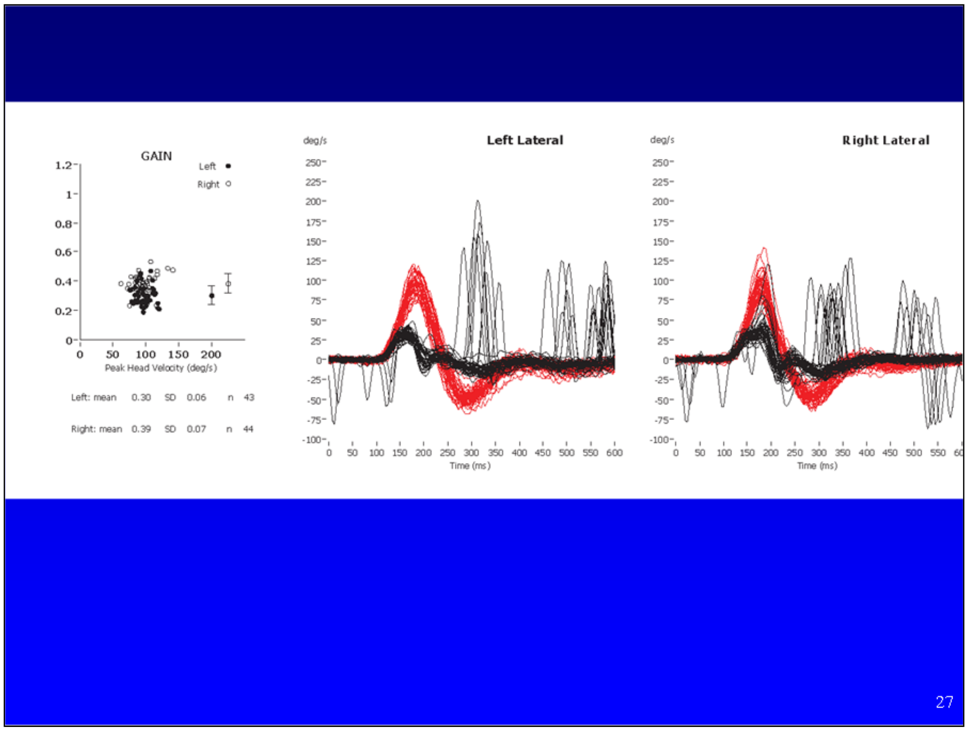

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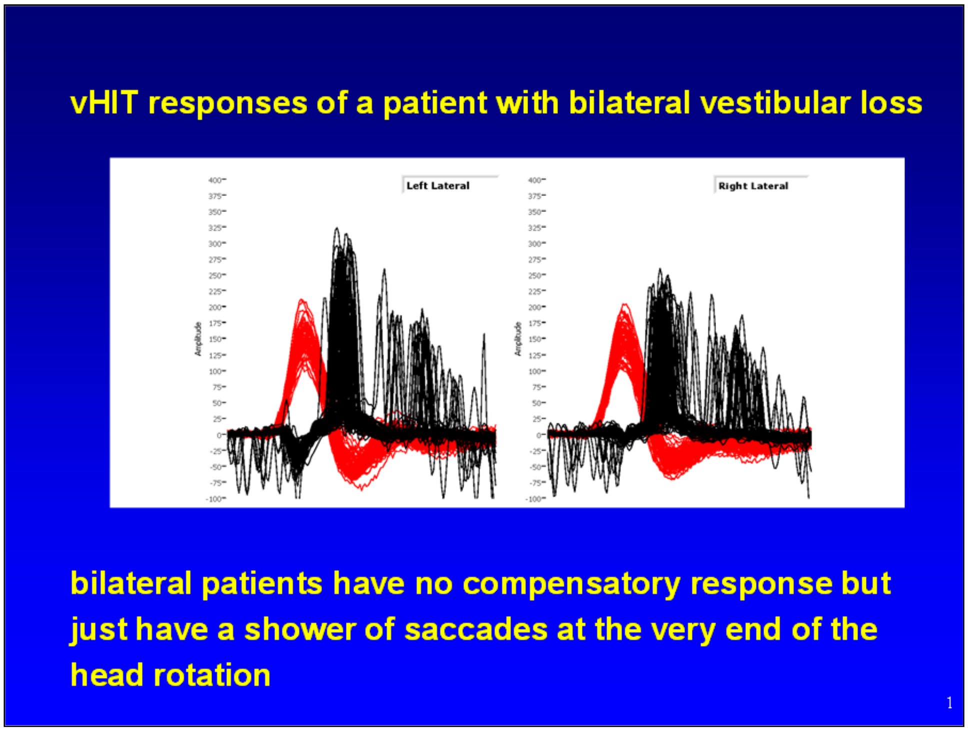


vHIT responses of a patient with bilateral vestibular loss

bilateral patients have no compensatory response but just have a shower of saccades at the very end of the head rotation

Slide 28

But now we are using these impulses in other vestibular disorders like Meniere’s Disease.

and showing

The HVOR gain fluctuates greatly in early MD patients – the same patient tested on different occasions – before, during and after an attack

PDFs

Firstly normals
then MD patients

Slide 29

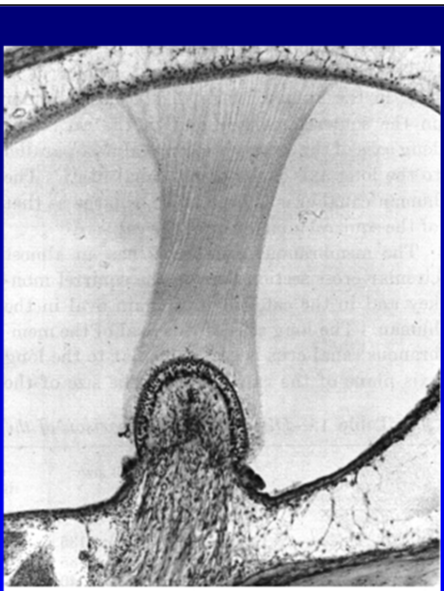
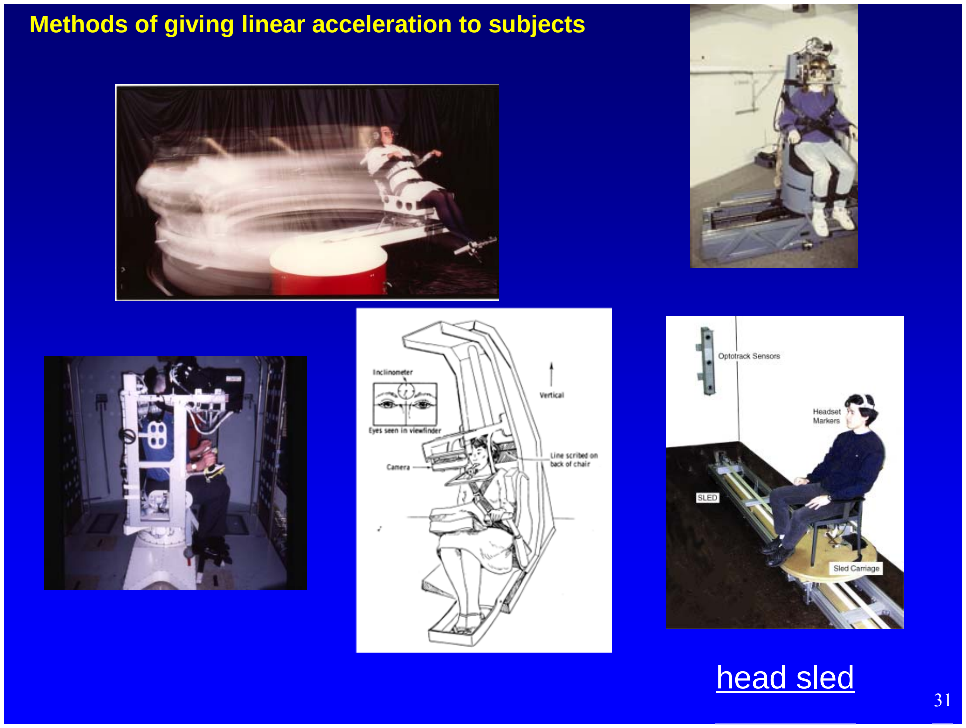


Figure 4.—*A view of crista-cupula system of the horizontal semicircular canal from a squirrel monkey.*

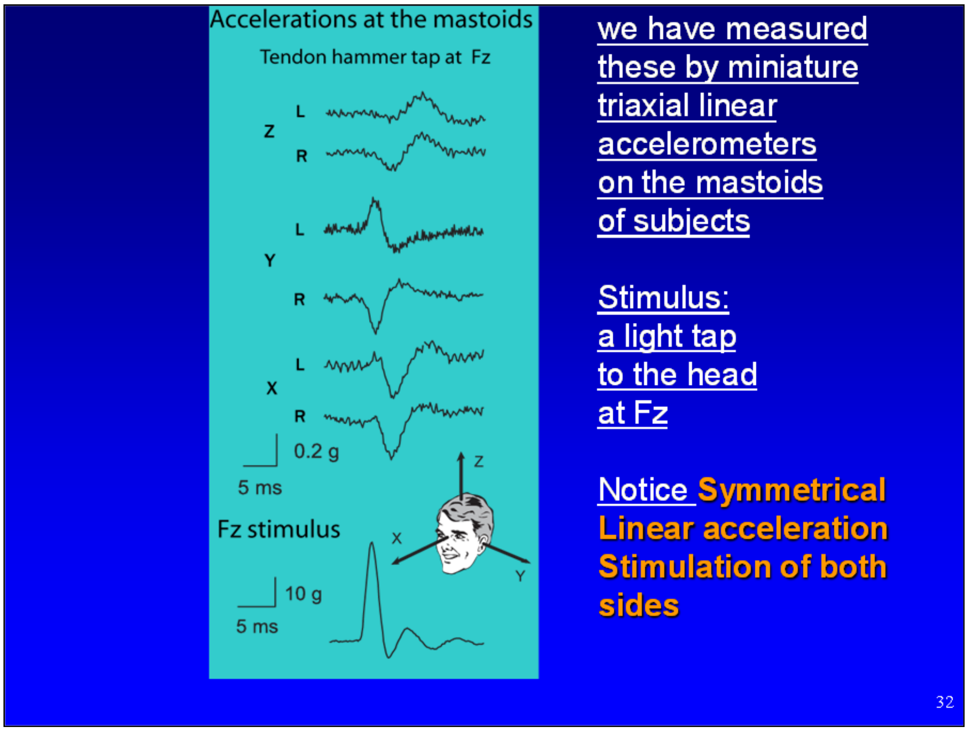
Slide 30



Methods of giving linear acceleration to subjects

head sled

Slide 31

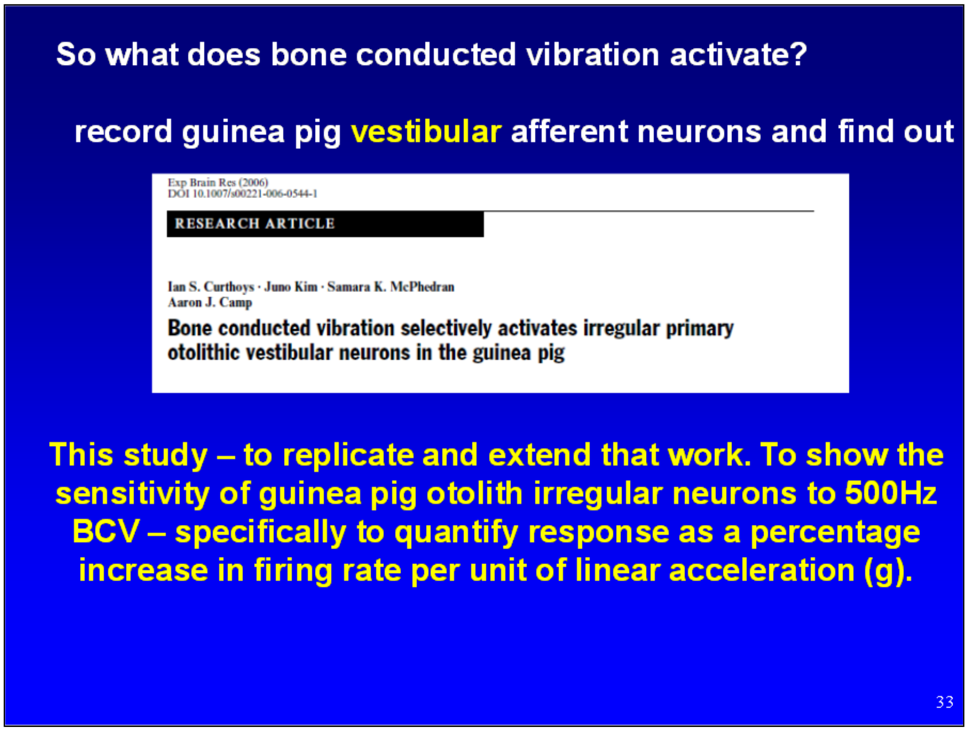


we have measured these by miniature triaxial linear accelerometers on the mastoids of subjects

Stimulus: a light tap to the head at Fz

Notice **Symmetrical Linear acceleration Stimulation of both sides**

Slide 32



So what does bone conducted vibration activate?

record guinea pig **vestibular** afferent neurons and find out

Exp Brain Res (2006)
DOI 10.1007/s00221-006-0544-1

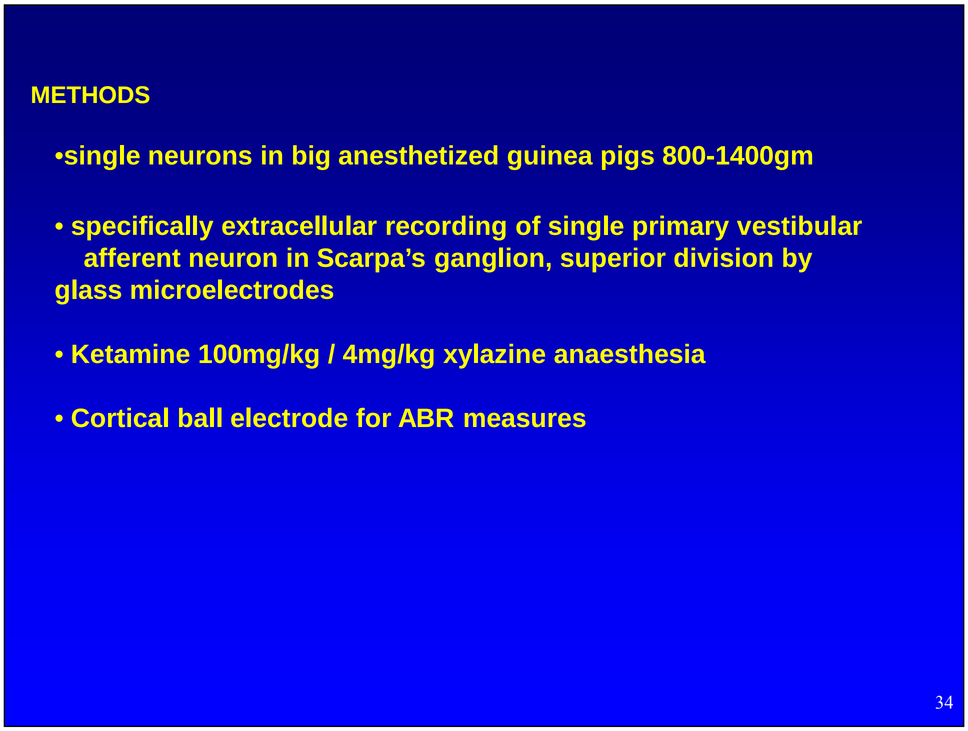
RESEARCH ARTICLE

Ian S. Curthoys · Juno Kim · Samara K. McPhedran
Aaron J. Camp

Bone conducted vibration selectively activates irregular primary otolithic vestibular neurons in the guinea pig

This study – to replicate and extend that work. To show the sensitivity of guinea pig otolith irregular neurons to 500Hz BCV – specifically to quantify response as a percentage increase in firing rate per unit of linear acceleration (g).

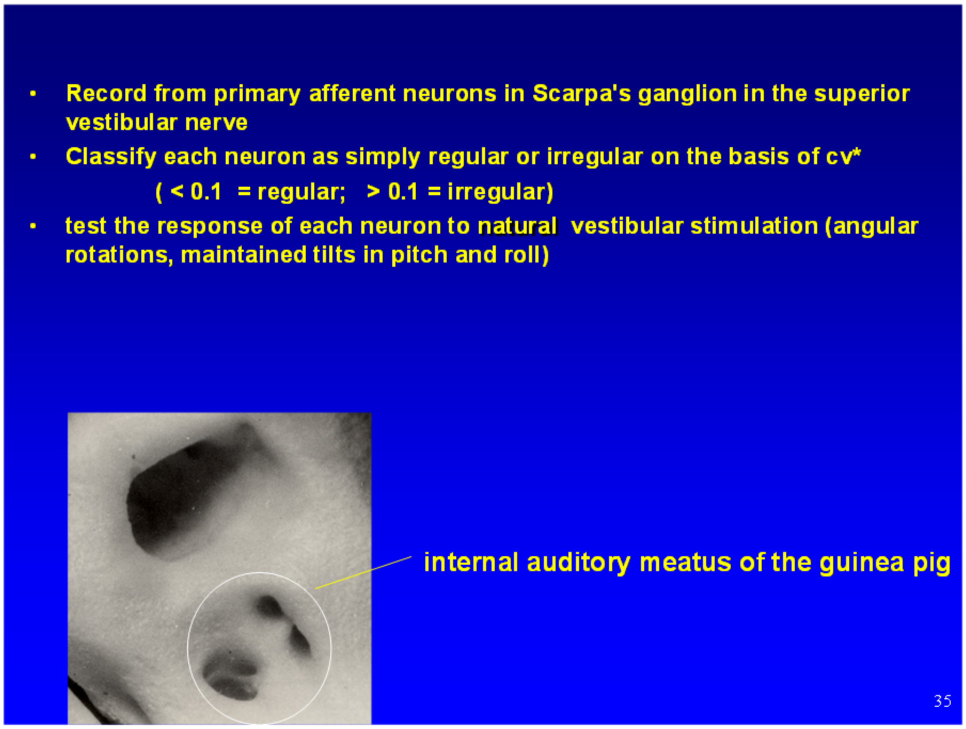
Slide 33



METHODS

- single neurons in big anesthetized guinea pigs 800-1400gm
- specifically extracellular recording of single primary vestibular afferent neuron in Scarpa's ganglion, superior division by glass microelectrodes
- Ketamine 100mg/kg / 4mg/kg xylazine anaesthesia
- Cortical ball electrode for ABR measures

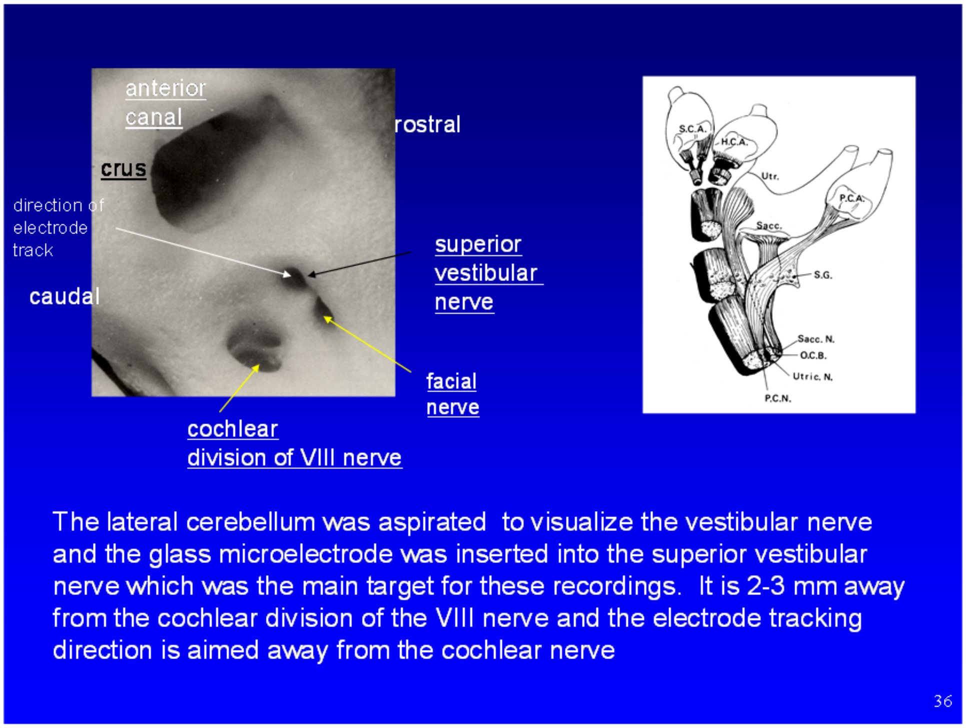
Slide 34



- Record from primary afferent neurons in Scarpa's ganglion in the superior vestibular nerve
- Classify each neuron as simply regular or irregular on the basis of cv*
  (< 0.1 = regular; > 0.1 = irregular)
- test the response of each neuron to natural vestibular stimulation (angular rotations, maintained tilts in pitch and roll)

