Modeling and Mitigating Spatial Disorientation in Low G Environments: Year 3 Report

Submitted to NASA's National Space Biomedical Research Institute (NSBRI)

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Acknowledgements

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Executive Summary

This report describes the goals and progress of the project entitled *Modeling and mitigating spatial disorientation in low g environments* for NASA's National Space Biomedical Research Institute (NSBRI) by the team of Alion Science and Technology Corp., and the Massachusetts Institute of Technology's (MIT's) Man Vehicle Laboratory. The report captures the team's Year 3 (9/1/09-8/31/10) progress during this four-year project and outlines the team's Year 4 plans.

The goal of this collaborative industry-university research and technology development project is to extend Alion's spatial disorientation mitigation software – originally developed for aviation – to NASA's space applications, including the Space Shuttle, Crew Exploration Vehicle, International Space Station, commercial space vehicles, lunar lander, and in near-Earth object and Mars exploration missions. Extensions to Alion's software include adapting and adopting algorithms from MIT's spatial orientation models, as well as Frame-of-Reference Transformation (FORT) theory concepts.

The four overall specific aims of the project, and third year progress on each, are as follows:

1. Extend Alion's Spatial Disorientation Analysis Tool (SDAT) by incorporating an enhanced MIT *Observer* model into SDAT. Validate enhancements with existing and new flight data sets.
   - Progress: A compiled version of Observer was developed for incorporation into SDAT processing. When Observer includes vestibular thresholds, we intend to fully integrate it into SDAT. In the mean time, we are adapting SDAT algorithms to include a full set of vector math functions.

2. Extend SDAT assessments to include typical space vehicle illusions. Validation will include assessment of Shuttle landing data, and Altair simulator data.
   - Progress: We designed new illusion models for vertical landing vehicles (e.g., helicopters and lunar landers) and obtained actual helicopter flight data sets that include SD events. Shuttle data sets are unusable. Altair simulator data (e.g., from the NASA-Ames vertical motion simulator) are being analyzed. Furthermore, we are distributing an IRB-approved survey to Shuttle commanders and pilots to quantify their experiences with illusory sensations resulting from the transition from 1 g to 0 g and back.

3. Further extend SDAT by examining alternative visual reference frames. FORT is used to predict the cognitive cost of transitioning between reference frames. Validation of Aims 1-3 for SDAT may include parabolic flight experiments.
   - Progress: The FORT tool has been partially validated; further validation is ongoing. Flight experiments will likely not occur since 0 g adapted humans are only available on the ISS.

4. To further enhance SDAT assessor performance, pilot multi-sensory workload is considered in countermeasure selection. Validation experiments are not detailed, but will involve evaluations in ground-based simulators.
   - Progress: We have added a representation of the N-SEEV attention model to SDAT/SOAS to improve countermeasure triggering.

Introduction

This report describes the goals and progress of the project entitled *Modeling and mitigating spatial disorientation in low g environments* for NASA's National Space Biomedical Research Institute (NSBRI) by the team of Alion Science and Technology Corp., and the Massachusetts Institute of Technology's (MIT's) Man Vehicle Laboratory. The report captures the team's third year (1 Sep 09 – 31 Aug 10) accomplishments during this four-year project and outlines the team's Year 4 plans.

Interested readers are encouraged to review our Year 1 (Small et al., 2008) and Year 2 (Small et al., 2010) reports for details about the project's overall goals and for descriptions of SDAT, Observer, and the FORT tool, as this document is a progress report only.

We first list the project's original four goals, and summarize the progress on each. The following sections of this report will elaborate on the progress made.

1. Extend Alion's Spatial Disorientation Analysis Tool (SDAT) by incorporating an enhanced MIT *Observer* model into SDAT. Validate enhancements with existing and new flight data sets.

   - Progress: A compiled stand-alone version of Observer was developed for incorporation into SDAT processing. When Observer includes semi-circular canal (SCC) and otolith thresholds, we will complete its integration into SDAT. In the mean time, we are adapting SDAT algorithms to include a full set of vector math functions. Analyses revealed a potential convolution problem within SDAT – that is, how SDAT mimics SCC dynamics for sustained supra-threshold motions. We are further analyzing this potential problem and will devise a suitable correction, if needed.

2. Extend SDAT assessments to include typical space vehicle illusions. Validation will include assessment of Shuttle landing data, and Altair simulator data.