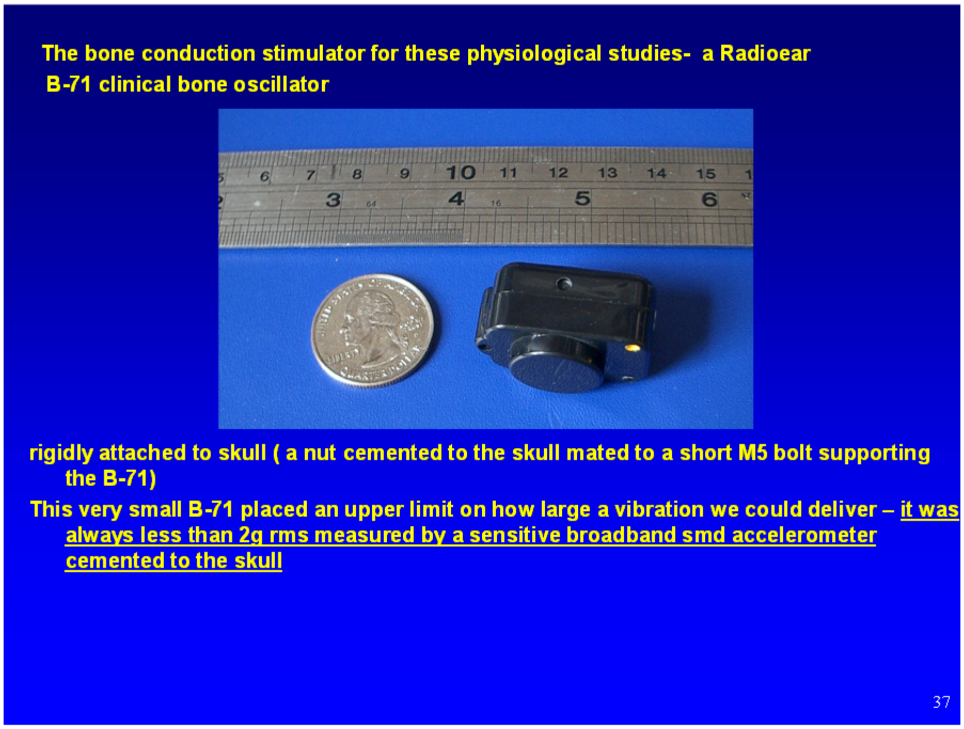
internal auditory meatus of the guinea pig

Slide 35



The lateral cerebellum was aspirated to visualize the vestibular nerve and the glass microelectrode was inserted into the superior vestibular nerve which was the main target for these recordings. It is 2-3 mm away from the cochlear division of the VIII nerve and the electrode tracking direction is aimed away from the cochlear nerve

Slide 36

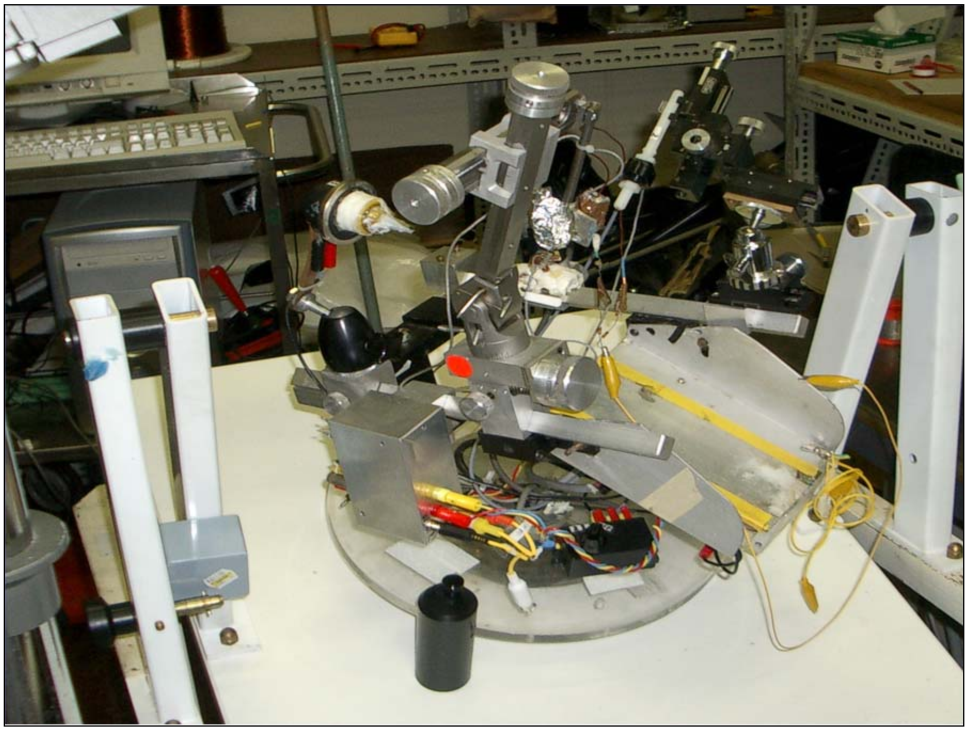


The bone conduction stimulator for these physiological studies- a Radioear B-71 clinical bone oscillator

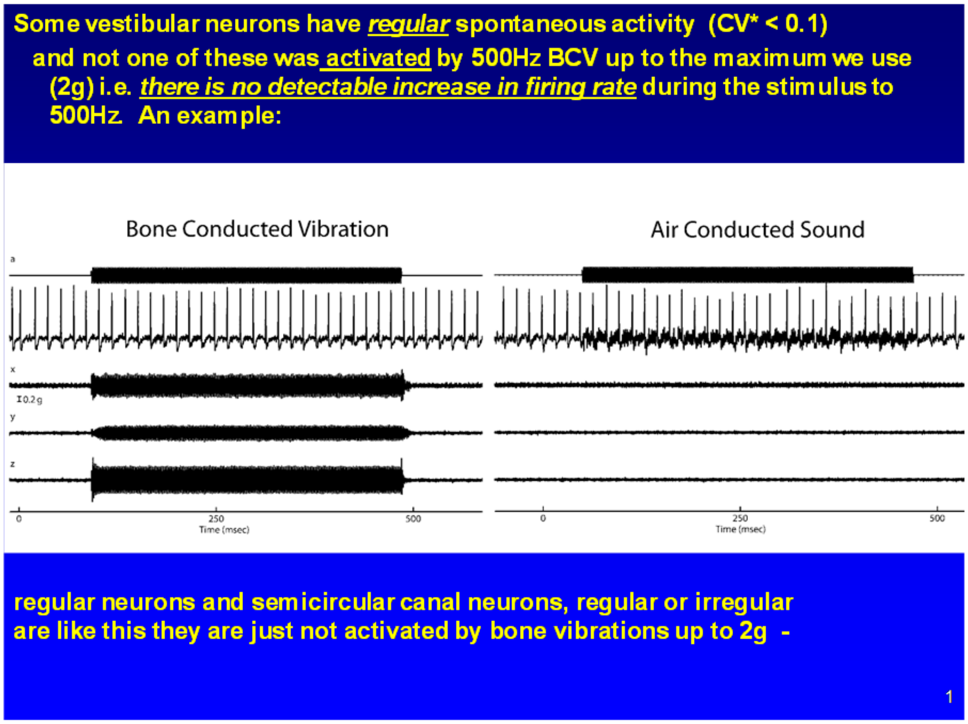
rigidly attached to skull (a nut cemented to the skull mated to a short M5 bolt supporting the B-71)

This very small B-71 placed an upper limit on how large a vibration we could deliver – it was always less than 2g rms measured by a sensitive broadband smd accelerometer cemented to the skull

Slide 37



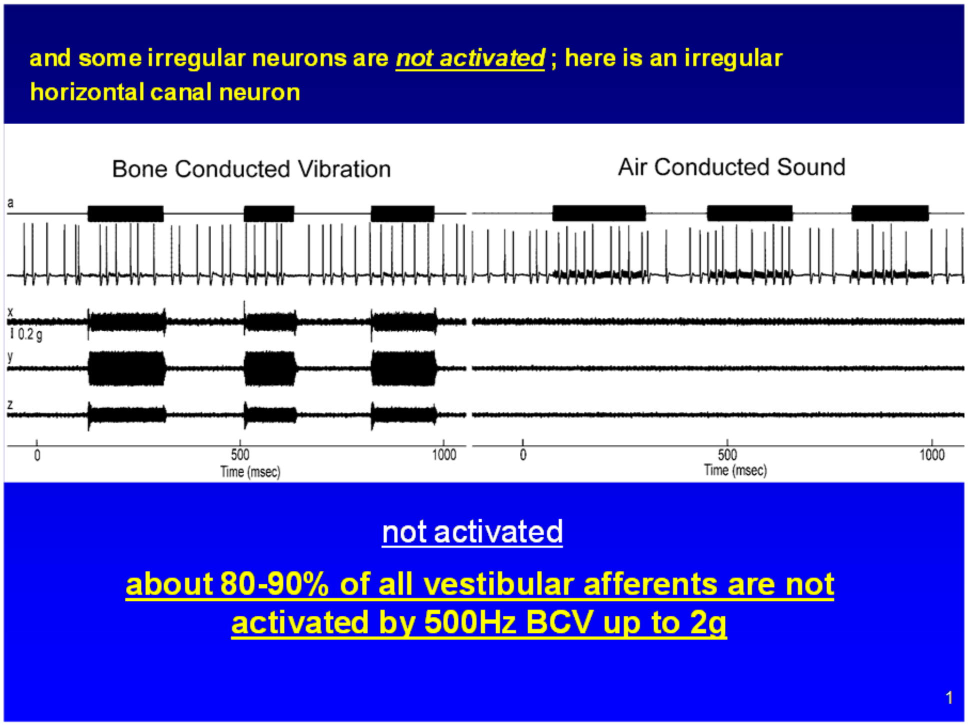
Slide 38


Some vestibular neurons have *regular* spontaneous activity (CV* < 0.1) and not one of these was activated by 500Hz BCV up to the maximum we use (2g) i.e. *there is no detectable increase in firing rate* during the stimulus to 500Hz. An example:

regular neurons and semicircular canal neurons, regular or irregular are like this they are just not activated by bone vibrations up to 2g -

1

Slide 39

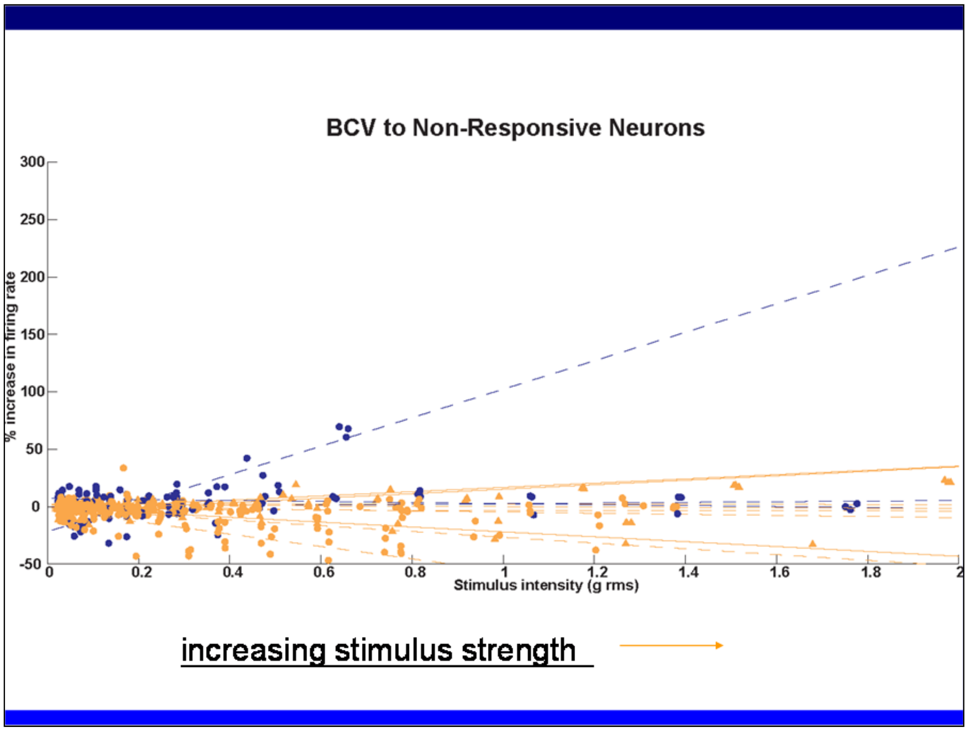

and some irregular neurons are *not activated* ; here is an irregular horizontal canal neuron

not activated

about 80-90% of all vestibular afferents are not activated by 500Hz BCV up to 2g

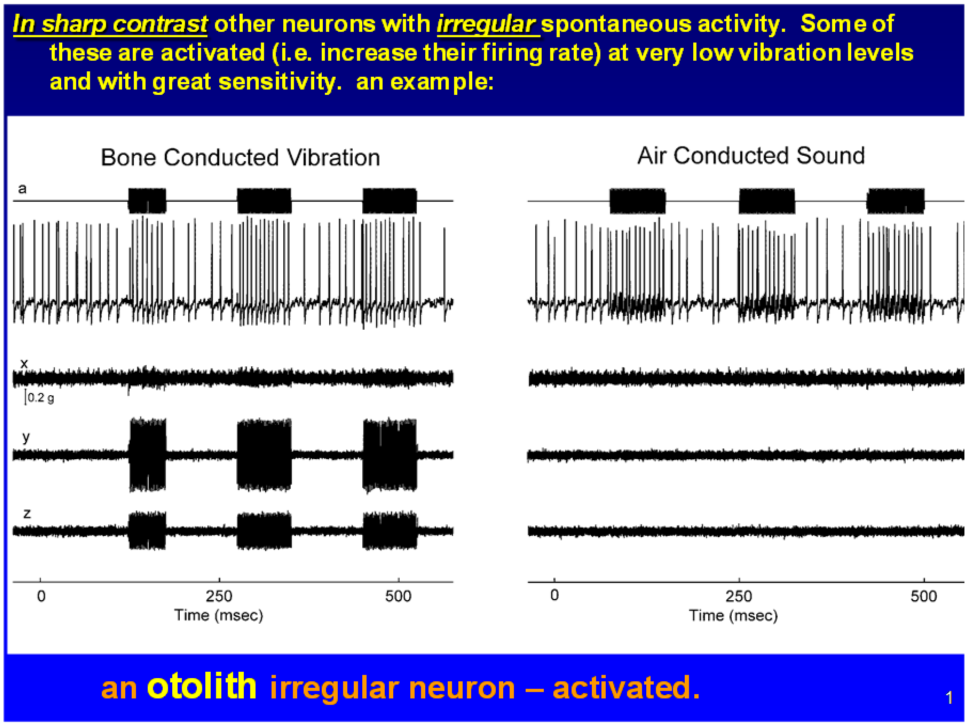
1

Slide 40



increasing stimulus strength →

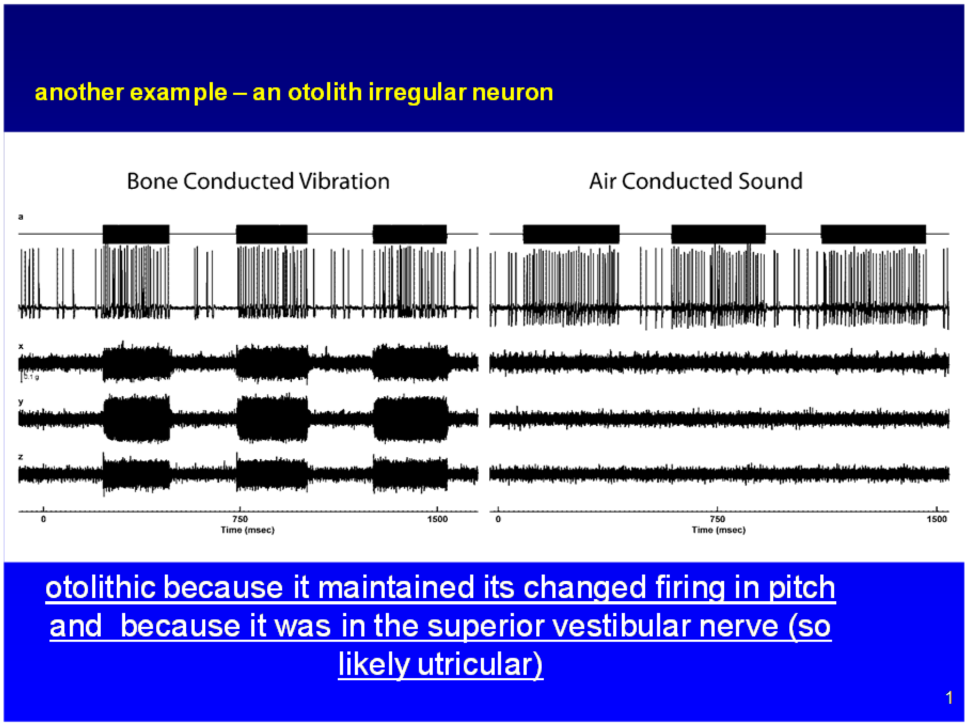
Slide 41


In sharp contrast **other neurons with *irregular* spontaneous activity. Some of these are activated (i.e. increase their firing rate) at very low vibration levels and with great sensitivity. an example:**

an otolith irregular neuron – activated.

1

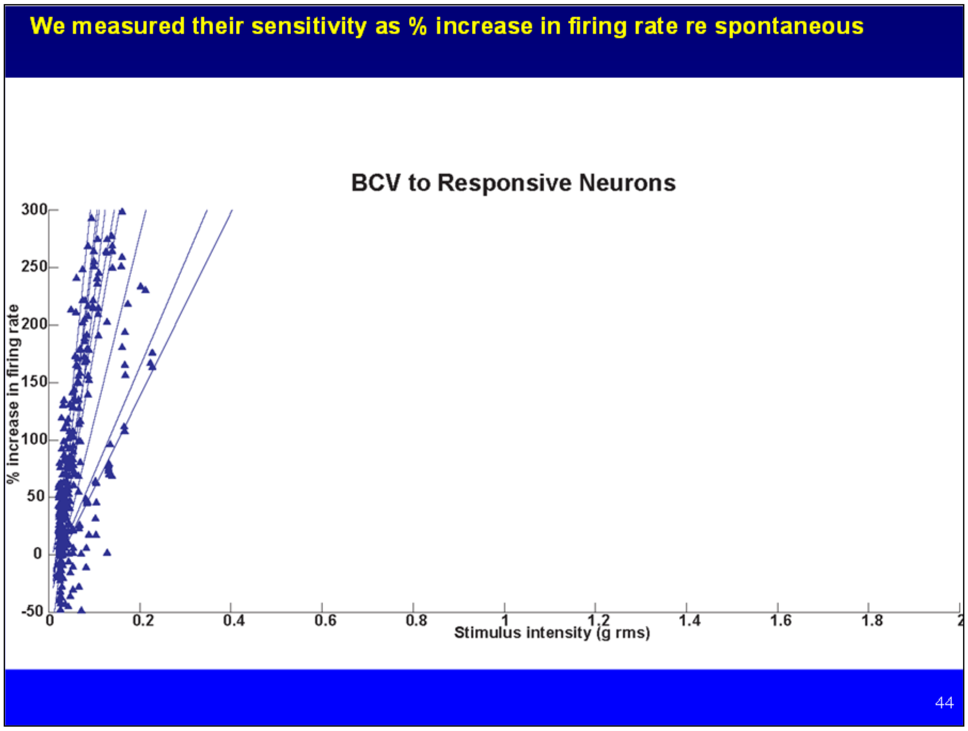
Slide 42



another example – an otolith irregular neuron

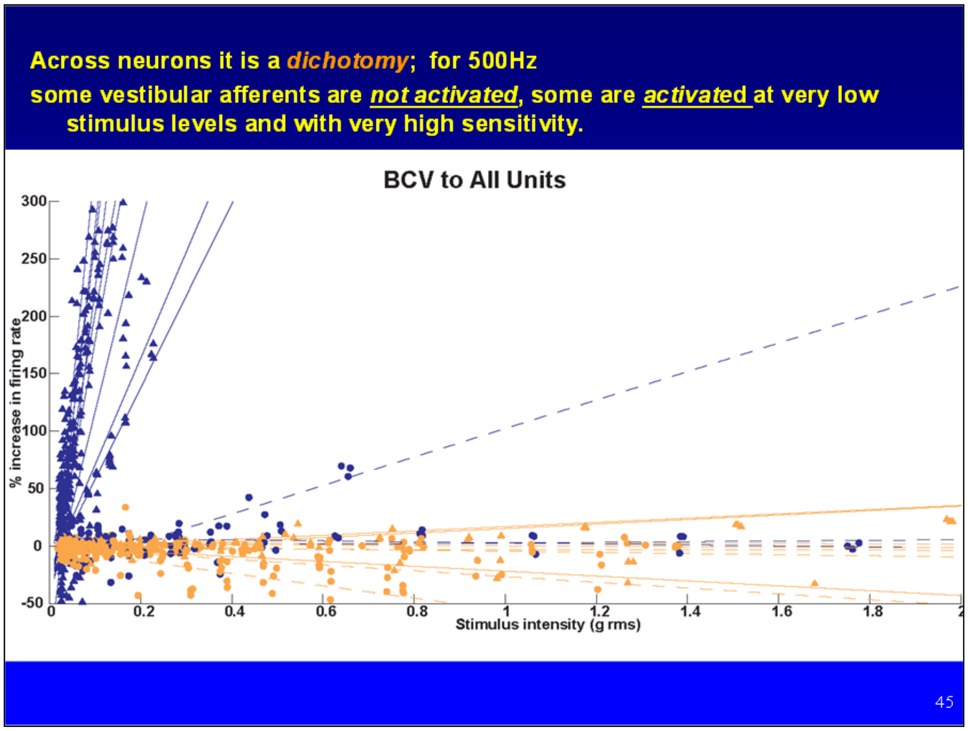
otolithic because it maintained its changed firing in pitch and because it was in the superior vestibular nerve (so likely utricular)