   - Progress: We designed new illusion heuristics for vertical landing vehicles (e.g., helicopters and lunar landers) and obtained actual helicopter flight data sets that include SD events. Shuttle data sets are unusable. We created and are distributing an IRB-approved survey to Shuttle commanders and pilots to quantify their experiences with illusory sensations resulting from the transition from 1 g to 0 g and back (i.e., launch and re-entry perceptions). Appendix A is the survey package.

3. Further extend SDAT by examining alternative visual reference frames. FORT is used to predict the cognitive cost of transitioning between reference frames. Validation of Aims 1-3 for SDAT may include parabolic flight experiments.

   - Progress: The FORT tool has been partially validated; further validation is ongoing. The tool has received very favorable comments from peers (e.g., HFES presentation) and is being modified to incorporate feedback and further validation. Flight experiments will likely not occur since 0 g adapted humans are only available on the ISS.

4. To further enhance SDAT assessor performance, pilot multi-sensory workload is considered in countermeasure selection. Validation experiments are not detailed, but will involve evaluations in ground-based simulators.

    - Progress: We have added a representation of the N-SEEV attention model to SDAT/SOAS to improve countermeasure triggering. Once we have verified and validated our models, we hope to assess the efficacy of various countermeasures triggered by SDAT during Year 4.

The specific aims of Year 3 of the project were to:

1. Enhance the utility of SDAT/SOAS by replacing the SDAT/SOAS vestibular attitude calculator (VAC) with MIT's Observer perception models, once Observer has vestibular thresholds incorporated. Verify and validate changes using our library of aeronautical and simulator data sets.

2. Extend SDAT/SOAS with heuristics for known vertical landing vehicle (VLV) SD event types and with frame of reference transformation (FORT) costs that impact the calculation of SD probability.

3. Survey astronauts to determine the prevalence and severity of illusory sensations during space missions, including re-entry.

4. Plan and conduct data gathering and/or countermeasure demonstration experiments; report results in refereed professional journal (e.g., ASEM).

The Alion-MIT team achieved the following on the above specific aims.

Merging SDAT & Observer

We have a compiled version of Observer (i.e., *eObserver*) that we can run from SDAT, but this is not the intended merging of the two products; rather, it is as far as we can go until Observer includes vestibular thresholds. Because SDAT illusion heuristics or models depend upon undetected sub-threshold motions (rotations and translations) we are working to incorporate SCC and otolith thresholds within Observer before Observer algorithms can replace SDAT's vestibular attitude calculator algorithms. However, a primary goal of this research remains to merge Observer and SDAT into a single tool. We hope to complete this goal in Year 4.

SDAT Enhancements

The first enhancement to SDAT in Year 3 was done while awaiting the successful incorporation of thresholds into Observer. Alion enhanced SDAT with a partial implementation of the required vector math functions to calculate the perceived gravito-inertial force (or "down" vector). This enhancement continues into Year 4 and will include combining SCC and otolith sensations, as well as default thresholds for all planes of rotation and all axes of translation. SDAT users will be able to modify thresholds to suit analytical needs because Alion recognizes that there is significant inter-human variability, as well as variability for an individual under varying circumstances. From the initial SDAT designs in 2004, it has accommodated users setting different thresholds than the defaults we selected based upon our literature reviews.

SDAT's default thresholds are 1.5 deg/sec for all three SCCs, and 0.005 g or 20 cm/sec for all three linear (otolith) axes (although there is some debate about the vertical body axis sensitivity being the same as horizontal axes). In each case, instantaneous motions that yield a velocity exceeding the respective threshold are considered perceived. Sustained sub-threshold accelerations that yield the target velocity are also considered perceived. SDAT's default definition of "sustained" is 10 seconds; that is, we use a 10-second sliding window to calculate if a combination of sub-threshold motions exceeds a respective threshold.

We next designed illusion heuristics for vertical landing vehicles (VLVs) using known SD event helicopter data sets from a source who demanded anonymity. Our prior research to develop SDAT for AFRL led us to ignore otolith thresholds for fixed-wing aircraft. But, while analyzing the anonymous helicopter data sets, we determined that horizontal (x, y) linear motion (otolith) thresholds are needed when analyzing VLV data sets. These observations led us to design two new illusion heuristics or models:

1. Undetected drift while hovering. While hovering a VLV near the surface, if an undetected horizontal drift occurs, the VLV might strike an obstacle. SDAT/SOAS can and should alert the pilot to sub-threshold drift over a specified distance (e.g., one vehicle length).

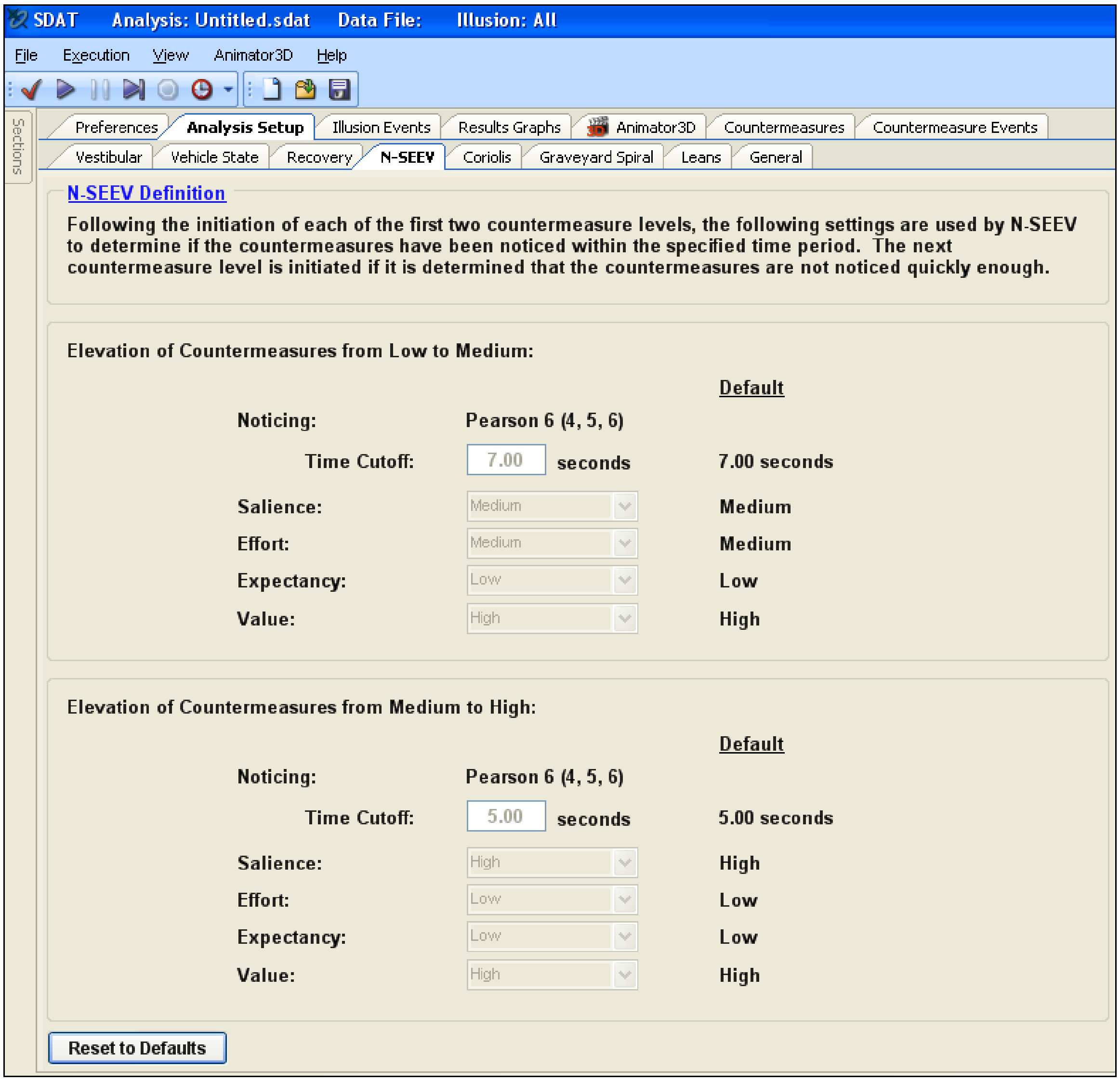
2. Undetected altitude increase and power decay. If the VLV increases altitude without a commensurate increase in power or thrust, the VLV might plunge toward the surface. SDAT/SOAS can and should alert the pilot to a sub-threshold increase in altitude, without an increase in thrust, that might put the vehicle into an unwanted dive due to the ensuing power decay.