Slide 43



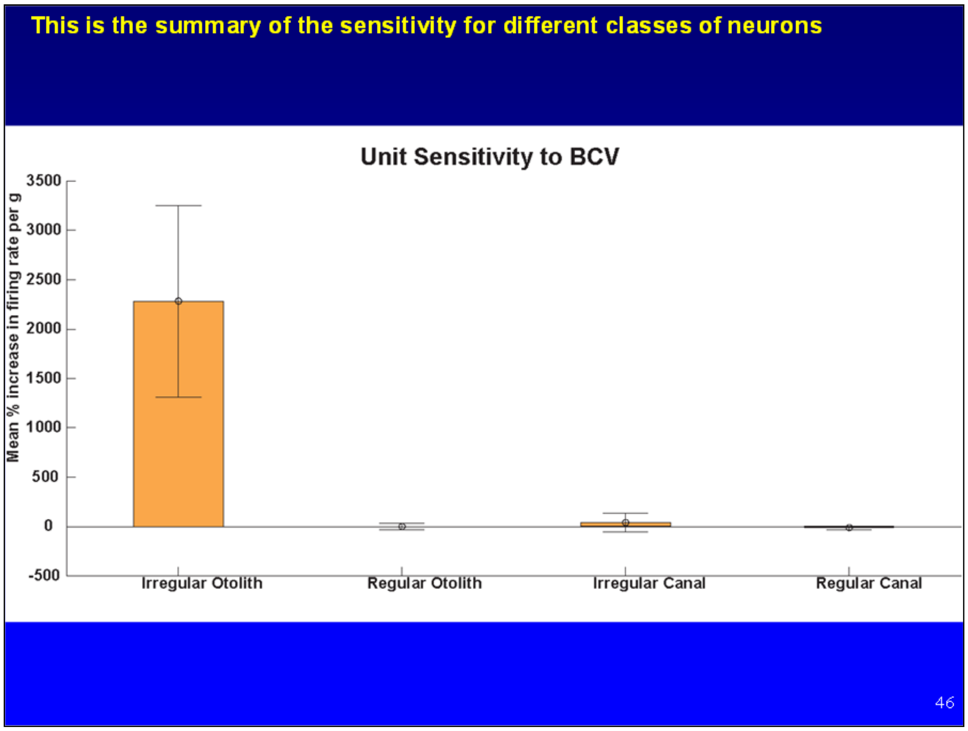
We measured their sensitivity as % increase in firing rate re spontaneous

Slide 44



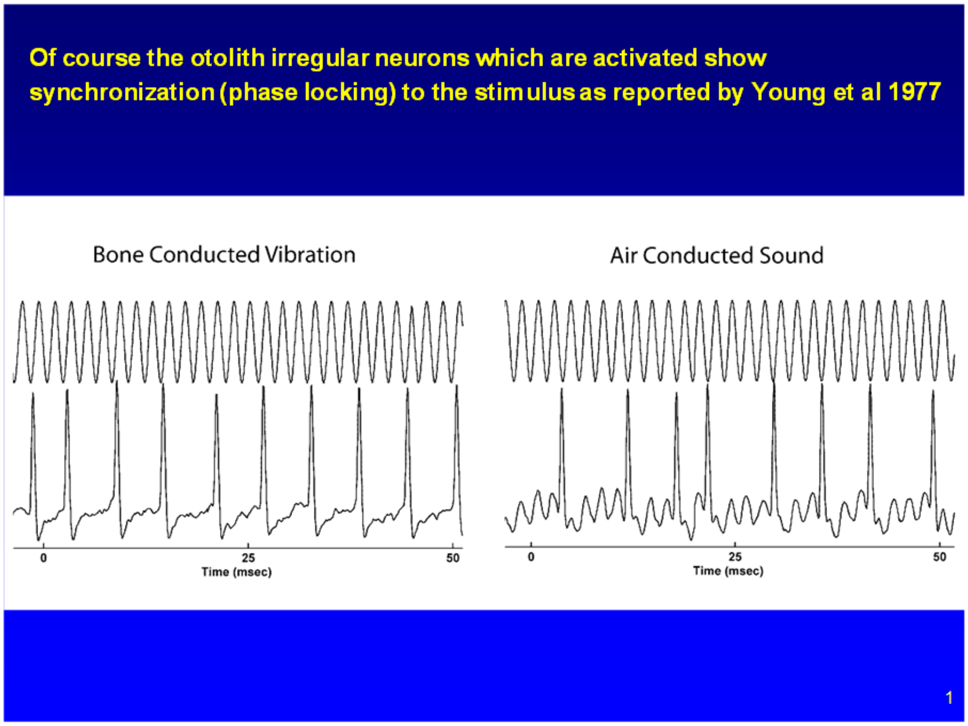
Across neurons it is a *dichotomy*; for 500Hz some vestibular afferents are *not activated*, some are *activated* at very low stimulus levels and with very high sensitivity.

Slide 45



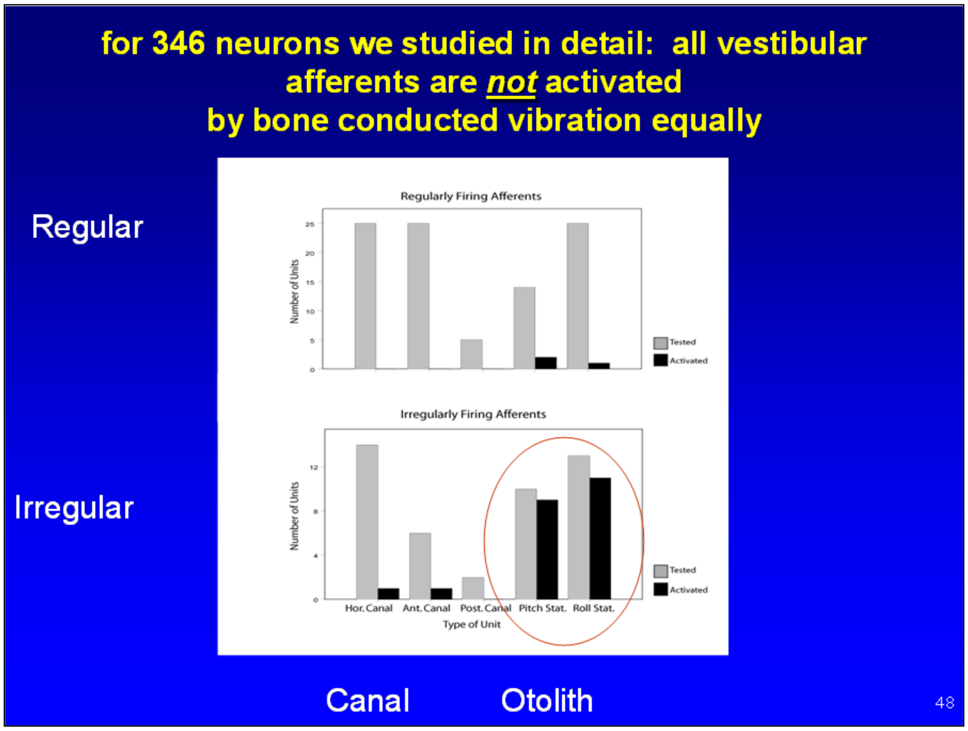
This is the summary of the sensitivity for different classes of neurons

Slide 46



Of course the otolith irregular neurons which are activated show synchronization (phase locking) to the stimulus as reported by Young et al 1977

Slide 47

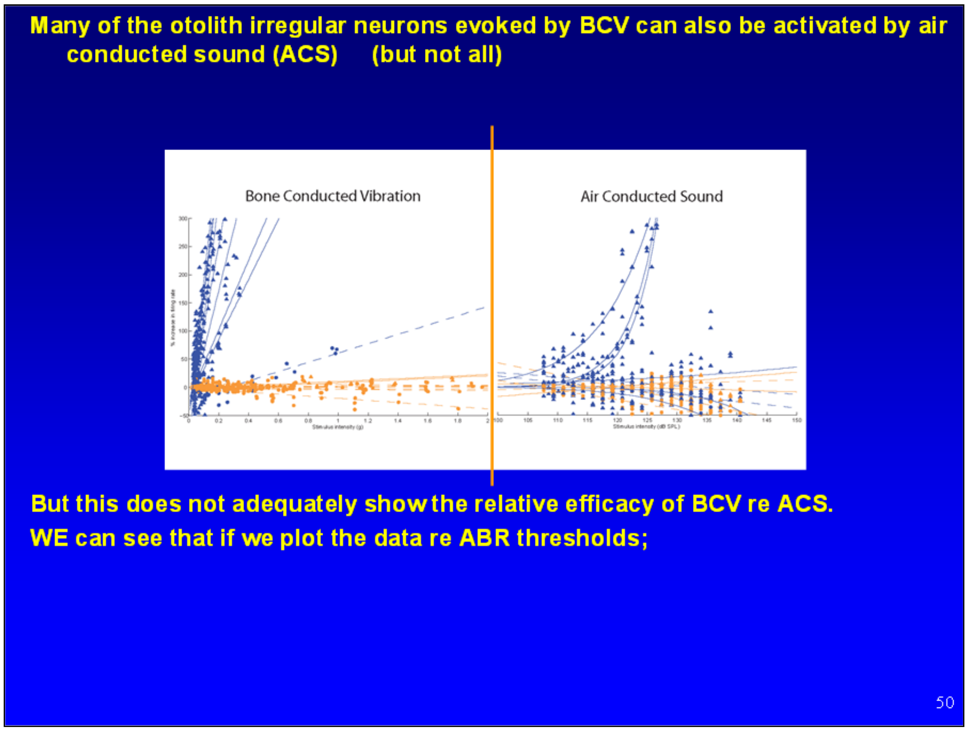


for 346 neurons we studied in detail: all vestibular afferents are *not* activated by bone conducted vibration equally

Slide 48

Activation by air-conducted sound (ACS)

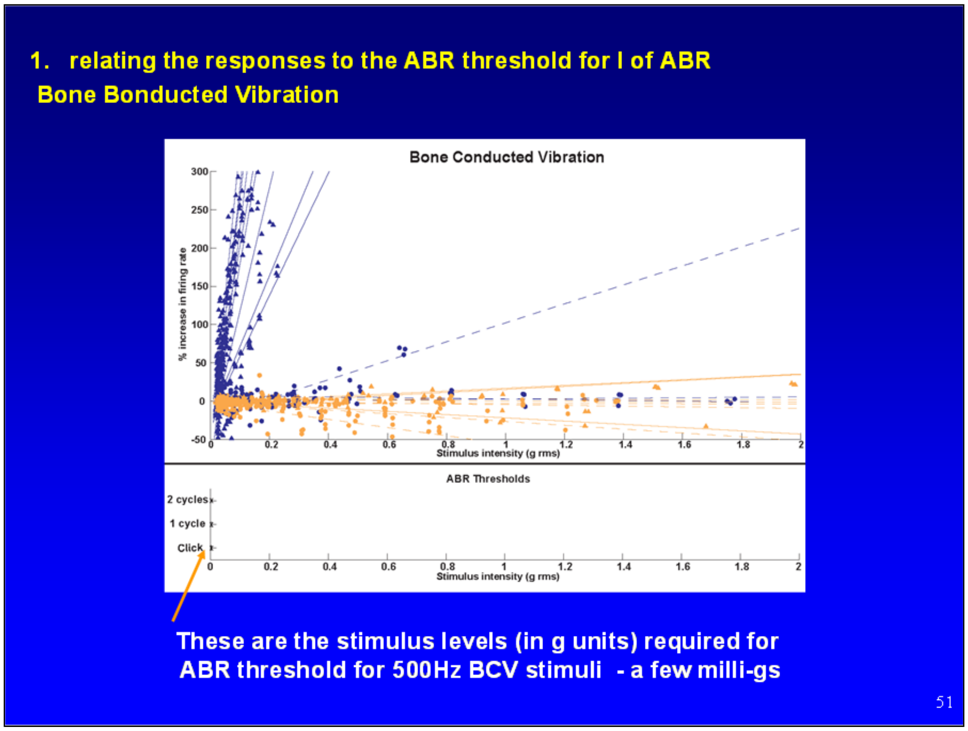
Slide 49



Many of the otolith irregular neurons evoked by BCV can also be activated by air conducted sound (ACS)   (but not all)

But this does not adequately show the relative efficacy of BCV re ACS.
WE can see that if we plot the data re ABR thresholds;

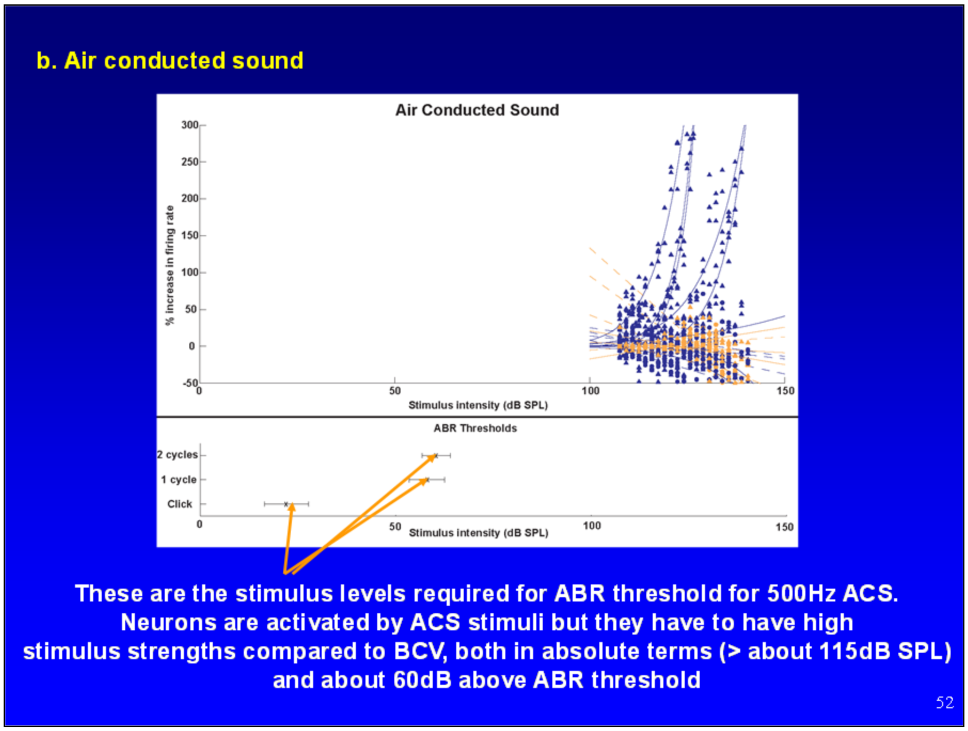
Slide 50



1. relating the responses to the ABR threshold for I of ABR
Bone Bonducted Vibration

These are the stimulus levels (in g units) required for ABR threshold for 500Hz BCV stimuli - a few milli-gs

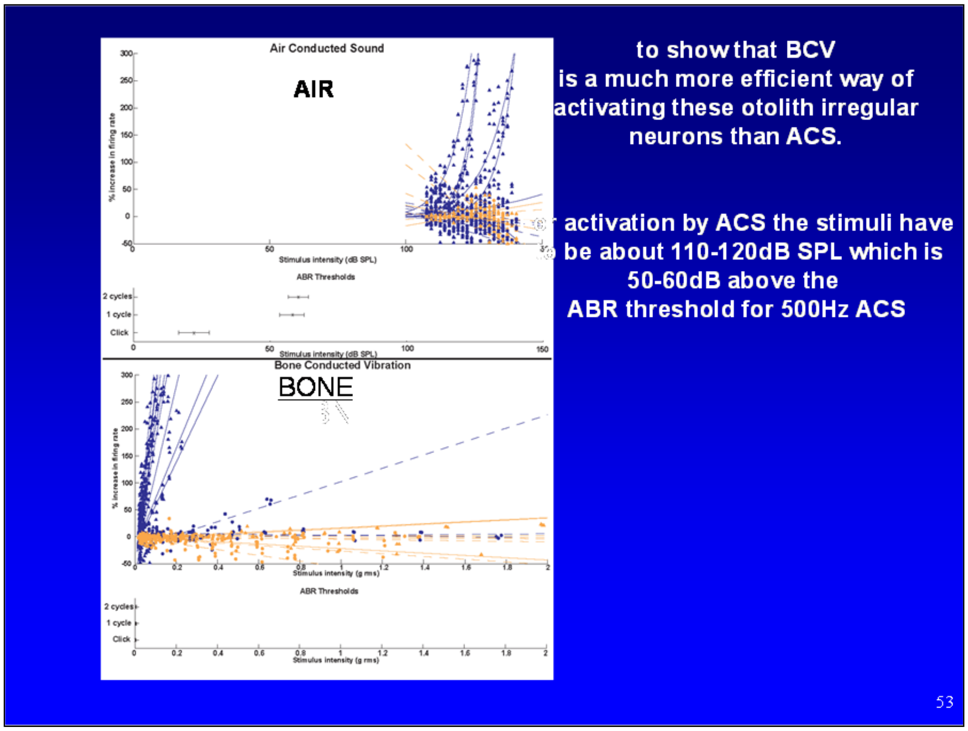
Slide 51



b. Air conducted sound

These are the stimulus levels required for ABR threshold for 500Hz ACS. Neurons are activated by ACS stimuli but they have to have high stimulus strengths compared to BCV, both in absolute terms (> about 115dB SPL) and about 60dB above ABR threshold

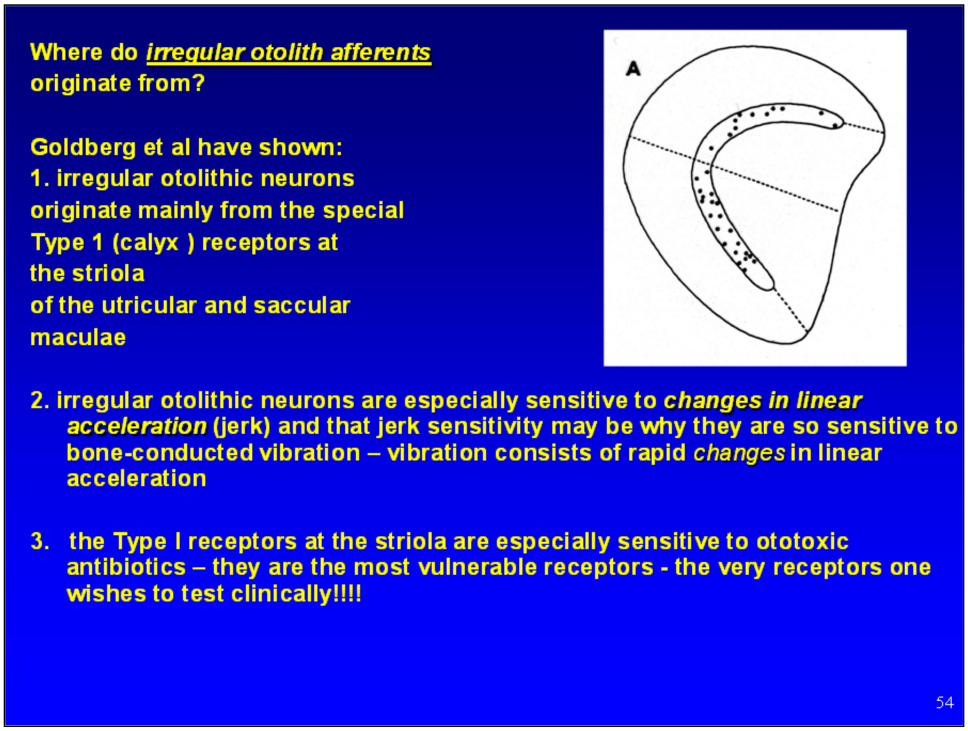
Slide 52



to show that BCV
is a much more efficient way of
activating these otolith irregular
neurons than ACS.

r activation by ACS the stimuli have
be about 110-120dB SPL which is
50-60dB above the
ABR threshold for 500Hz ACS

Slide 53

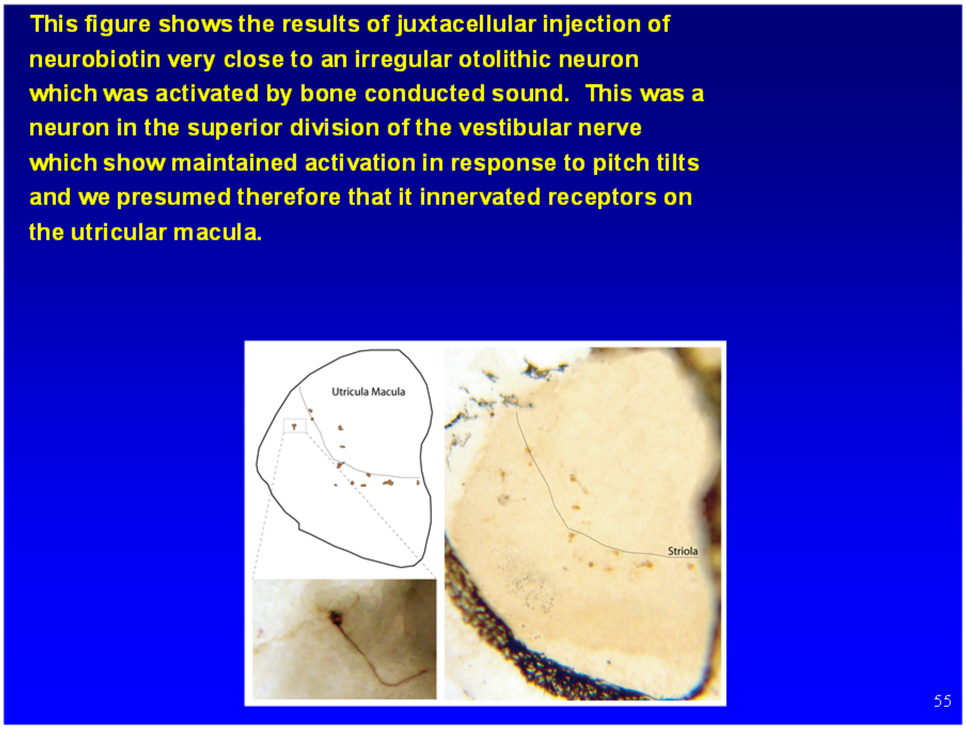


Where do *irregular otolith afferents* originate from?