Based upon prior enhancements to SDAT, we updated the SDAT User Guide (to version 2.0); available from this report's first author at rsmall@alionscience.com.

A final SDAT enhancement involved incorporating an attention model into the countermeasure portion of SDAT/SOAS. The goal is to elevate the intrusiveness of countermeasures, if the attention model predicts that the pilot has not detected a less-intrusive countermeasure. The selected attention model is N-SEEV (noticing – salience, effort, expectancy, value) (Wickens et al., 2009). The way the algorithm works is to begin processing when any low- or medium-level countermeasure first activates. A low-level countermeasure is a visual cue/command that we call the SD Icon (Wickens et al., 2007). A medium-level countermeasure is an auditory or tactile cue (Small et al., 2006). When SOAS triggers a low-level countermeasure, the default N-SEEV behavior is to wait 7.0 seconds and do a Pearson6 random draw to determine if the pilot noticed the low-level countermeasure or not. If the pilot did not notice, SOAS elevates the countermeasure to medium. This time, the default is 5.0 seconds. If the pilot still does not notice the countermeasure, SOAS elevates to a high-level countermeasure; i.e., an audio or tactile command.

Previously, countermeasures only increased in intrusiveness if the SD situation deteriorated. Now, with the N-SEEV model, countermeasures will become more intrusive if N-SEEV predicts that the pilot has not noticed a lower-level countermeasure within a specified time. As in the original SOAS, if the pilot recovers, all countermeasures cease.

The following figure shows the new SDAT GUI tab for N-SEEV, and Appendix B is the pseudo-code for the current implementation.



The eventual N-SEEV implementation will use more sophisticated models of the cockpit layout (areas of interest) and pilot eye scan to determine if the pilot noticed or not. The 7.0 and 5.0 seconds for the current default waiting values are based upon our experiences in aviation, and have not been validated. The N-SEEV model will use three levels of salience, effort, expectancy, and value – low, medium, and high – to assess the likelihood of the pilot noticing the SD countermeasure. As with most SDAT parameters, values will be user selectable (although the SEEV parameter values are not currently selectable as shown in the above figure).

Observer Enhancements

A major focus of Year 3 was to validate the Observer enhancements made in Year 2, which were to add visual inputs and calculations to account for the impact of visual cues on a human's perception of attitude, velocity and displacement (Newman, 2009). The validations included:

- Comparison to perception data from a NASA-Ames vertical motion simulator (VMS) lunar landing simulator experiment (in collaboration with Dr. Young's NSBRI-funded lunar landing project at MIT)
- A dynamic swinging experiment (in collaboration with Drs. Rader and Merfeld at the Massachusetts Eye and Ear Infirmary)
- Linear and angular acceleration steps
- Post-rotation tilt
- Vertical yaw rotations (with and without vision cues)
- Somatogravic illusions (linear acceleration with and without vision cues, and fixed and variable radius centrifugation)
- Static and dynamic roll tilt
- Off vertical axis rotation
- Large amplitude horizontal and vertical sinusoidal displacements
- Circular vection
- Linear vection
- Coriolis and pseudo-Coriolis illusions
- Astronaut post-flight tilt-gain and tilt-translation illusions

To facilitate integration with SDAT, *eObserver*, a stand-alone compiled version of Observer was developed; eObserver does not require a MatLab license to run. It includes a GUI (developed by Alion) to ease data file and processing step selections. Vestibular threshold literature was studied to determine the best way to represent SCC and otolith thresholds within Observer as a prerequisite for replacing SDAT's vestibular attitude calculator with Observer. Further details are in Venkatesan's master's thesis (2010), and Appendix C is the abstract from that thesis.

A final accomplishment for the Observer team was to submit a paper to *Biological Cybernetics* defining the theoretical relationships between Observer and Kalman Filter models for spatial orientation (Selva & Oman, in press). Appendix D is the abstract from that submitted journal article.