Goldberg et al have shown:

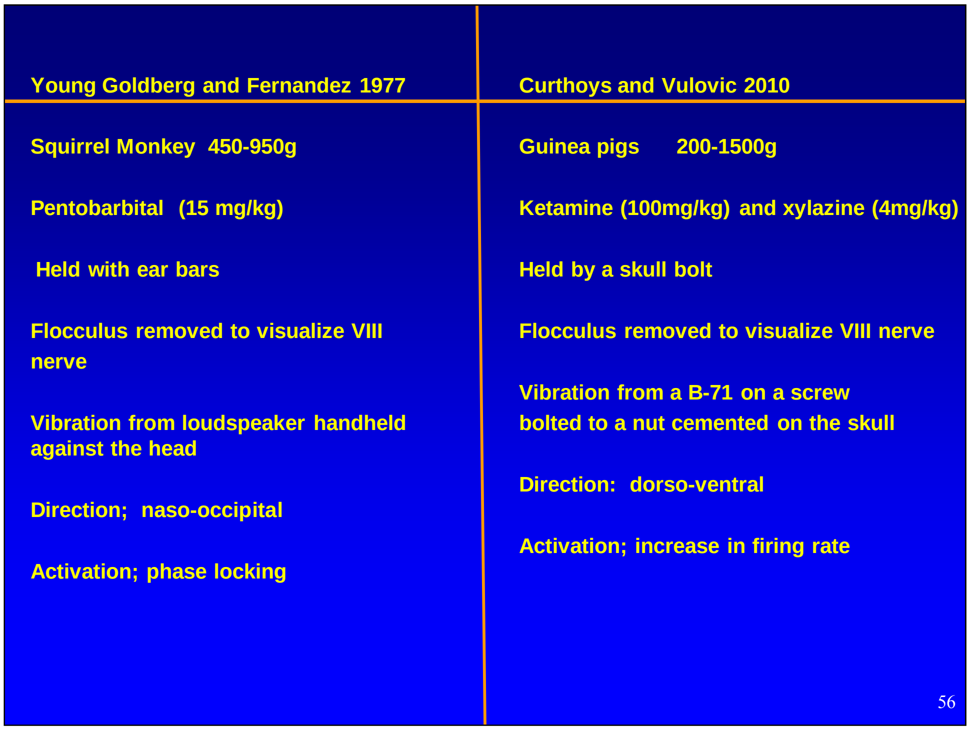
1. **irregular otolithic neurons originate mainly from the special Type 1 (calyx) receptors at the striola of the utricular and saccular maculae**
2. **irregular otolithic neurons are especially sensitive to *changes in linear acceleration* (jerk) and that jerk sensitivity may be why they are so sensitive to bone-conducted vibration – vibration consists of rapid *changes* in linear acceleration**
3. **the Type I receptors at the striola are especially sensitive to ototoxic antibiotics – they are the most vulnerable receptors - the very receptors one wishes to test clinically!!!!**

Slide 54



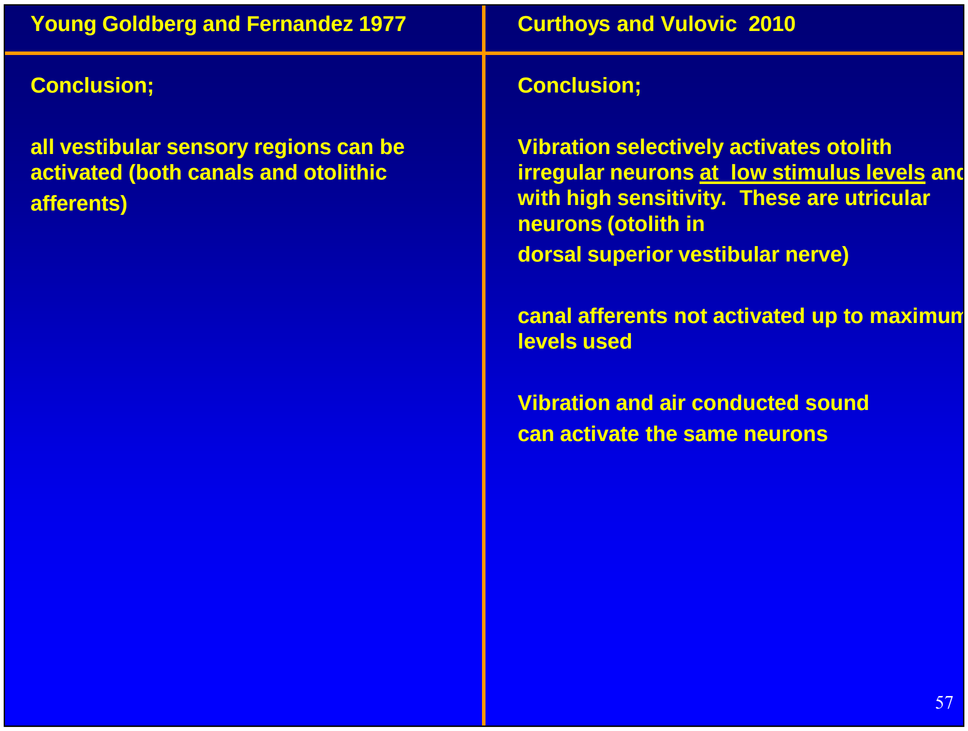
This figure shows the results of juxtacellular injection of neurobiotin very close to an irregular otolithic neuron which was activated by bone conducted sound. This was a neuron in the superior division of the vestibular nerve which show maintained activation in response to pitch tilts and we presumed therefore that it innervated receptors on the utricular macula.

Slide 55



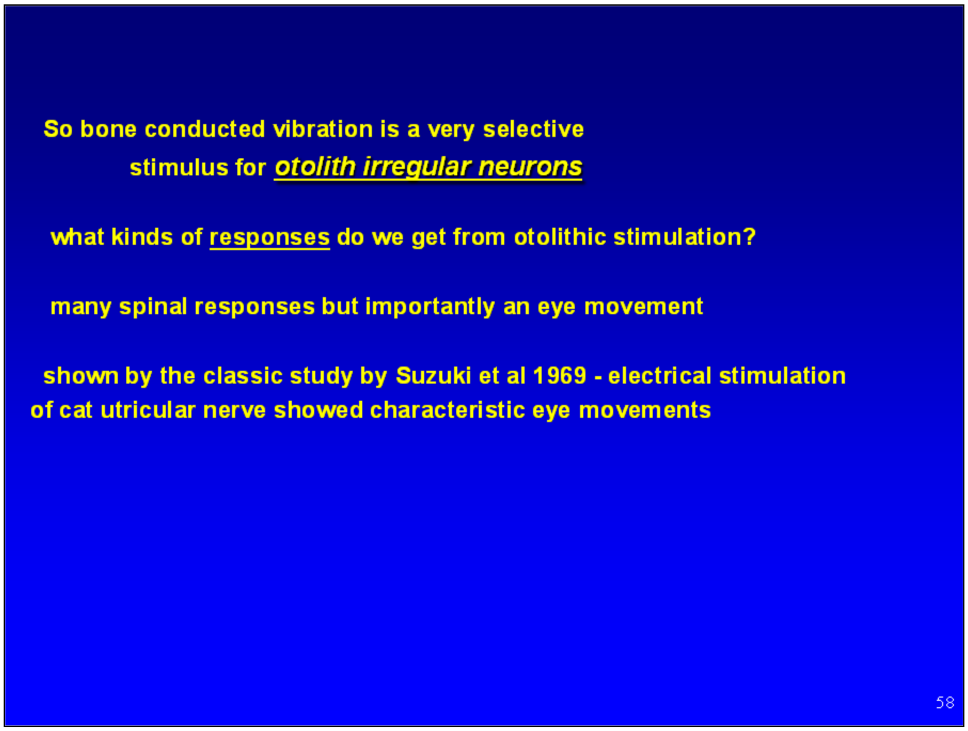
Young Goldberg and Fernandez 1977	Curthoys and Vulovic 2010
Squirrel Monkey 450-950g	Guinea pigs 200-1500g
Pentobarbital (15 mg/kg)	Ketamine (100mg/kg) and xylazine (4mg/kg)
Held with ear bars	Held by a skull bolt
Flocculus removed to visualize VIII nerve	Flocculus removed to visualize VIII nerve
Vibration from loudspeaker handheld against the head	Vibration from a B-71 on a screw bolted to a nut cemented on the skull
Direction; naso-occipital	Direction: dorso-ventral
Activation; phase locking	Activation; increase in firing rate

Slide 56



Young Goldberg and Fernandez 1977	Curthoys and Vulovic 2010
Conclusion;	Conclusion;
all vestibular sensory regions can be activated (both canals and otolithic afferents)	Vibration selectively activates otolith irregular neurons <u>at low stimulus levels</u> anc with high sensitivity. These are utricular neurons (otolith in dorsal superior vestibular nerve) canal afferents not activated up to maximun levels used Vibration and air conducted sound can activate the same neurons

Slide 57



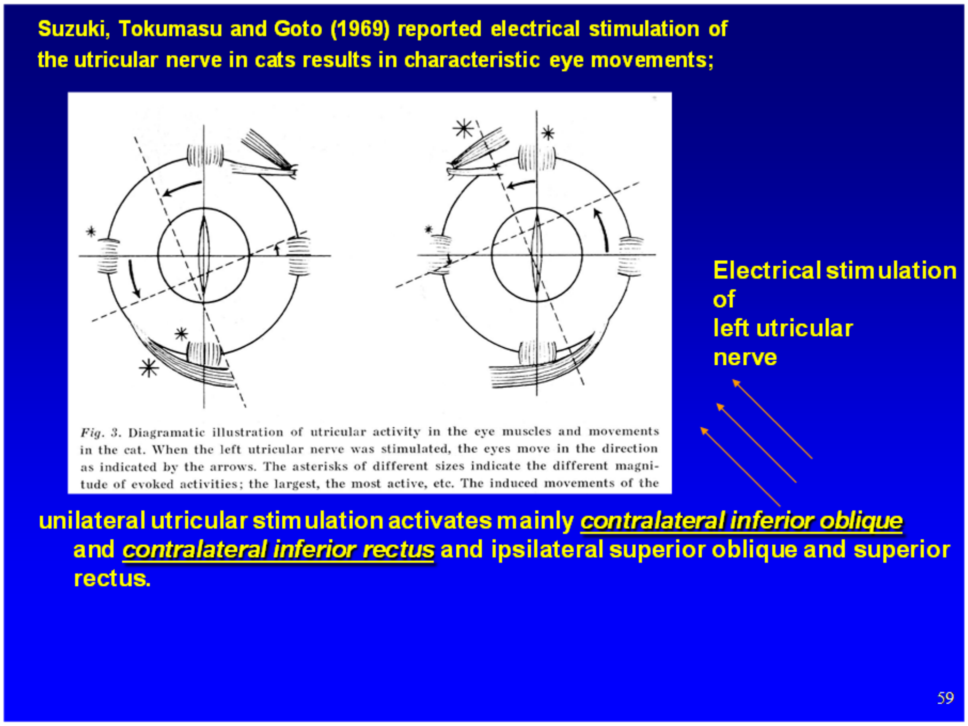
So bone conducted vibration is a very selective stimulus for ***<u>otolith irregular neurons</u>***

what kinds of <u>responses</u> do we get from otolithic stimulation?

many spinal responses but importantly an eye movement

shown by the classic study by Suzuki et al 1969 - electrical stimulation of cat utricular nerve showed characteristic eye movements

Slide 58



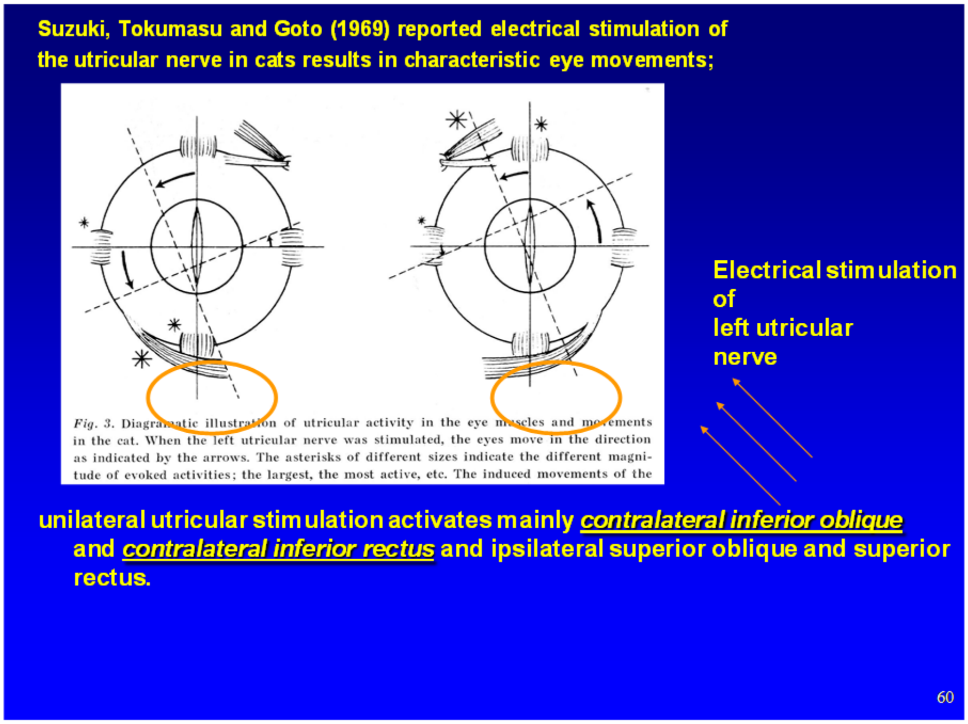
Suzuki, Tokumasu and Goto (1969) reported electrical stimulation of the utricular nerve in cats results in characteristic eye movements;

Fig. 3. Diagramatic illustration of utricular activity in the eye muscles and movements in the cat. When the left utricular nerve was stimulated, the eyes move in the direction as indicated by the arrows. The asterisks of different sizes indicate the different magnitude of evoked activities; the largest, the most active, etc. The induced movements of the

Electrical stimulation of left utricular nerve

unilateral utricular stimulation activates mainly *contralateral inferior oblique* and *contralateral inferior rectus* and ipsilateral superior oblique and superior rectus.

Slide 59



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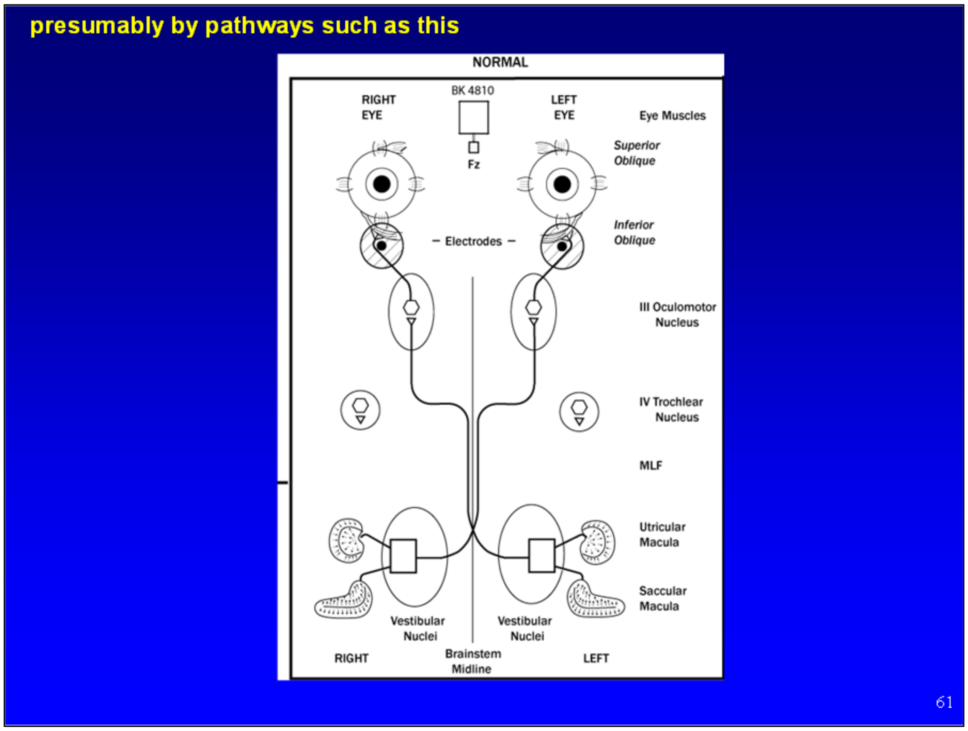
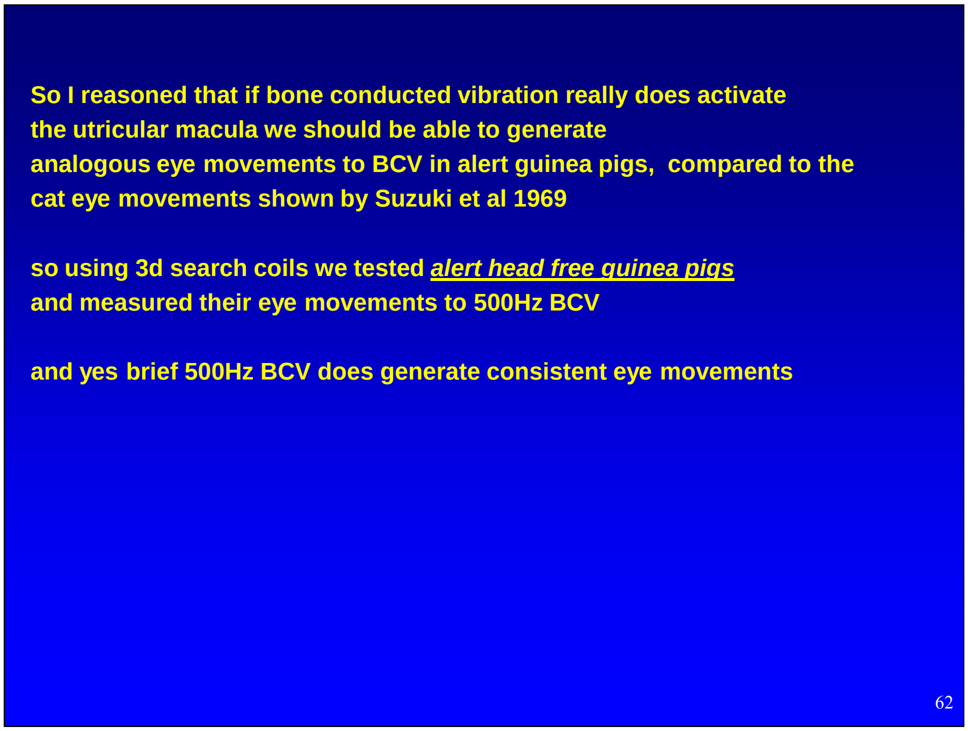


presumably by pathways such as this

Slide 61

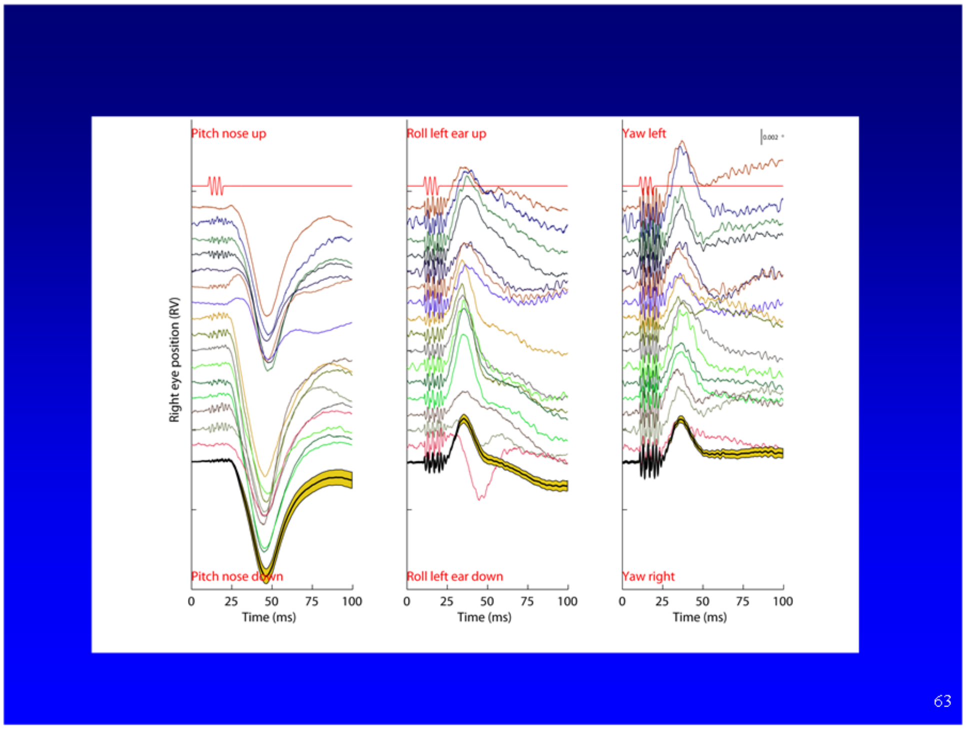


So I reasoned that if bone conducted vibration really does activate the utricular macula we should be able to generate analogous eye movements to BCV in alert guinea pigs, compared to the cat eye movements shown by Suzuki et al 1969

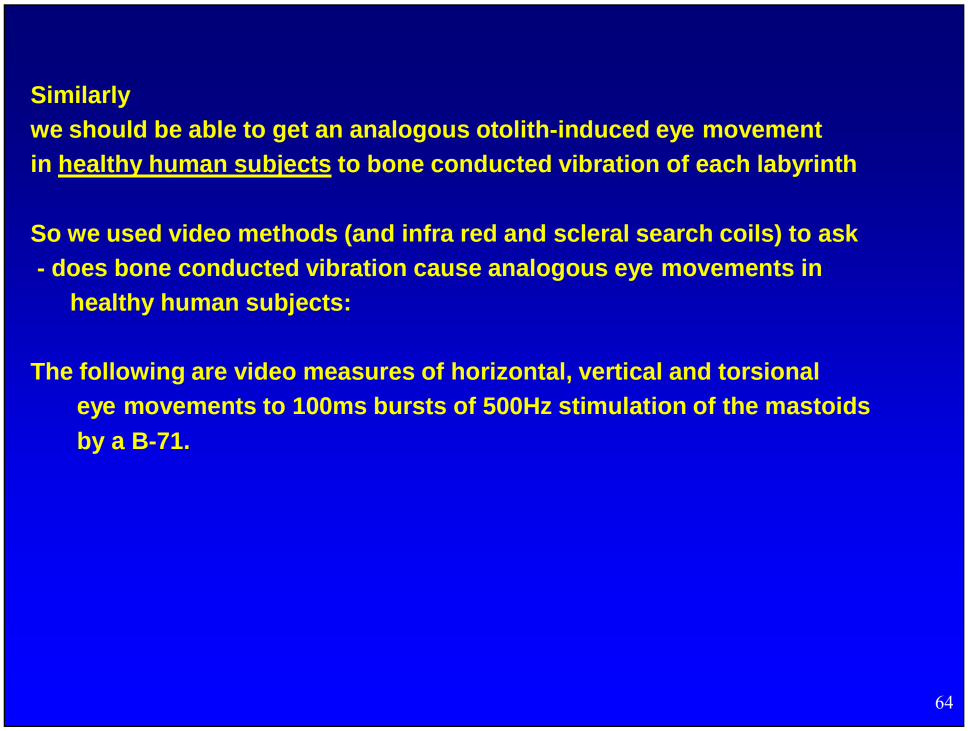
so using 3d search coils we tested ***alert head free guinea pigs*** and measured their eye movements to 500Hz BCV

and yes brief 500Hz BCV does generate consistent eye movements

Slide 62



Slide 63

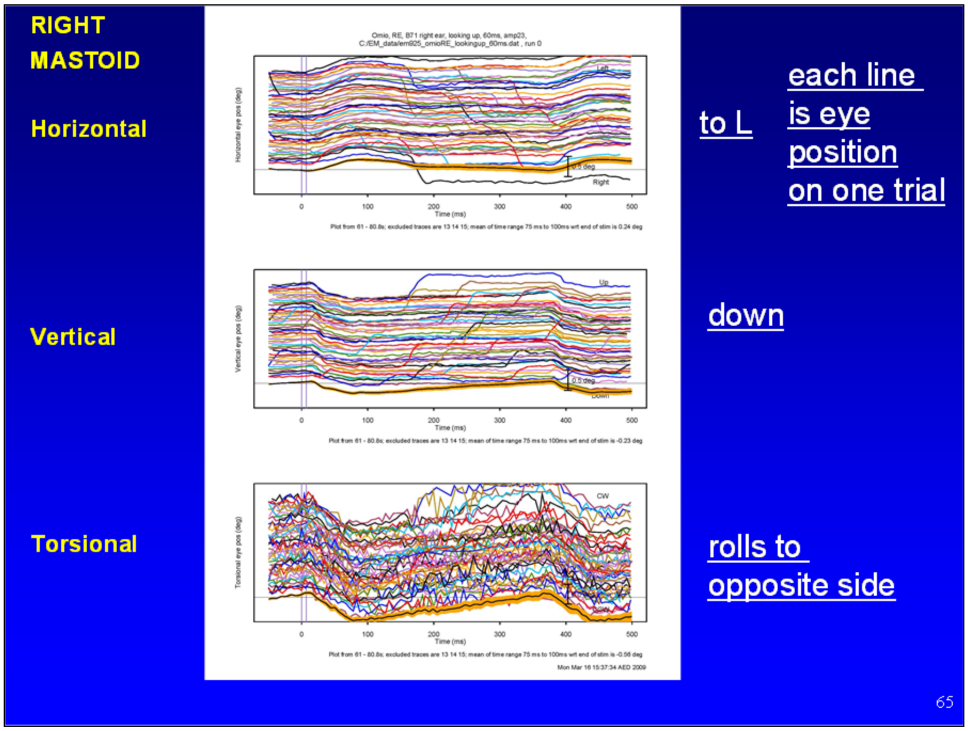


Similarly
we should be able to get an analogous otolith-induced eye movement
in <u>healthy human subjects</u> to bone conducted vibration of each labyrinth

So we used video methods (and infra red and scleral search coils) to ask
- does bone conducted vibration cause analogous eye movements in healthy human subjects:

The following are video measures of horizontal, vertical and torsional eye movements to 100ms bursts of 500Hz stimulation of the mastoids by a B-71.

Slide 64



RIGHT MASTOID

Horizontal

to L

each line is eye position on one trial

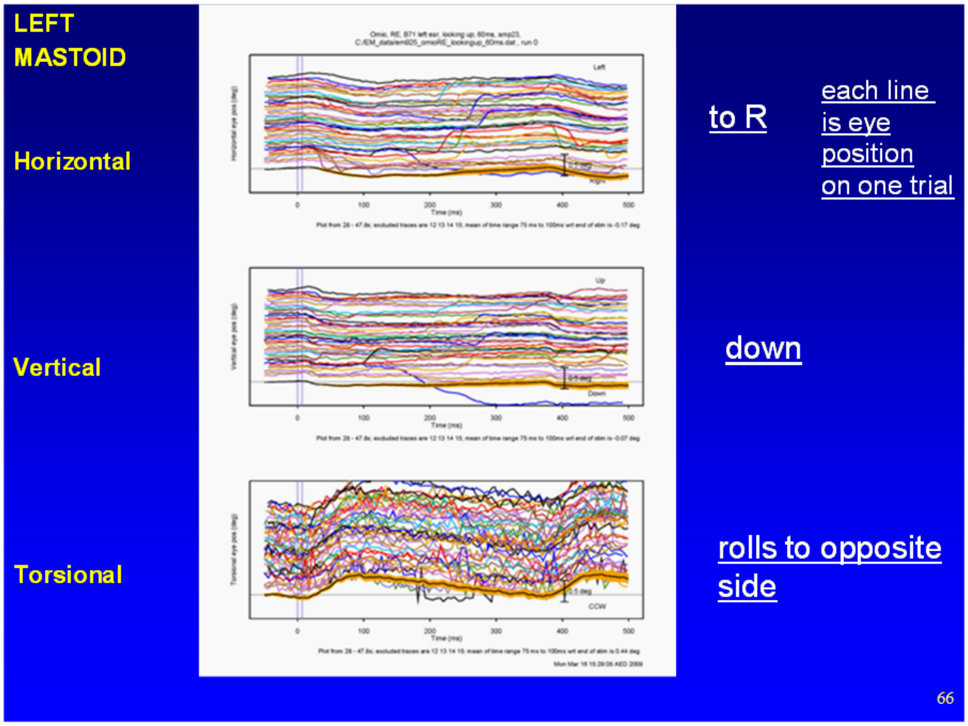
Vertical

down

Torsional

rolls to opposite side

Slide 65



LEFT MASTOID

Horizontal

to R

each line is eye position on one trial

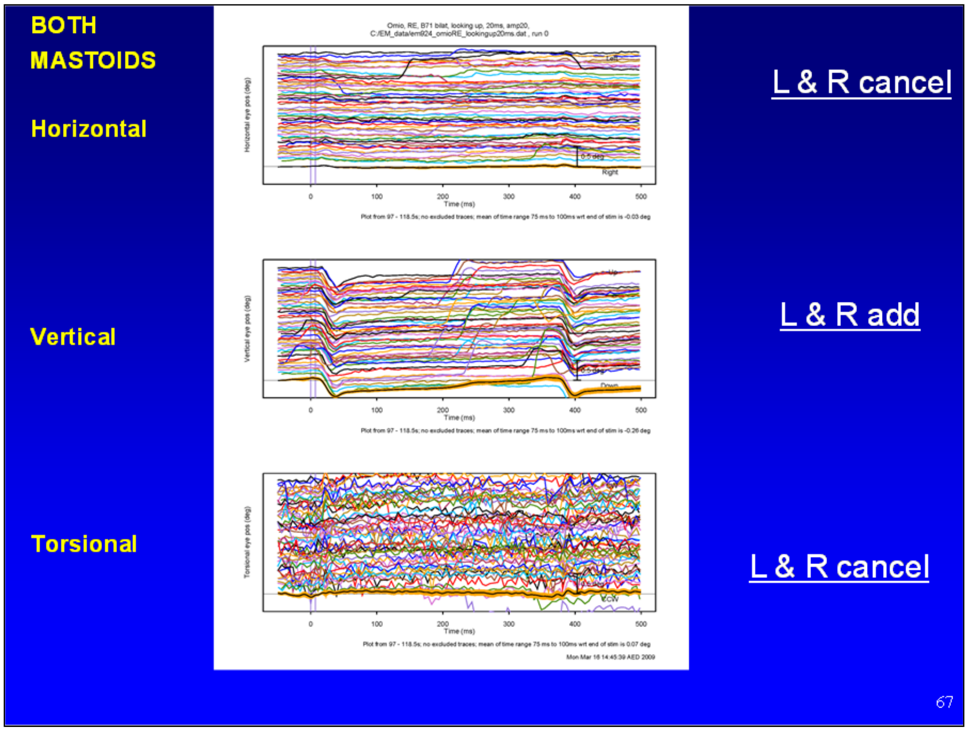
Vertical

down

Torsional

rolls to opposite side

Slide 66



BOTH MASTOIDS

Horizontal

Vertical

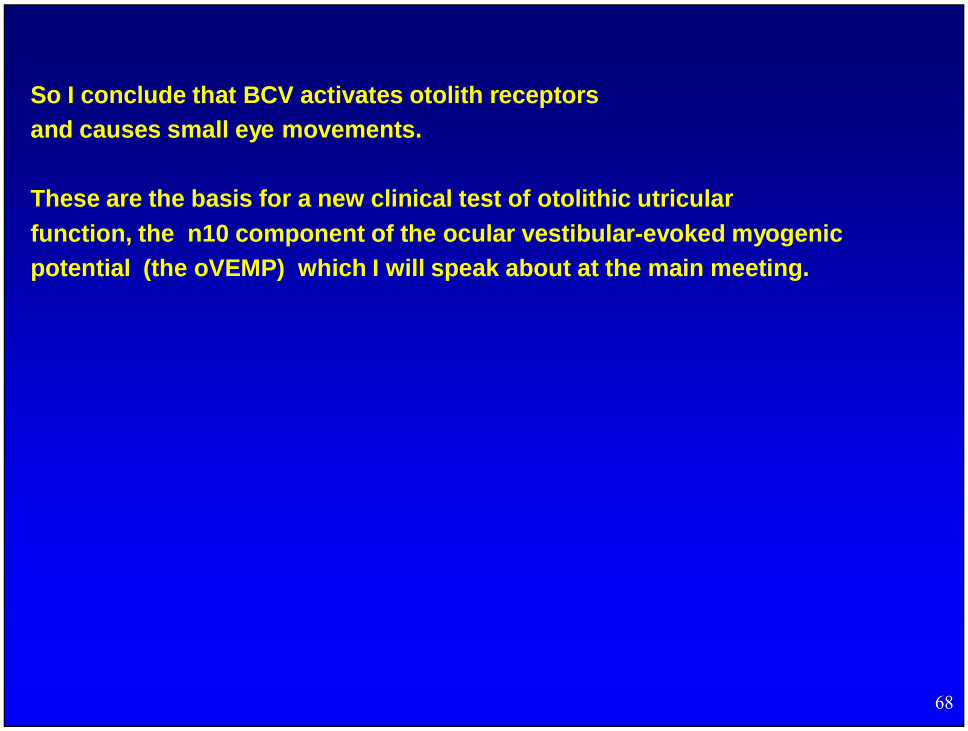
Torsional

L & R cancel

L & R add

L & R cancel

Slide 67



So I conclude that BCV activates otolith receptors and causes small eye movements.

These are the basis for a new clinical test of otolithic utricular function, the n10 component of the ocular vestibular-evoked myogenic potential (the oVEMP) which I will speak about at the main meeting.

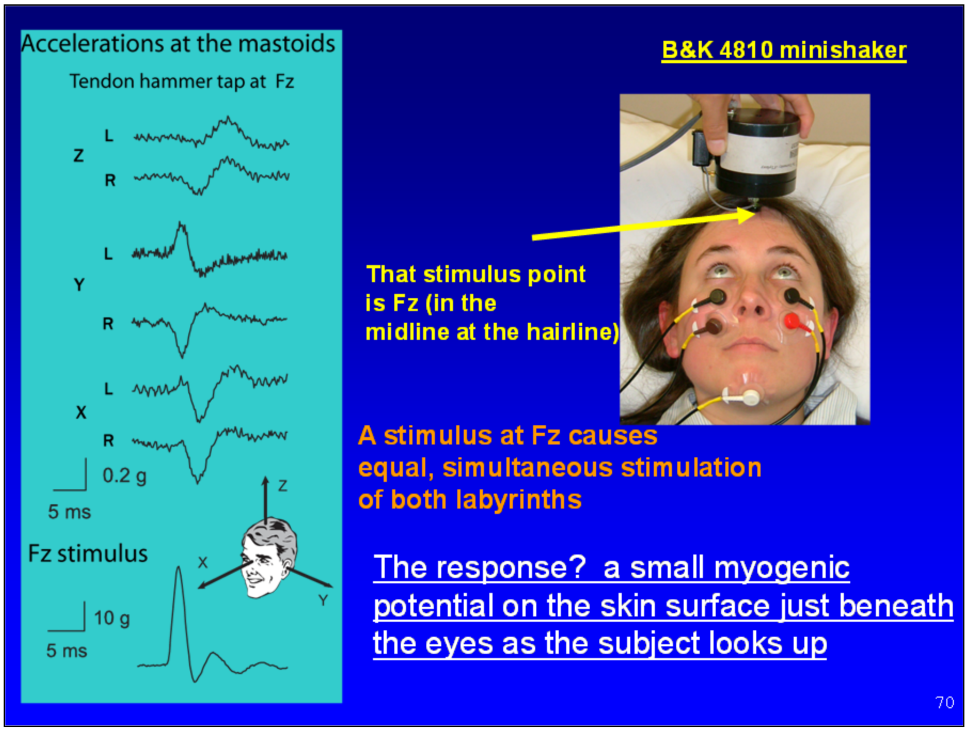
Slide 68

but using B-71s it is very difficult to get equal stimulation of both mastoids –

very small changes in B-71 location cause large changes in eye movements

How can we deliver equal stimuli to both otoliths ??
By using *midline stimuli* such as
a tap of the forehead at the midline (Fz)
or
a Bruel and Kjaer 4810 minishaker at the midline – brief 500Hz vibration

Slide 69



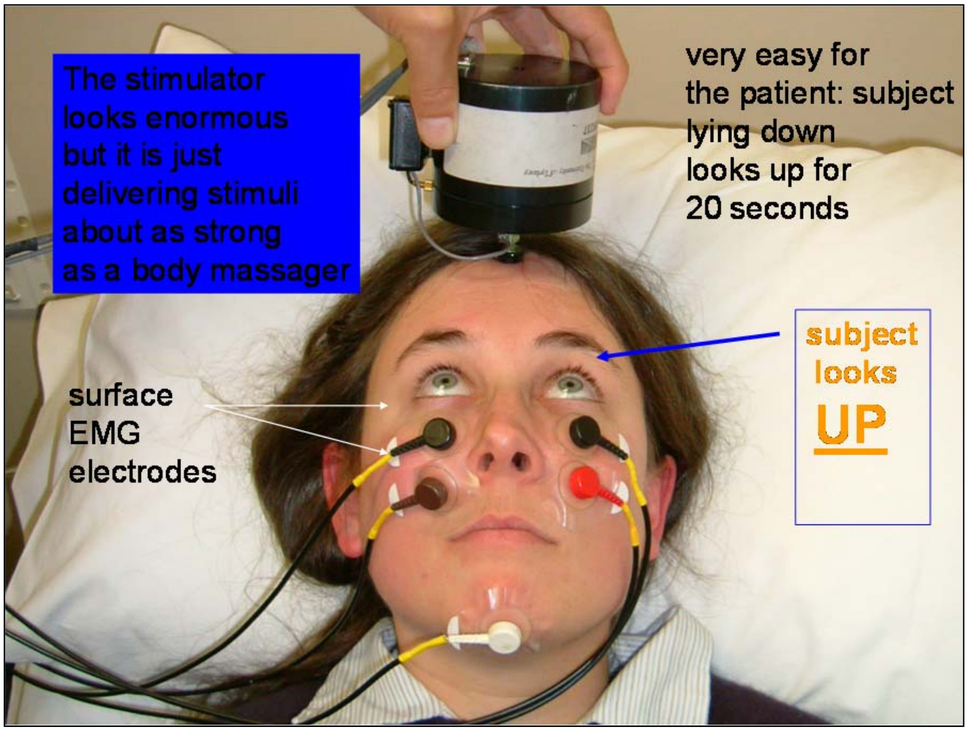
B&K 4810 minishaker

That stimulus point is Fz (in the midline at the hairline)

A stimulus at Fz causes equal, simultaneous stimulation of both labyrinths

The response? a small myogenic potential on the skin surface just beneath the eyes as the subject looks up

Slide 70



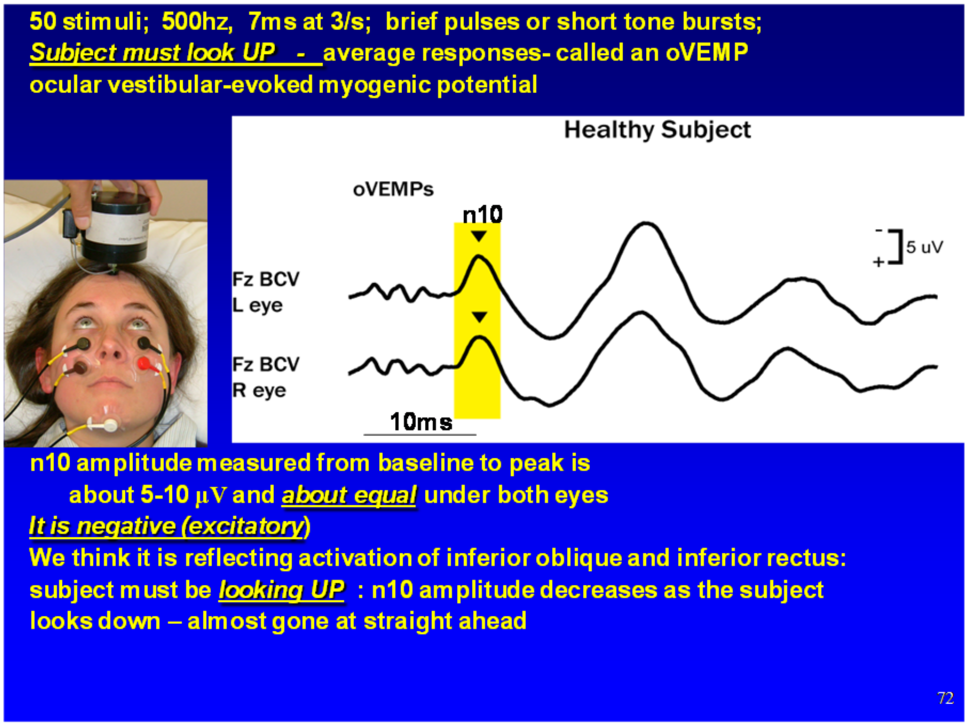
The stimulator looks enormous but it is just delivering stimuli about as strong as a body massager

very easy for the patient: subject lying down looks up for 20 seconds

subject looks **UP**

surface EMG electrodes

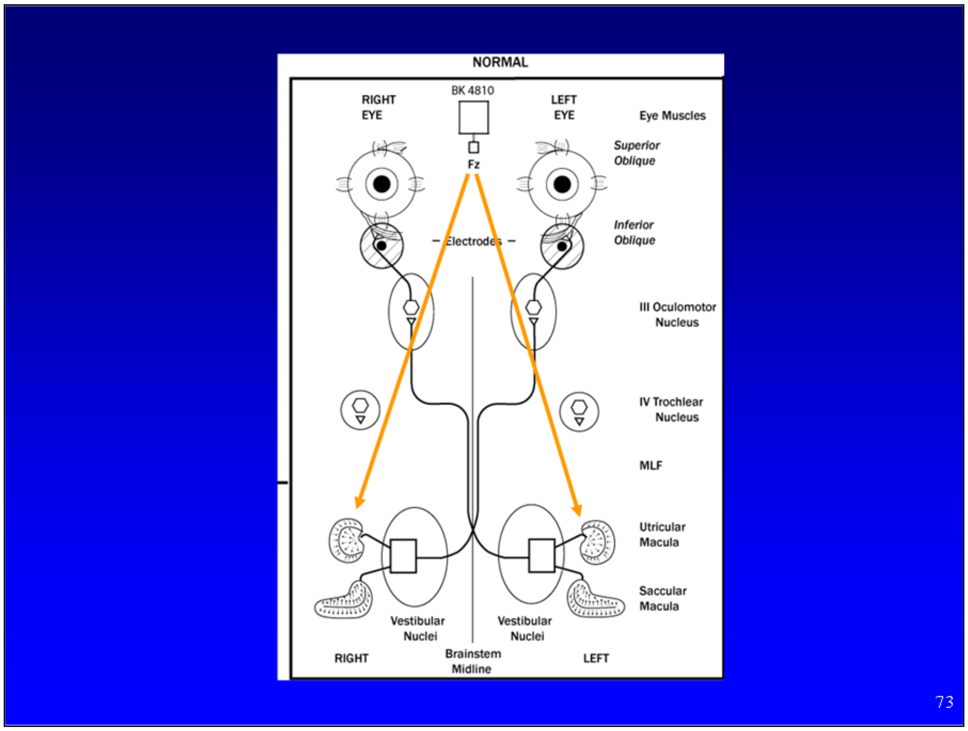
Slide 71



50 stimuli; 500hz, 7ms at 3/s; brief pulses or short tone bursts;
Subject must look UP - **average responses- called an oVEMP**
ocular vestibular-evoked myogenic potential

n10 amplitude measured from baseline to peak is
about 5-10 µV and *about equal* under both eyes
It is negative (excitatory)
We think it is reflecting activation of inferior oblique and inferior rectus:
subject must be *looking UP* : n10 amplitude decreases as the subject looks down – almost gone at straight ahead

Slide 72



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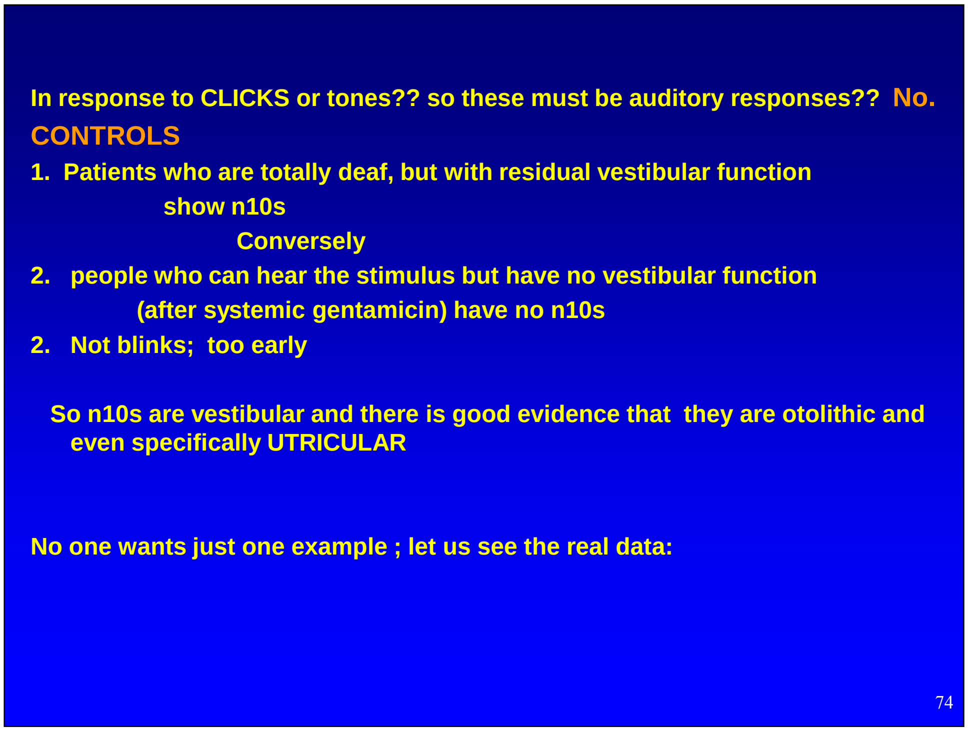


In response to CLICKS or tones?? so these must be auditory responses?? No.