FORT Tool Enhancements

The FORT tool was partially validated and modified using the available literature to adjust FORT costs and achieve higher correlations with previous experimental data. After a presentation about the tool to peers at the annual Human Factors and Ergonomics Society (HFES) annual meeting (Wickens et al., 2010), further validation efforts are on-going. This validation is iterative with tuning of the parameters within the FORT model. In particular, the FORT model contains seven different perceptual-cognitive-motor mechanisms which impose penalties upon a particular work station design – penalties that mimic the cost of operations such as mental rotation or resolving 3D ambiguity. Currently the model does not contain differential weightings for the penalties imposed by different mechanisms. Additional empirical data from existing studies are sought that can provide evidence of what these weightings should be in order to refine the model. To the extent that new literature provides evidence for equal weighting between subsets of the seven mechanisms, such evidence provides retrospective validation of the current equal weighting version. This additional validation and its resulting adjustment to the tool's cost model, is ongoing in the preparation of an article to be submitted to a peer-reviewed journal, such as *Human Factors*.

An initial objective was to somehow incorporate FORT costs into SDAT's assessment of SD event likelihood or severity. This seems impractical now and will not be undertaken.

A progress report about the FORT tool is planned for the 2011 Aerospace Medical Association (AsMA) annual meeting; an abstract was submitted for review that describes how the FORT tool can be applied to aerospace problems, such as to help design ISS robotic arm work stations.

Understanding Space Operations SD

In pursuit of an original goal to better understand and quantify space operations SD, we developed a Shuttle orientation survey (Appendix A) that seeks to capture relevant historical information from Shuttle commanders and pilots before the Shuttle is retired. The survey package received approvals from the MIT and JSC IRBs. We sent an initial batch of about a dozen survey packages to potential subjects at the end of Year 3 and the beginning of Year 4. We anticipate sending a total of about 40 survey packages and hope to receive replies from 20 or more voluntary participants. Data will be compiled and analyzed, and may be reported in a peer-reviewed journal article (e.g., *Aviation Space and Environmental Medicine*) toward the end of Year 4.

A related effort is to present SDAT analytical results of actual flight data sets that contain a reported SD event at the 2011 annual AsMA meeting; an abstract has been submitted.

Year 3 Key Accomplishments

The most important accomplishments from Year 3 are: we have a method for integrating Observer into SDAT; we developed a partially validated FORT tool; we designed new illusion heuristics for vertical landing vehicles (e.g., helicopters and lunar landers); we obtained helicopter SD event data sets for verifying and validating perception models and enhancements; and, we created a survey with which to capture the prevalence and severity of Space Shuttle orientation issues. We also have good working relationships with VMS staff and related researchers with whom we can collaborate on experiments that may help validate Observer and SDAT models.

Another key collaboration is that the FORT model is a module within a larger computational model of an astronaut robotics controller for a NASA project that is identifying functional allocation strategies between humans and automation (*MIDAS FAST*, contract # NNX09AM81G, COTR is Barbara Woolford).

Proposed Research Plan for Year 4

In the fourth year of this project, the Alion-MIT team will:

1. Complete enhancements to, and the merging of, SDAT and Observer, and continue comparing analytical results from common data sets.

2. Validate enhancements with previous aircraft flight data sets and new data sets (from actual vehicles and simulators). Included will be helicopter SD event data sets and data sets from space vehicle simulators (e.g. NASA-Ames' VMS; see Clark (2010)).

3. Finish incorporating an N-SEEV attention model into SDAT/SOAS to help guide the presentation of cockpit countermeasures that will help pilots avoid the adverse consequences of SD.

4. Characterize the prevalence and severity of Space Shuttle launch, re-entry and landing orientation issues.

5. If time and budget constraints permit, plan and conduct experiments to generate validation data (e.g., vertical motion threshold data) and/or to demonstrate the value of SD countermeasures.

Conclusion

Merging Observer into SDAT has proved to be much more difficult than originally imagined, which has impacted all other plans for this research project. The difficulty is primarily due to the fundamentally different approaches of the two models of human orientation perception. Observer is a physiologically-based representation of the vestibular and visual systems that models how the central nervous system (CNS) disambiguates gravity from linear accelerations using a combination of SCC, otolith and visual cues. It operates best with data sampled at a high rate. SDAT, on the other hand, does not attempt to represent physiology; rather it models perceptual responses to motion (with no vision cues) as captured within low frequency noisy flight data sets. Observer is the product of academic researchers seeking to model quantitative data from laboratory experiments in order to understand how motion cues determine orientation perception. SDAT is the product of a human performance and applied research engineering company that seeks to mitigate the adverse consequences of spatial disorientation.

The team is also working together to add value to the spatial orientation knowledge base, such as the FORT tool and capturing relevant historical experiences from Shuttle operations.

We will continue to pursue other worthy goals in parallel to the primary effort of the integration of Observer into SDAT.

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Appendix A. Shuttle Survey Package

The package was approved by the MIT and JSC IRBs on 8/4/10. It includes a cover letter, subject information handout, consent form, and the survey.

Cover Letter

From: Thomas D. Jones {date}
To: {subject's name and address}

Subject: Shuttle entry and landing spatial orientation survey

Enclosures: *Subject Information Handout* (yours to keep), *Consent Form* (please sign and return in the enclosed envelope), *Survey* (please complete and return in the enclosed envelope)

Dear {subject's name}:

As you may already know, I've been working with Ron Small at Alion Science and Technology Corp. (Boulder, Colo) and Charles Oman of MIT on a project called ***Modeling and Mitigating Spatial Disorientation in Low G Environments***. It is funded by NASA's Human Research Program through the National Space Biomedical Research Institute. Our main focus is to develop math models to predict human spatial orientation in 0-G and upon return to Earth, and to develop potential spatial disorientation countermeasures.

A component of the project is to better understand the tilting and tumbling sensations many of us felt during Shuttle missions, especially at MECO after launch, and when we made head movements during and after return to Earth. For me, the sensations depended on G level during re-entry, and were strongest during and immediately after landing, but faded within a few hours.

Neurovestibular researchers have some ideas about what might cause the tilting and tumbling sensations; however, data are limited and incomplete. Published descriptions – such as the ones I included in *Sky Walking* – are anecdotal. So are flight surgeon and crew debriefing notes. We don't know if different people have similar sensations, or if vehicle maneuvers, as well as deliberate head movements, cause such sensations.

Certainly commanders and pilots are aware of the phenomena, and have successfully overcome any such sensations – presumably by avoiding head movements at critical times, or simply by "flying through it." Some crew members have tried making small ("trial") head movements to hasten their re-adaptation, although we don't know how useful those are.

With the imminent retirement of Shuttle, it may be many years until crews again fly a spacecraft through an approach and landing. Because you are one of the few who has flown the Shuttle, we think it is historically and scientifically important to capture your personal experiences with these sensations, and to understand how you dealt with them. Therefore, we request that you complete the enclosed survey. You may have seen earlier versions of this survey; this version incorporates feedback from initial respondents and a peer review, and therefore supersedes earlier versions.

If you agree, please read the *Subject Information Handout*, complete the *Consent Form*, and then answer the questions in the *Survey*. Please return the signed *Consent Form* and your completed *Survey* in the enclosed stamped envelope. Based upon initial samples, we estimate that the whole process will take you only 30 minutes.

Thank you for considering my request!

Best wishes,
Thomas D. Jones
281-286-7626 (office)
skywalking@comcast.net

Subject Information Handout

Subject Information Handout
Modeling and Mitigating Spatial Disorientation in Low G Environments
Shuttle entry and landing spatial orientation survey

Introduction

The principal investigator for this survey study is Ron Small at Alion Science and Technology Corp. in Boulder, Colorado, with Dr. Charles Oman of MIT as a co-investigator, and Dr. Thomas Jones as a co-investigator and the primary contact with astronaut subjects, such as you. Another Alion employee, John Keller, will help with data analyses.

We ask you to take part in this study because of your past experience as a Space Shuttle commander or pilot. Your participation is entirely voluntary.

Purpose and Background

(See Tom's cover letter.)

Number of People

We are asking as many Shuttle commanders and pilots as practical to complete our *Survey*.

Procedures

Please read through the enclosed multiple-choice *Survey*, and decide if you are willing to complete it. If you are, please sign and date where indicated on the *Consent Form*, and provide the mission data requested. We estimate that the *Survey* will take you up to 30 minutes to complete. Your participation is entirely voluntary. You may skip any question for any reason.

After you complete the survey, make a copy for your records, or we will send you a copy (depending on which line you check on the *Consent Form*). Please mail your completed *Consent Form* and *Survey* in the enclosed envelope.

Voluntary Participation

Your participation in this study is completely voluntary and you are free to withdraw your consent and terminate your participation at any time by notifying the investigator (see Questions for contact information). Your withdrawal from this study will be entirely without penalty and will not affect your participation in future studies.