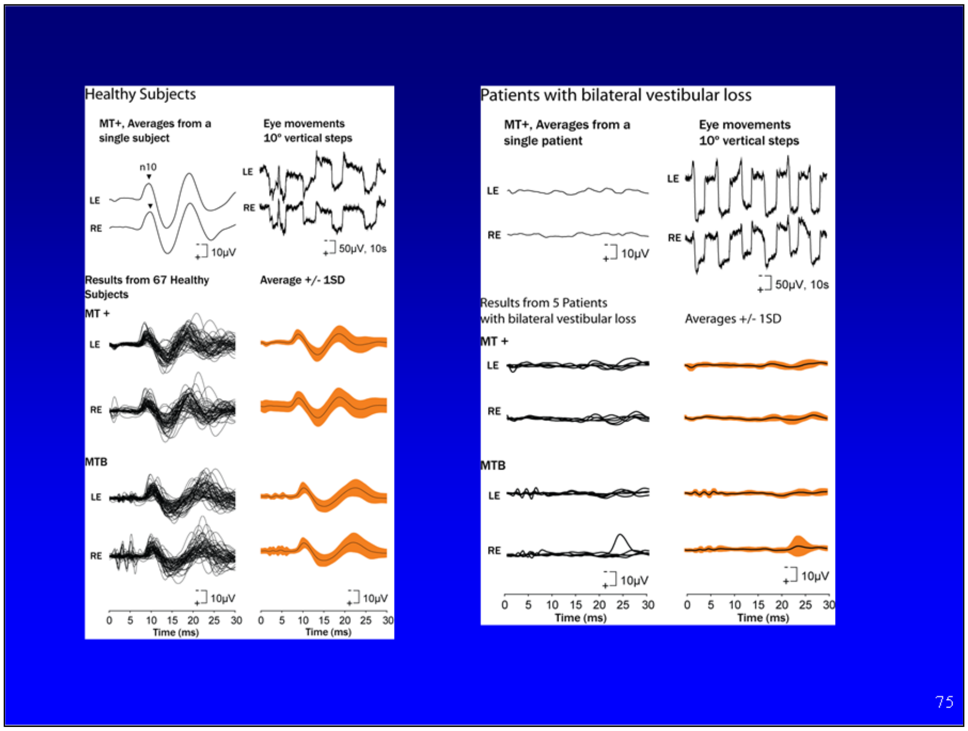
CONTROLS

1. Patients who are totally deaf, but with residual vestibular function
show n10s
Conversely
2. people who can hear the stimulus but have no vestibular function
(after systemic gentamicin) have no n10s
2. Not blinks; too early

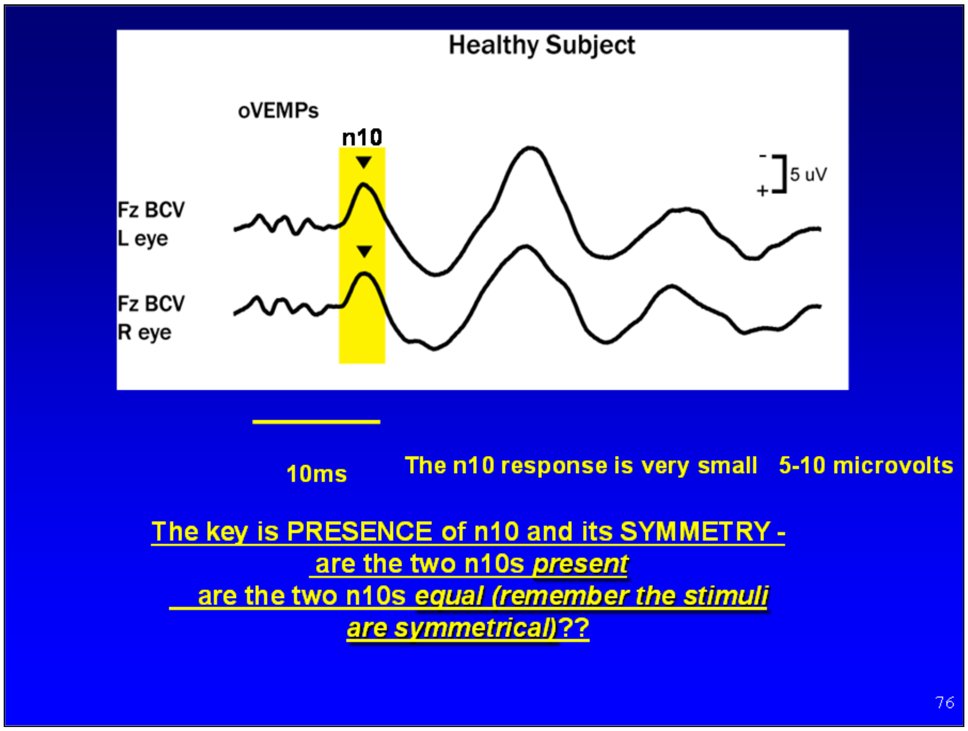
So n10s are vestibular and there is good evidence that they are otolithic and even specifically UTRICULAR

No one wants just one example ; let us see the real data:

Slide 74



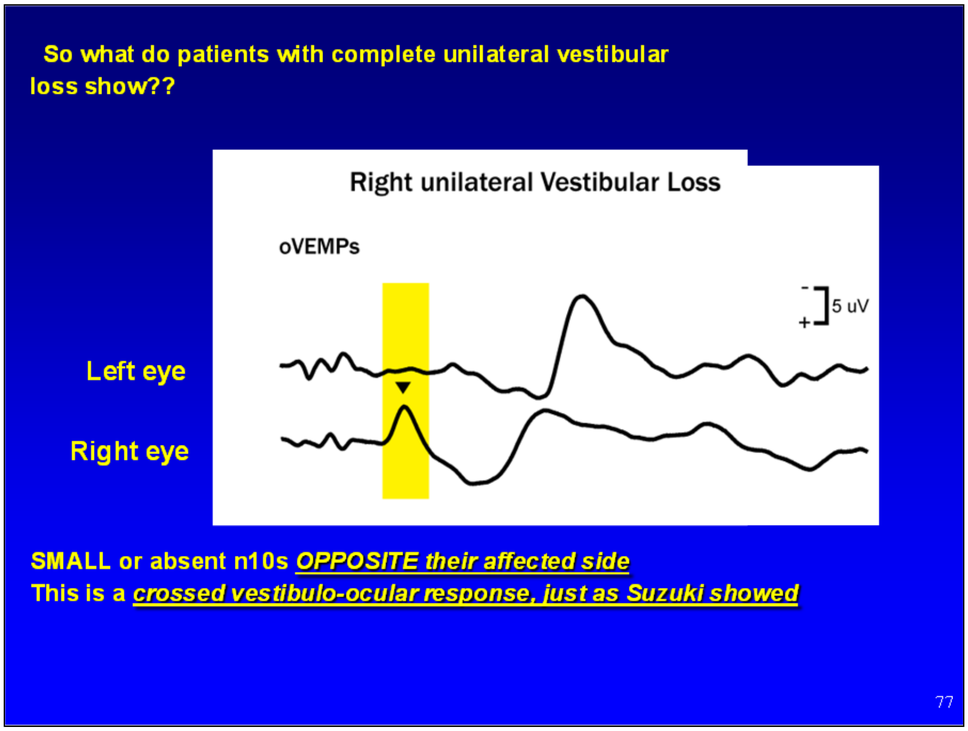
Slide 75



The n10 response is very small 5-10 microvolts

The key is PRESENCE of n10 and its SYMMETRY -
are the two n10s *present*
are the two n10s *equal (remember the stimuli are symmetrical)*??

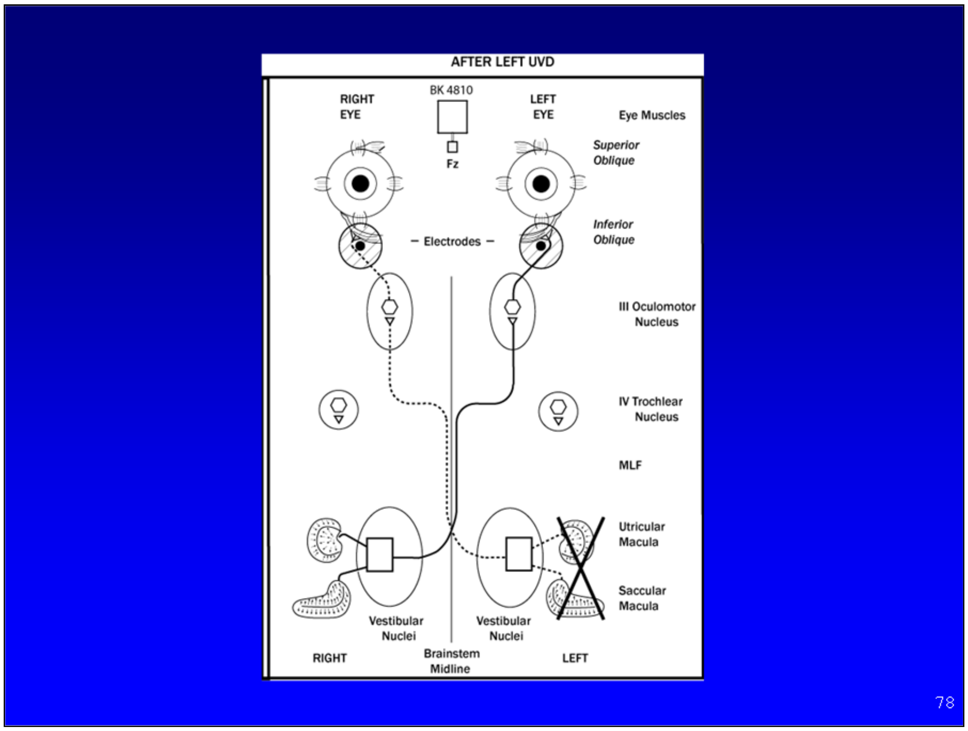
Slide 76



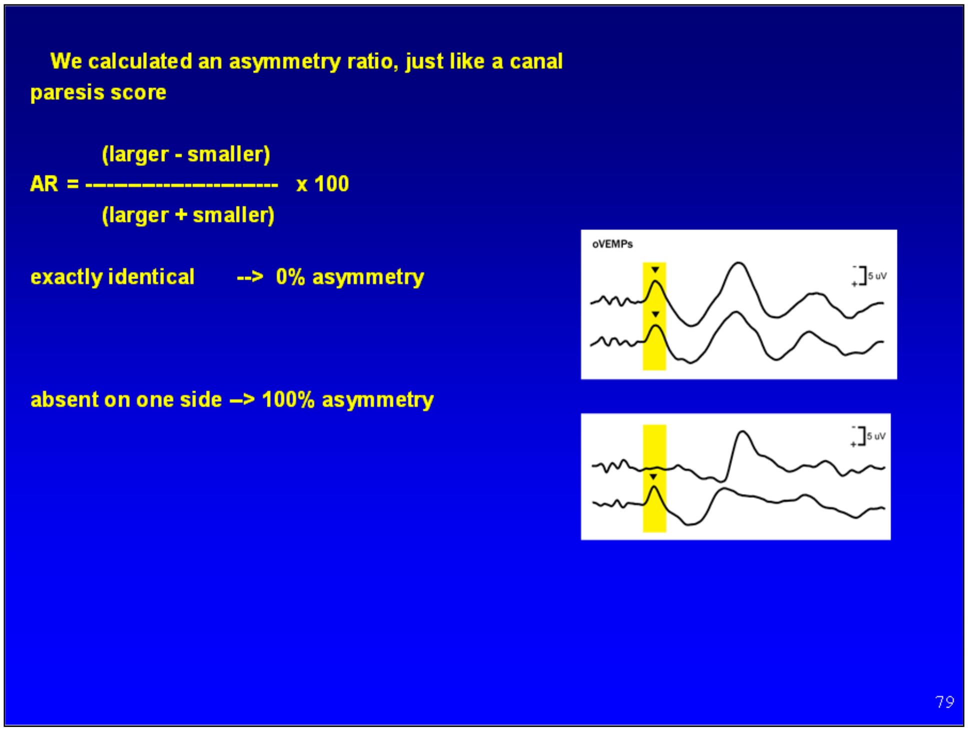
So what do patients with complete unilateral vestibular loss show??

SMALL or absent n10s ***OPPOSITE their affected side***
This is a ***crossed vestibulo-ocular response, just as Suzuki showed***

Slide 77



Slide 78



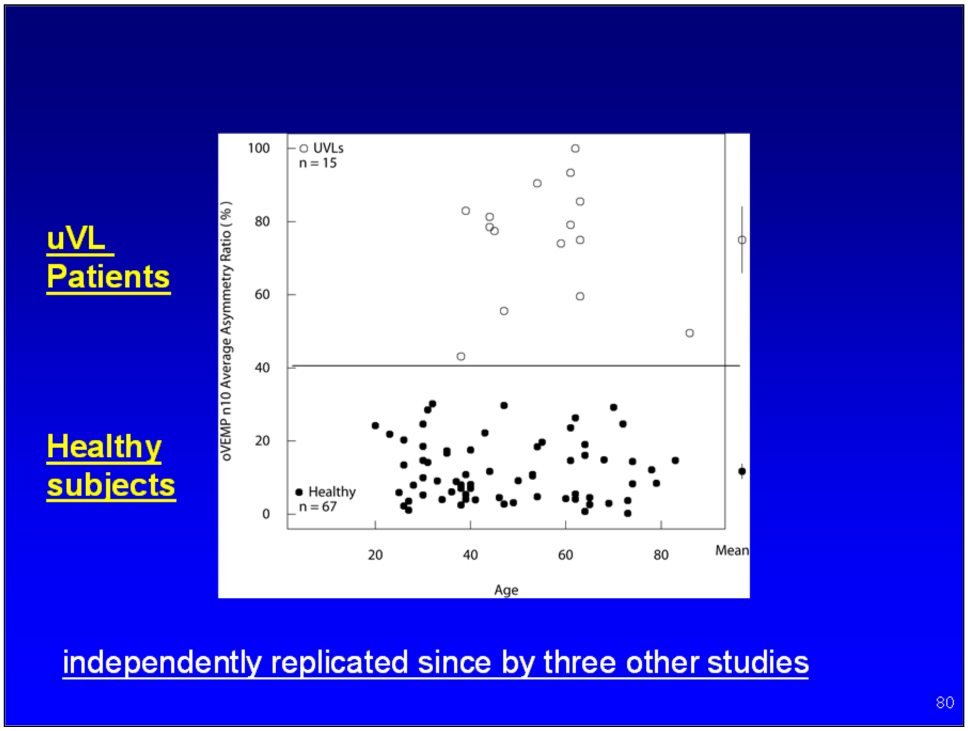
We calculated an asymmetry ratio, just like a canal paresis score

$$AR = \frac{(\text{larger} - \text{smaller})}{(\text{larger} + \text{smaller})} \times 100$$

exactly identical --> 0% asymmetry

absent on one side --> 100% asymmetry

Slide 79

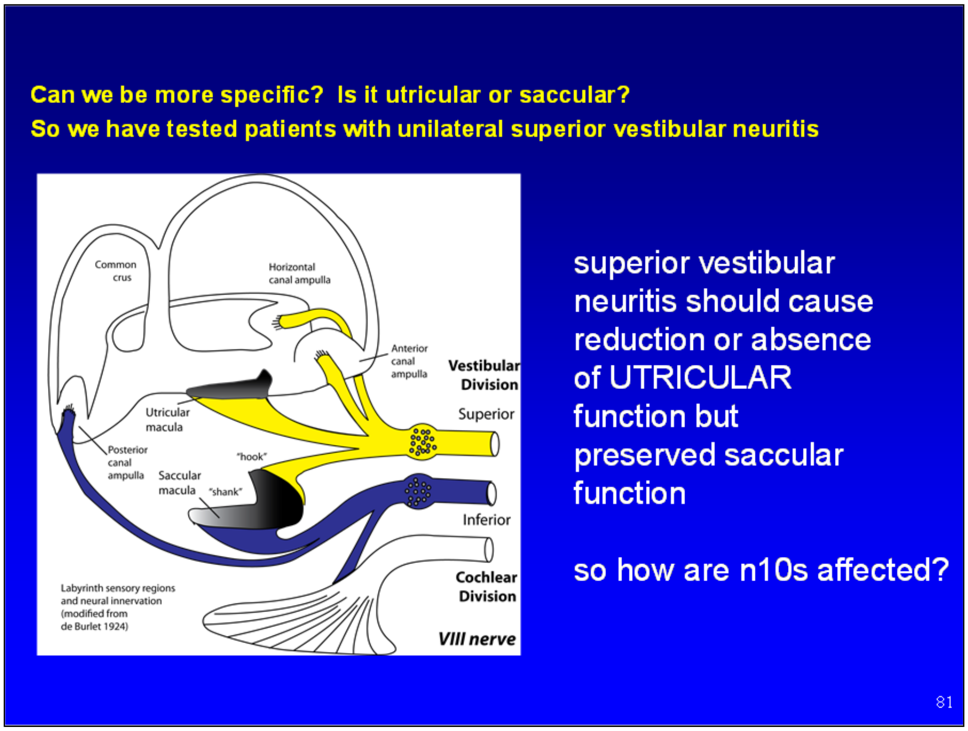


uVL Patients

Healthy subjects

independently replicated since by three other studies

Slide 80



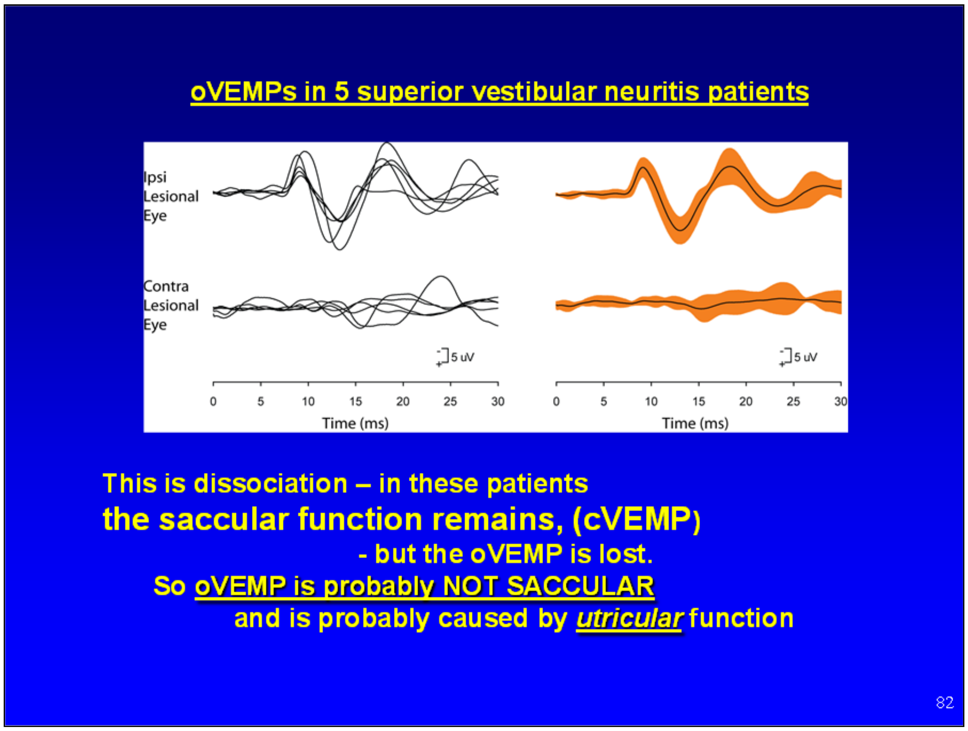
Can we be more specific? Is it utricular or saccular?
So we have tested patients with unilateral superior vestibular neuritis

superior vestibular neuritis should cause reduction or absence of UTRICULAR function but preserved saccular function

so how are n10s affected?

81

Slide 81

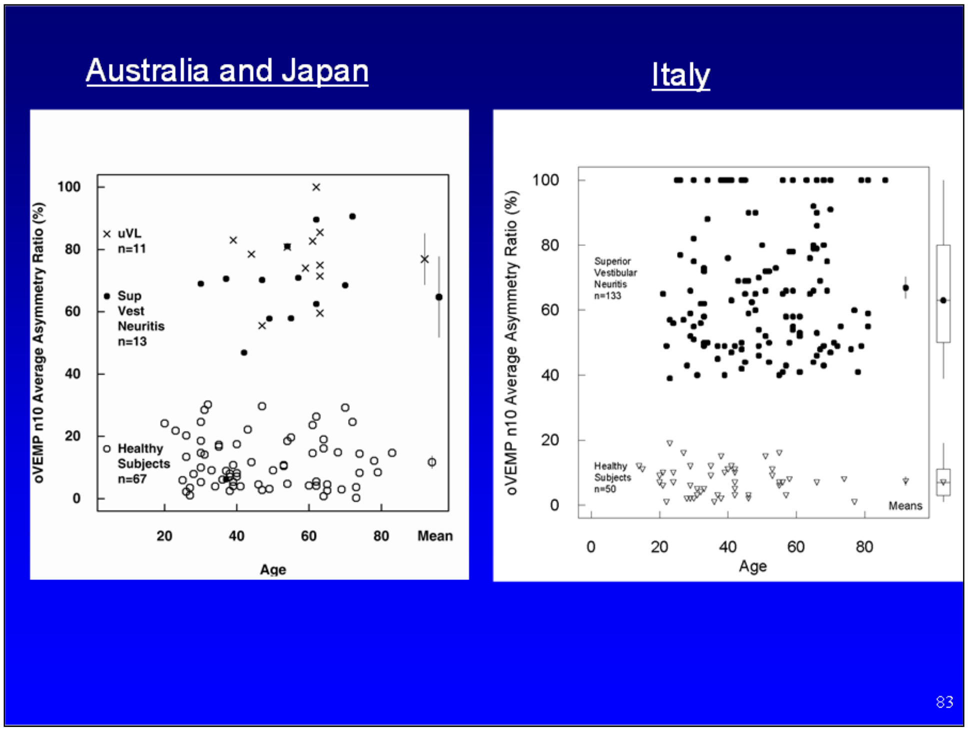


oVEMPs in 5 superior vestibular neuritis patients

This is dissociation – in these patients
the saccular function remains, (cVEMP)
- but the oVEMP is lost.
So oVEMP is probably NOT SACCULAR
and is probably caused by *utricular* function

82

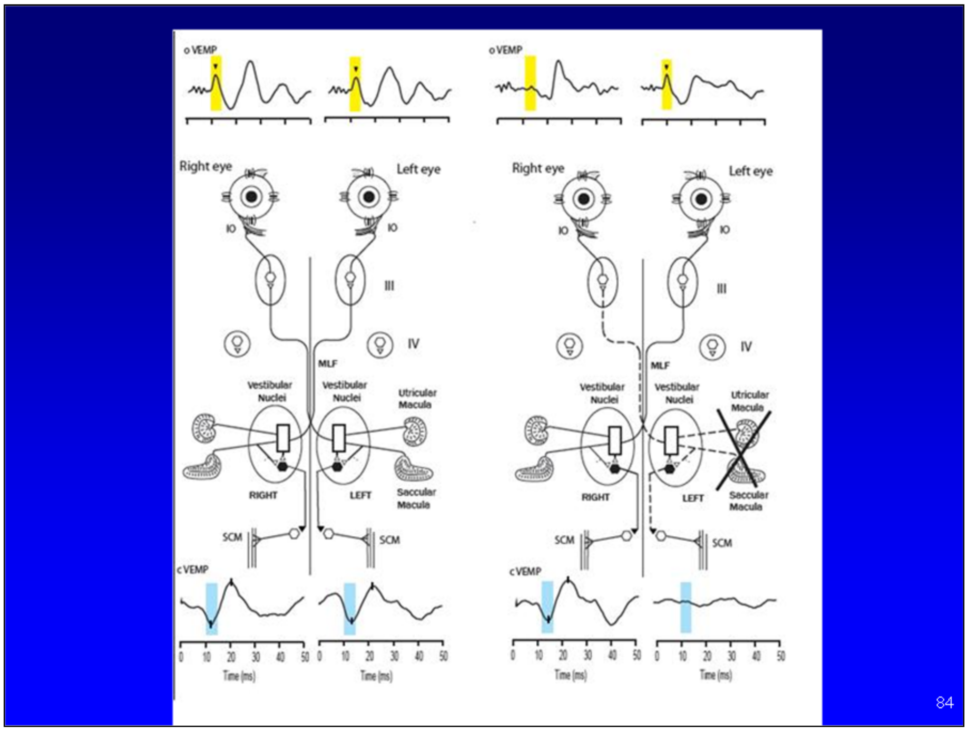
Slide 82



Australia and Japan

Italy

Slide 83



Slide 84

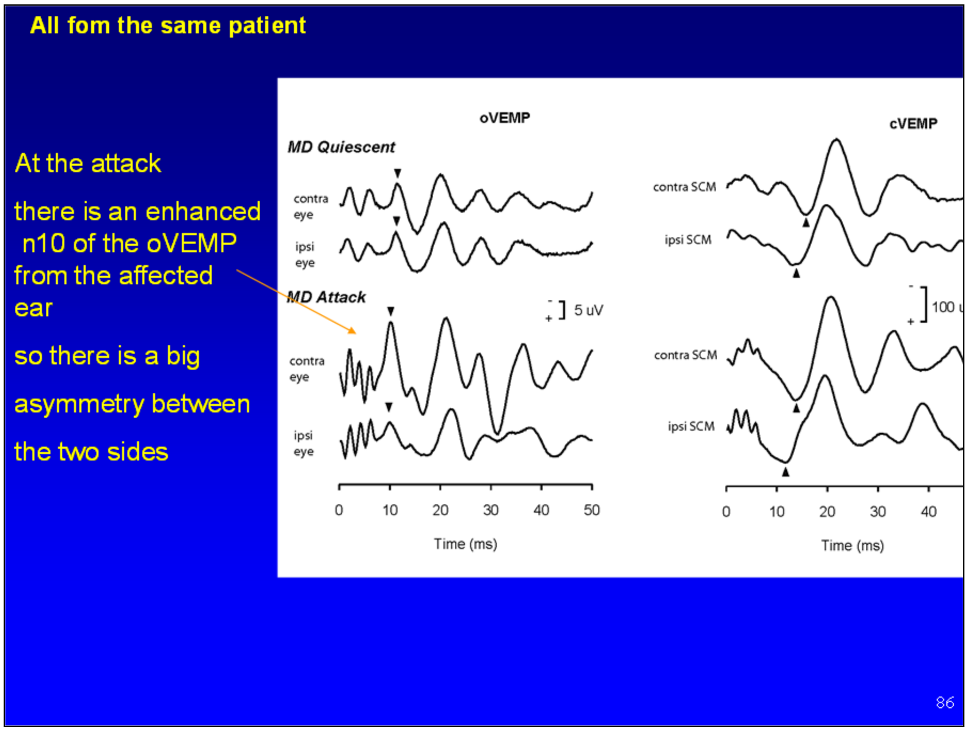
Recently we have applied this to pathology

Meniere’s Disease

EARLY MD patients (AAO-HNS criteria)

comparing n10s tested *at quiescence*
and again
during an MD attack

Slide 85



All fom the same patient

At the attack

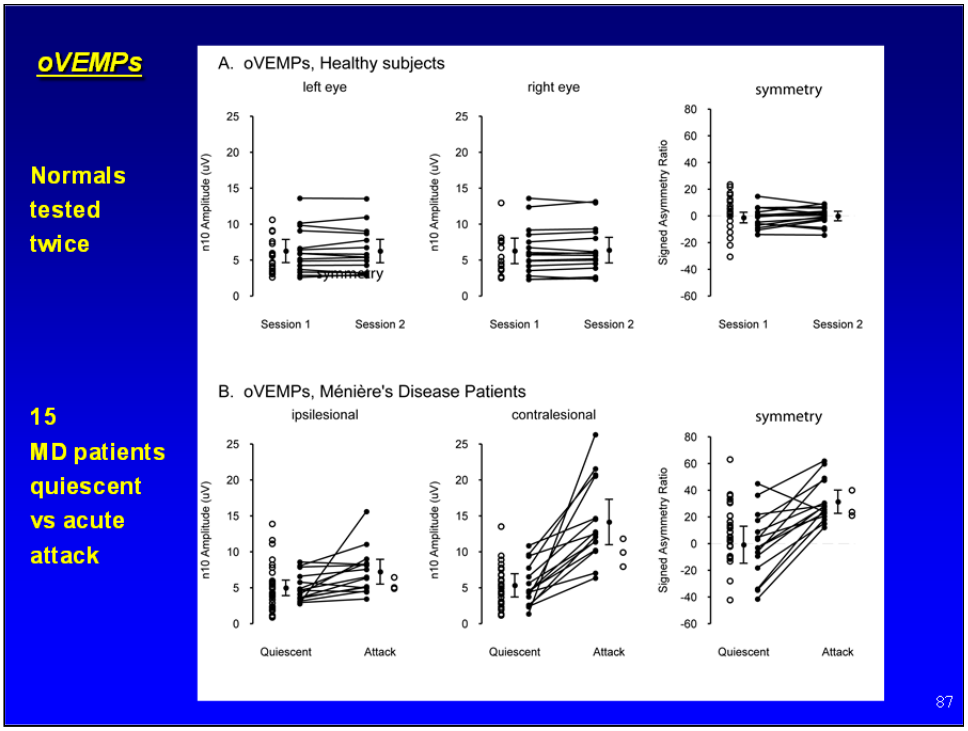
there is an enhanced n10 of the oVEMP from the affected ear

so there is a big

asymmetry between

the two sides

Slide 86

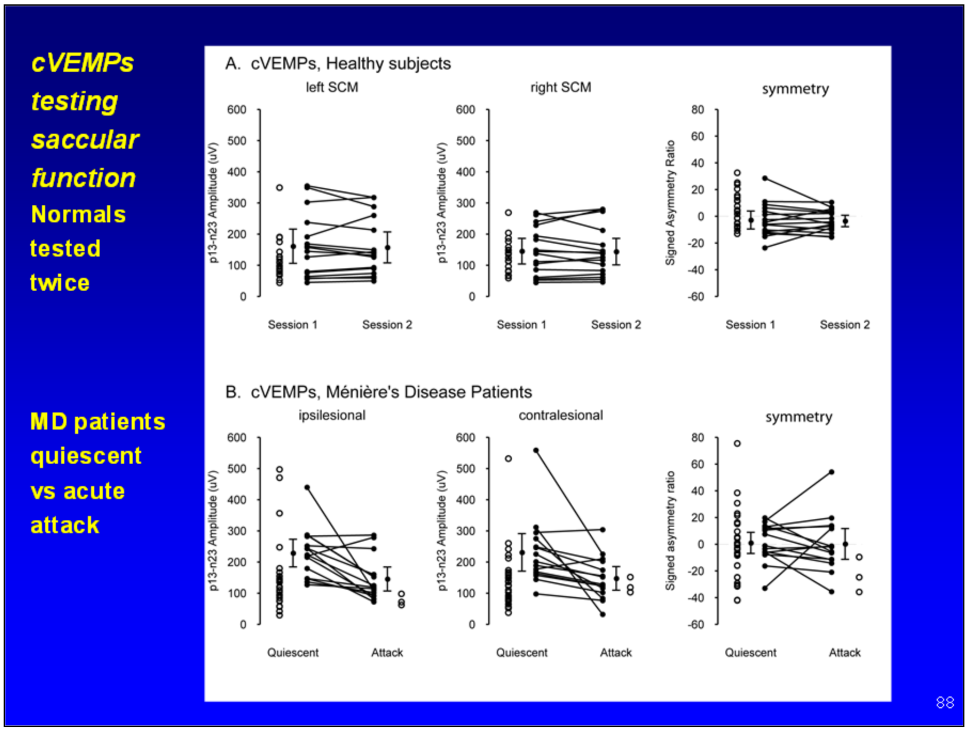


oVEMPs

Normals tested twice

15 MD patients quiescent vs acute attack

Slide 87



cVEMPs testing saccular function

Normals tested twice

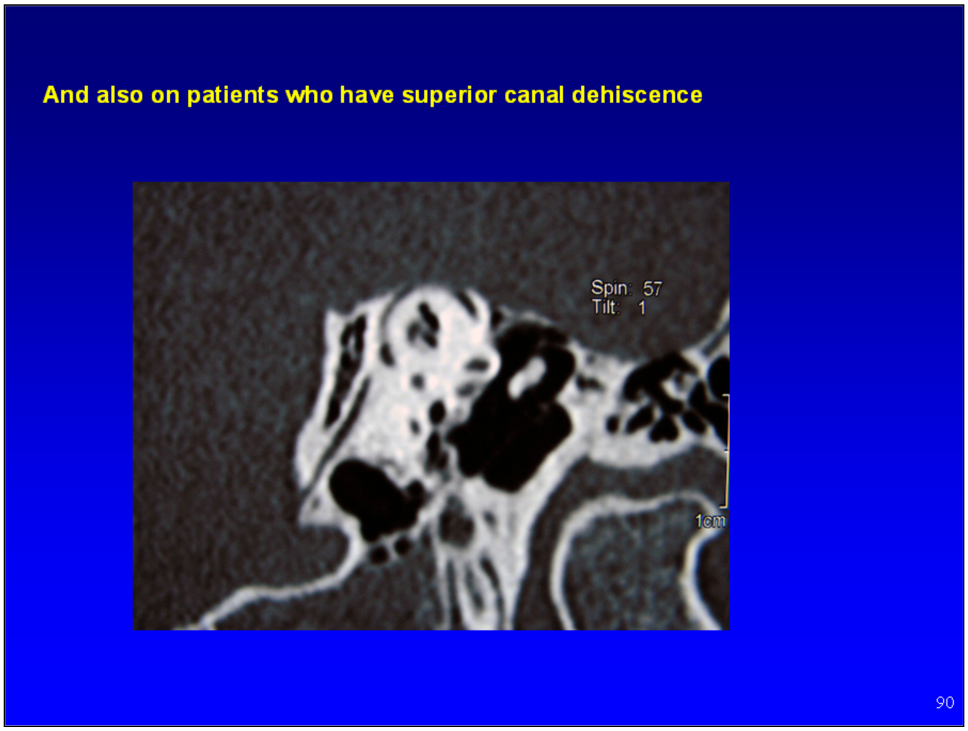
MD patients quiescent vs acute attack

Slide 88

It seems that during the MD attack, the utricular sensitivity for dynamic otolith stimuli is increased.

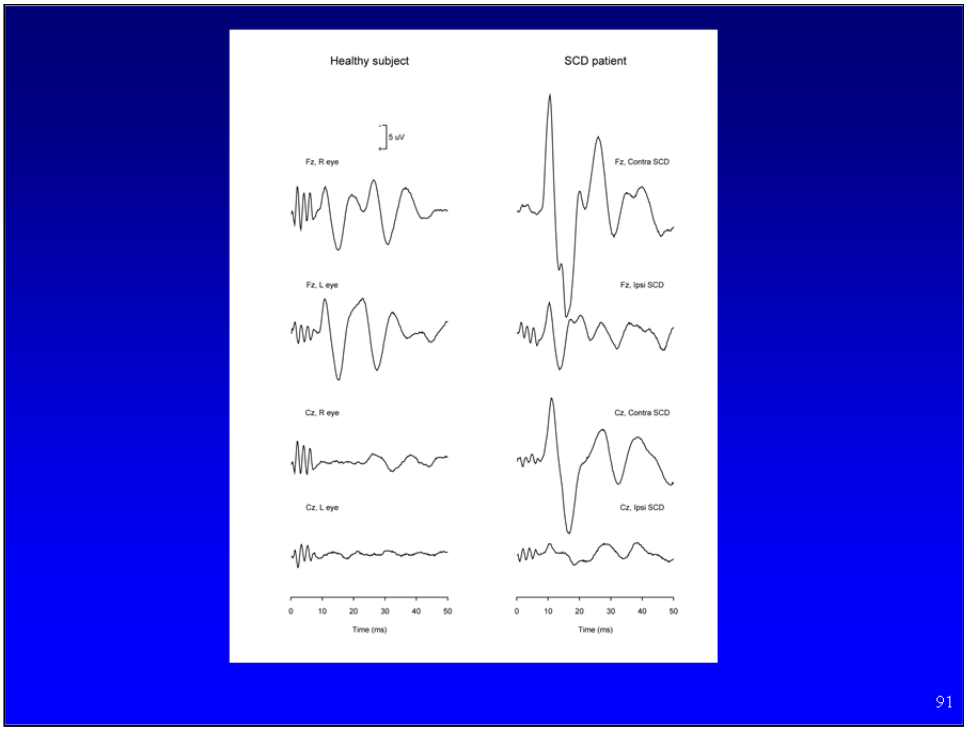
But it appears that there is little change in the saccular sensitivity (as shown by the patients neck VEMPs, their cVEMPs, being unaffected)

Slide 89

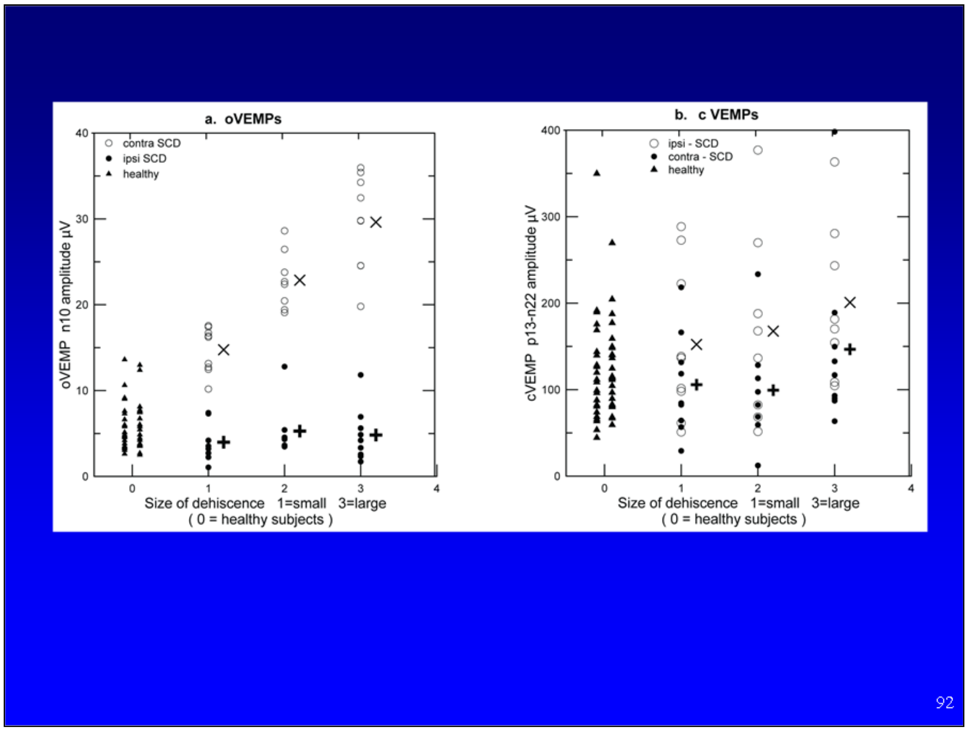


And also on patients who have superior canal dehiscence

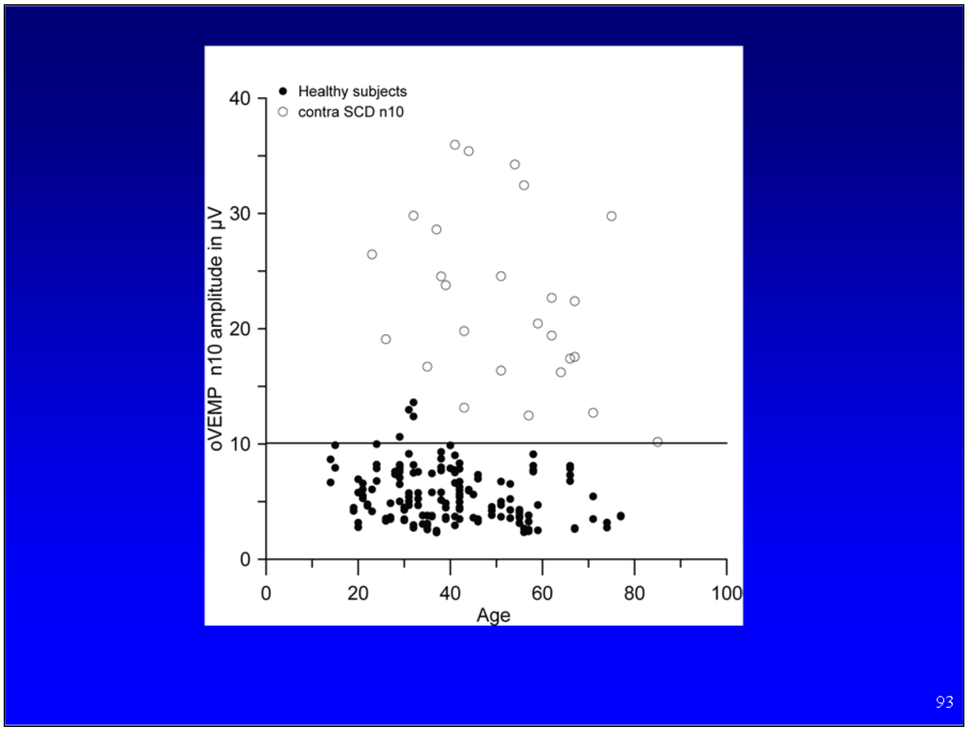
Slide 90



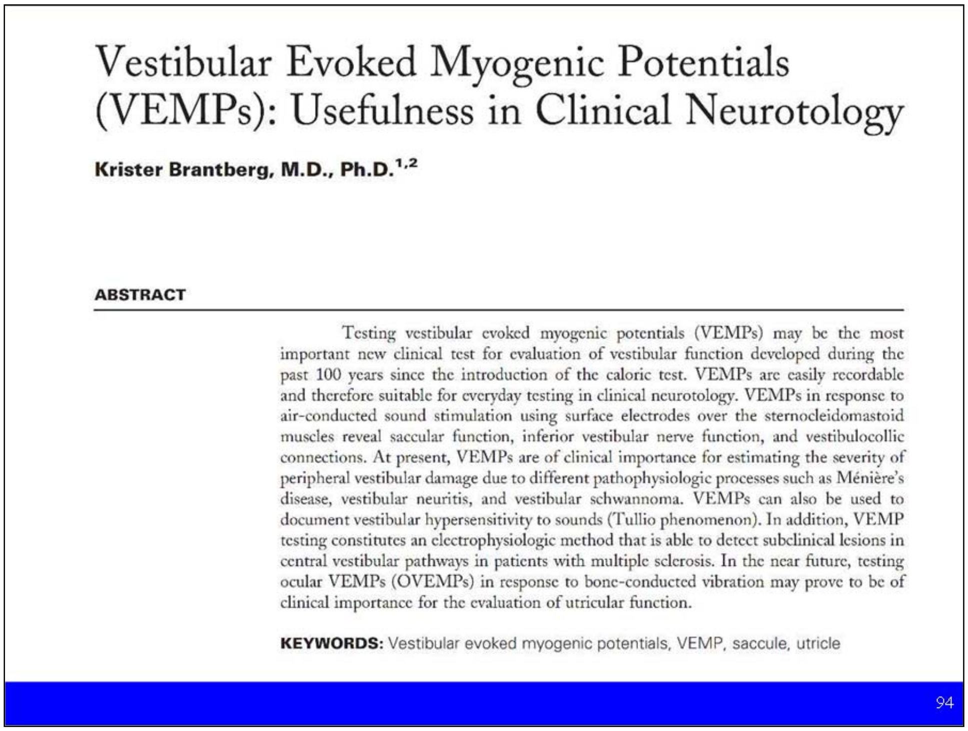
Slide 91



Slide 92



Slide 93



Vestibular Evoked Myogenic Potentials (VEMPs): Usefulness in Clinical Neurotology

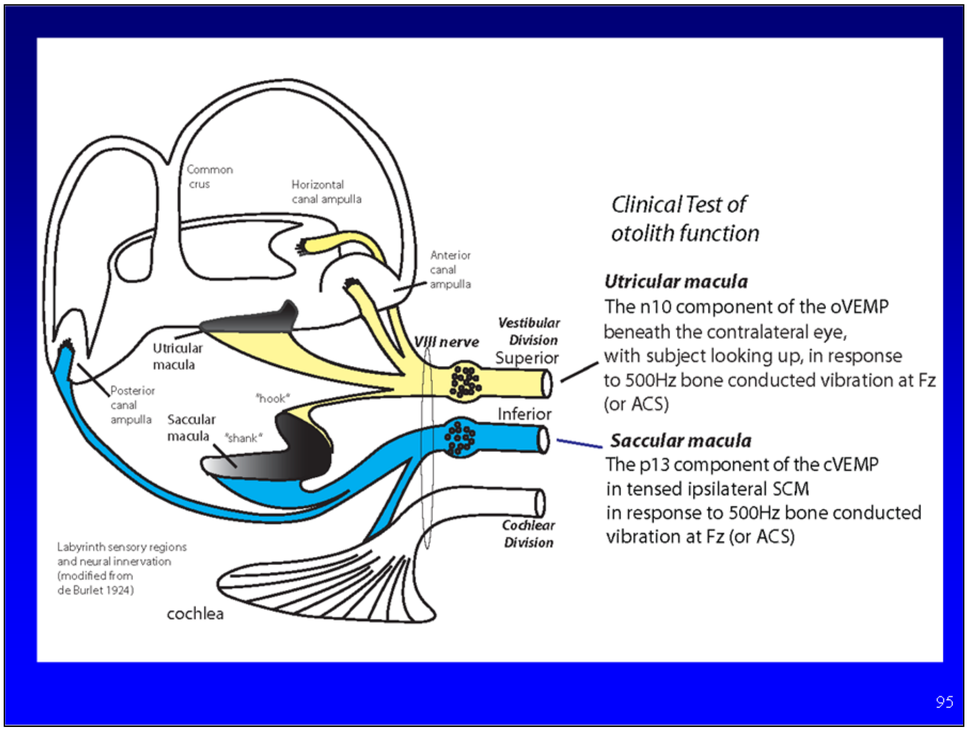
Krister Brantberg, M.D., Ph.D.[1,2]

ABSTRACT

Testing vestibular evoked myogenic potentials (VEMPs) may be the most important new clinical test for evaluation of vestibular function developed during the past 100 years since the introduction of the caloric test. VEMPs are easily recordable and therefore suitable for everyday testing in clinical neurotology. VEMPs in response to air-conducted sound stimulation using surface electrodes over the sternocleidomastoid muscles reveal saccular function, inferior vestibular nerve function, and vestibulocollic connections. At present, VEMPs are of clinical importance for estimating the severity of peripheral vestibular damage due to different pathophysiologic processes such as Ménière's disease, vestibular neuritis, and vestibular schwannoma. VEMPs can also be used to document vestibular hypersensitivity to sounds (Tullio phenomenon). In addition, VEMP testing constitutes an electrophysiologic method that is able to detect subclinical lesions in central vestibular pathways in patients with multiple sclerosis. In the near future, testing ocular VEMPs (OVEMPs) in response to bone-conducted vibration may prove to be of clinical importance for the evaluation of utricular function.

KEYWORDS: Vestibular evoked myogenic potentials, VEMP, saccule, utricle

Slide 94



Clinical Test of otolith function

Utricular macula
The n10 component of the oVEMP beneath the contralateral eye, with subject looking up, in response to 500Hz bone conducted vibration at Fz (or ACS)

Saccular macula
The p13 component of the cVEMP in tensed ipsilateral SCM in response to 500Hz bone conducted vibration at Fz (or ACS)

Slide 95

Question and answer session

[Goldberg] I don't have a pencil, so I think I have three questions, but I am going to have to depend on my memory. What do you think the recording of the electrodes does below the orbit? I saw the differential. Was that differential, well regardless, what do you think you're recording?

[Curthoys] I think I'm recording myogenic potential from inferior oblique and inferior rectus. The reason I think that is people who've got absent inferior oblique and inferior rectus don't show those potentials. That's one good thing -- one good control. There are a lot of controls in the literature. These are not blinks. These occur before blinks. This is a very fast pre-blink potential. We've done all that, Jay [Goldberg] -- we've published that.

[Goldberg] Okay, another question would be the statement about the SCM because I think that this is not oVEMP, right? Did you try unilateral air-conducted sound for these patients?

[Curthoys] Our SCD patients?

[Goldberg] No. That's a different question. That's a different question. Second question, in your (I believe it was your) otolith patients, I believe you said you got big responses in the SLM bilaterally, and I'm asking you, did you try or what effect did you get if you only used air-conducted sound?

[Curthoys] I didn't say that. If I did say that, that's not what I meant.

[Goldberg] Oh. The third question is that I think Lloyd [Minor] -- needs no defense, I thought he showed without any questions that in at least some of his patients (and I don't know the work that well) that the eye movement responses were precisely those to be expected from unilateral excitation of the anterior canal.

[Curthoys] Um, well…

[Goldberg] I mean very precisely. This was a big point of his, so it's…

[Curthoys] Firstly, those measures go back to my own anatomical data that I published back in 1975. I'll just make that point. Secondly, those measures, when you look at them, to me they aren't that convincing. I guess I'm…

[Goldberg] Ian [Curthoys], as you know, I've just finished a textbook to the publisher and there is a beautiful figure in there from Lloyd [Minor] which would be convincing to anybody because it shows that the response is precisely in the plane of the anterior canal.

[Curthoys] That's an eye movement response. As I said, I'm not denying the anterior canal has a function in it. What I'm making the point about is that I think there is a very strong otolithic component as well. That doesn't have to disagree.

[Goldberg] Oh yeah, I don't disagree, but I thought you were saying there was not an anterior canal [response].

[Curthoys] No, I did not say that, and I did not mean to say that. I believe there is, but I am saying there is an additional otolithic component that I think is reflecting the kind of stuff Tullio was writing about in the thirties. I think once you open the labyrinth, the whole system starts operating very differently. That's not the usual closed labyrinth system like you meant to have.

[Goldberg] Let me make one semi-humorous comment. Over the years, you have put up these tables of the differences between your study and our study, and I would say with all prejudice to the quality of our study, that your study has been going on because of the importance to your clinical work for many, many years and [using] many different methods, and for us this was a quickie. We did five or six animals. These were monkeys. They were reasonably expensive, and César [Fernandéz] actually wanted to go on and study the Tullio phenomenon, and I said, "Over my dead body" [laughter]. Because, in my view this was a vestibular epiphenomenon, but that doesn't constitute a potentially wonderful test, in fact, most wonderful tests are epiphenomenon.

[Curthoys] Let me make one point and answer that I thought it was an epiphenomenon too until I met Leonardo Manzari because in Australia SCD, these patients that come in with SCD are comparably rare. I see about 4 or 5 a year, and I said, "What's the point of studying them." In Italy they get 30 of them, 30 a year. I don't know whether that is geographical differences or what, but these are 30 people who are potentially going for high resolution CT scans, and you want to make sure you don't dose up people incorrectly because of a screening test like that. The beauty about what I showed you is that tapping there and tapping there has about a zero false positive rate. It gets about everyone of the 29 patients that we have identified as having SCD.

[Black] I was just going to comment, relative to the semicircular canal dehiscence syndrome, there was an excellent paper from (I assume) your colleagues in Australia. I'm not sure if it was from your group. I think it was from a different group. It was titled, "Does size matter?" because these dehiscences can be very, very small. They [also] can be very, very large. They can be in the superior part of the canal. They can be on one side, especially the medial side, of the canal. One of their points was that sometimes the tests that are used for detection, at least the early detection, in the superior semicircular canals are not consistent with what has been published in the past, and their theory was that the larger the dehiscence, the more likely the dura would compress the membranous canal and obviously that would change the dynamic of the response. I don't know if you are familiar with that paper or not, but I think the important point is that they provide a potential explanation for why some patients have a Tullio phenomenon and a nystagmus in the superior canal plane whereas others don't, and there are some others that we have talked about before. I have a couple of questions.

[Curthoys] Can I make a response to that?

[Black] Sure.

[Curthoys] This is one of the slides I didn't show, and this shows you the relationship between the size of the oVEMP and the size of the dehiscence. [Slides 92-95] As you can see pretty clearly here, one of the reasons that literature has been so befuddled is people have used cVEMPs, which are highly variable. But look at these oVEMPs, these ocular VEMPs. As you can see there is a very strong relation, just categorizing the size of the dehiscence and magnitude of the n10 oVEMP response compared to the other eye. Anyway, that was that point.

[Black] Back to the Meniere's patients, I was trying to drag up the actual numbers from a study Conrad Wall and I did a number of years ago on Meniere's patients, actually hydrops patients...endolymphatic hydrops patients, and the VOR gain appeared at that time, if I recall correctly, seemed to be most consistent with the fact that the ration between the canal and the ampulla sometimes changed, and you could see those changes on histo-pathological data. I want to remind you that the problem with histo-pathological data is that it is obtained sometime after the physiological test, but that might possibly another explanation for why you are seeing the gain changes in the VOR.

[Curthoys] My comment about that would be that we're measuring VOR gain to much higher accelerations than most people have delivered. I mean these head accelerations [are] around about 3000 to 4000 degrees per second squared. I also happen to think that what you said about the swelling, etc., the hydrops, may well be correct because it is very puzzling to me that these people without any, or many Meniere's patients during a quiescent phase, show this enhanced gain. That does make a bit of sense if you think about increased pressure in the labyrinth affecting the response of the cupular system, but that's about where I've got to.

[Black] Well there have been studies using the caloric showing that the involved-side actually has a ‘hyperactive’ response to the caloric test, which is another observation. I think from a histo-pathological standpoint, it might also be worth pointing out that endolymphatic hydrops is segmental in that the endolymphatic duct throughout the labyrinth is not affected equally throughout the duct and it can change from time to time. So not only do you have a disease or disorder process that’s fluctuation, you also have a disease that is affecting different parts of the labyrinth at different parts of the time, which makes it of course very difficult to study, and if you apply for an NIH grant on that basis, you’ll never get funded. The other -- [laughter] a political comment -- the other question that I had is a question related to the cVEMPs versus the oVEMPs. We haven’t had as much experience with the oVEMPs as you’ve had, but with the patients we’ve seen with vestibular neuritis, some of those subjects recover [and] some of them don’t. I think that might be worthwhile pointing out in your comments regarding the involvement of the superior versus the inferior vestibular nerve, but the important point still remains that it is extremely valuable clinical information, regardless.

[Curthoys] Yeah, we have got some data from some people with inferior vestibular neuritis. They’ve got absent cVEMPs but the oVEMPs are still present on the other side. All of these kind of predictions based on this simple idea seem to be coming out. We’ve just published recently, but that idea about recovery is very good. What we did do with Leonardo [Manzari] is compare the efficacy of this n10 response, the asymmetry ratio, with calorics, and we discovered because we’ve got both canal paresis data and otolith asymmetry on the same people, the n10 asymmetry was about 94 percent as good as calorics in detected the side which was effected. To me this was a remarkable number. It is just, it shows you which side is affected, as it should. They’re traveling in the superior canal, superior vestibular nerve, but I know which test I’d much rather have. A tap on the forehead rather than a caloric, thank you very much.

[Black] One more comment, and then I will shut up here. But I think I would like to strongly support your contention that we need objective tests that can be done quickly and efficiently in the clinic. One looks at the way (otology) is practiced, no one would ever take a patient to the room without an audiogram. Yet, it’s not infrequent that interventions, particularly interventions that cause further damage to the labyrinth, are done and often with disastrous results. The best example that I can think of is doing a procedure, such as a vestibulo nerve section or ototoxic drug installation in the middle ear, and not having an idea of what the opposite ear function is. Anyway, I strongly concur with your efforts, and they are very clinically applicable, and in my opinion essential.

[Curthoys] I came here via [a conference in] Shanghai [China], and I heard some data in Shanghai that in fact underlines the importance of what you just said, the assumption that if you give intratympanic gentamycin it’s just affecting one ear. I think that is really open to question, and people that have got patients who have had that know that is a great simplification.

[Black] May I make one other comment? I think the study from Mass Eye and Ear also strongly supports what you say regarding Meniere’s disease, and they’d show that bilateral absent cVEMPs predicted development of bilateral hydrops. So if you had a symptomatically normal ear, then the probability that they would develop bilateral hydrops in the future was very high if they had an abnormal cVEMP.

[Oman] Could you say a little more about your Meniere's and cupula stretching, is that what it is? Is the cupula detached? Just thinking about it, I've always thought that in Meniere's if the gain goes up and if it has a mechanical origin, it would be because the inertia of the fluid rim was essentially increasing because after all, the amount of cupula motion you get after making a brisk head movement like yours doesn't depend on cupula stimulus, it just is dependent on the inertia to drag ratio, so cupula stiffness shouldn't matter.

[Curthoys] Well, to be honest with you, we've been very puzzled by that enhanced gain. Very puzzled.

[Oman] Well, we should be able to figure out what the inertia is.

[Curthoys] It sounds [like] that idea is just wrong, and I am prepared to accept that. It is extremely puzzling to see these gains which are significantly enhanced, and it very pleasing to hear confirmation from other groups about that enhancement.

[Oman] Could it be paralymph biochemical changes or whatever?

[Curthoys] Well my comment to that is, why is it both sides?

[Oman] Oh, right.

[Curthoys] Sorry, Måns [Magnusson]. Måns is bursting at the bit.

[Magnusson] A comment on that is that I think Kim in Korea had some reports on the cupula loosening from the top, so the cupula going free and that would enhance.

[Oman] It's funny though because the fluid mechanics doesn't support it.

[Magnusson] No, but he had some ideas and exactly the Meniere's patient that you would perhaps have, in such a situation release of the cupula. Now, that was his suggestion. Secondly, about the gentomycin and bilateral defect, there are actually some studies that show that there is very little effect on the other ear even in the long run.

[Grant] If the human canal is really oval shaped, it's not circular, so if you increase the pressure in there, it would make it more circular which would decrease the drag and increase the inertia. That would give you that response. I agree with Chuck [Oman], it would be difficult to stretch.

[Unknown Speaker] Well it could be electrochemical.

[Multiple people] Yes.

[Goldberg] Did you not say it was present during the acute phase and during inter-symptom phase? I don't have the terminology.

[Curthoys] Well, I don't want to be pinned down about the gain during the attack just yet. It is certainly increased in some patients, in most patients, during quiescence. In fact, in some patients it might decrease at the time of the attack, but we're still working through that.

[Black] One of the criticisms of probably the best animal model, for hydrops, is Kimura's model in which he obstructs the endolymphatic duct, and one of the criticisms of that model is that the guinea pigs don't have vestibular disturbances apparently. I was just curious, what is your opinion on if it would be worthwhile reexamining those animals with your newly developed techniques.

[Curthoys] I think that is a great idea. In fact, there are two groups at the minute which are trying to do oVEMP recordings in guinea pigs because of a published study in Taiwan which has recorded oVEMPs in guinea pigs. Once you've got that, then you've got the opportunity to study things like Kimura's model and its effect on otolith function, but there are other groups as well.

[Black] I just thought of another question. Sando (several years ago) published a paper indicating that there is a sexual dimorphism of the otolith systems, that is the area, I think he was recording the area or calculating the area of the macula in the females versus males and showed that they are much, much smaller. So my question is, have you seen any dimorphism in your oVEMP and cVEMP studies?

[Curthoys] I haven't looked.

[Goldberg] It just dawned on me because I did not hear it correctly. It seems remarkable that the VOR would change so much during the quiescent phase because you know, there is a tremendous amount of adaptive plasticity. I mean, you are going to be going around with two time gain, you are going to be getting a lot of oscillopsia. Presumably, your ocular complex would somehow take care of that.

[Black] In fact you do see, patients complain of it during attacks. So…

[Goldberg] I'm not arguing. I know nothing about this.

[Curthoys] That's exactly the kind of problem I've been wrestling with. What is going on if the gain is going up so much?

[Goldberg] So why don't you do a plasticity study on them and see…

[Curthoys] Oh my. I'll put that on my list of things to do. I need another Australian 10 minutes to do that.

[Laughter]

[Magnusson] But actually, if you have a patient with Meniere's in a quiescent phase and you do a head shake, in many of those patients you will evoke a nystagmus toward the lesioned ear. We actually use that as a clinical sign for continuing, and if the patient is responding to some concerted treatment and we do a head shake on them and there is a still a nystagmus to that ear, we continue the treatment. We use that as a clinical sign actually.

[Goldberg] And it would be consistent with the hyperactivity?

[Magnusson] Yes.

[Black] Our conclusion, incorrect or correct, and this is actually if you look at both the vestibular function, VOR, and vestibulo-spinal, one of the problems we had with rehabbing those patients is that sometimes they're not rehab-able. They can't seem to adjust or compensate, or whatever term you want to use, because the function is changing all the time.

[Curthoys] Yes, that's what we find. We test these people and find their VOR gain has changed considerably from day to day.

[Unknown Speaker] If we are going to persist in this, I suggest we let everyone else escape.

[Laughter]

[Grant] It's a dumb question, but I'm going to ask it anyway. The vibrator…. you said it was 500 Hz. Is it always at 500 Hz? Have you ever looked at other frequencies? Would there be frequency effects?

[Curthoys] Yes. There are. We are moving to that area, but I wanted to get something without doing a whole parametric study on frequency responses or whatever 500 Hz stimulus was demonstrated to be a very effective stimulus for VEMP studies years ago in patients, so I simply adopted that when we did the guinea pig studies, and we have adopted that when we do the bone-conducted studies, but you are exactly right. I just want to make the point that this is just a start, and I think it is a pretty neat start because it has given us a new probe into these conditions, but whether it is optimal or not, I have no idea. I am fascinated by these different locations and the effects of those as well, and one reason I am fascinated is what that might be doing down at the hair cells in response to that. But anyway, that's another story.

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