Risks and Discomforts – Not applicable.

Benefits

There are no direct benefits to you from completing the *Survey*. Future benefits should include an improved knowledge of spatial disorientation during the transition from orbit to Earth and for the few days after landing.

Alternatives

The alternatives to completing the entire *Survey* are to only complete portions of it, or to not complete any of it.

Privacy and Confidentiality

Your completed *Survey* and *Consent Form* will be given an identifying code so as to protect your identity.

We will store the *Consent Forms* and *Surveys* in separate locked cabinets in a locked Alion office, with access to the full data by only four of the researchers on the project team. All *Surveys* and *Consent Forms* will be destroyed by September 1, 2014 which is three years after project completion.

Your privacy as a research subject and the confidentiality of any research data about you associated with this study will be maintained in accordance with 1) NASA Policy Directive (NPD) 7100.8, "Protection of Human Research Subjects," 2) NASA Procedural Requirements (NPR) 7100.1, "Protection of Human Research Subjects," and 3) to the extent allowed by Federal law.

Access to Research Records

Your data will be analyzed with others to determine the prevalence of illusory sensations and any statistical significance or trends. These data will not be identified by name. We may discuss data and analytical results at professional conferences or in publications. If we do, we will only report aggregate data (e.g., 28 of 34 commanders or pilots reported some orientation illusions during or immediately after Space Shuttle missions), or relevant de-identified quotes or paraphrasing (e.g., "During one of my flights, I [the commander] experienced an illusion during a head movement and so did not fly the HAC.").

Costs and Financial Considerations – Not applicable.

Payment and Reimbursement

You will not be paid to complete this *Survey*. You should have no costs associated with completing this *Survey*, other than your time.

Treatment and Compensation for Injury – Not applicable.

Questions

If you have questions, concerns or complaints about the *Survey*, please contact Dr. Thomas Jones at 281-286-7626 (office) or skywalking@comcast.net, or the project's principal investigator, Ron Small, at 303-518-5827 (cell), 303-442-6947 (office), or rsmall@alionscience.com.

You may also contact the NASA Johnson Space Center Committee for the Protection of Human Subjects (281-212-1468), or the MIT Committee on the Use of Humans as Experimental Subjects (617-253-6787). Both committees are independent of the research team and are available for questions regarding the rights and welfare of research subjects, such as you.

Consent

Your participation in this research is entirely voluntary. You have the right to decline to participate or to withdraw at any time without penalty or loss of benefits to which prospective subjects are otherwise entitled.

Your signature on the *Consent Form* indicates your agreement to participate.

Video and Photo Consent – Not applicable.

Consent Form

CONSENT TO PARTICIPATE IN SURVEY

My signature below acknowledges my voluntary participation in this research project. Such participation does not release the investigators, institutions, or granting agency from their professional and ethical responsibility to me. I have read and understand the information provided in the *Subject Information Handout* and have had my questions, if any, answered to my satisfaction. I voluntarily agree to participate in this study. I understand that I am free to retain my copy of the *Subject Information Handout* for as long as I would like.

Your printed name ____

Your signature ______________________________________ Date _______________

Please check one:
___ Please mail me a copy of this signed *Consent Form* and my completed *Survey*.
___ I made myself a copy before I returned the *Consent Form* and *Survey*.

Your Personal Shuttle Spaceflight History:

Flight Number	**Mission** (STS number)	**Mission Month & Year**	**Duration** (days)	**Role** (Commander or pilot)
1st				
2nd				
3rd				
4th				
5th				
6th				

What is your birth date? _________________ (To be used for analyses of age groups.)

Survey key number _____ (assigned by Tom or Ron)

Shuttle Survey

Shuttle Spatial Orientation Survey
Modeling and Mitigating Spatial Disorientation in Low G Environments
NASA/NSBRI Investigators: Tom Jones, Ron Small and Charles Oman

Survey key number _____ (assigned by Tom or Ron)

Instructions: Please circle the letter in front of the appropriate answer(s), based on your ***most recent*** mission. If you recall different experiences on one or more earlier missions, please feel free to note that in the margin. So that your survey responses remain anonymous, refer to your missions by your sequential Flight Number listed on the *Consent Form*, rather than STS mission number. For example, you might indicate "1" (for your 1st flight) next to Question 1, choice b, and "2 & 3" next to choice a.

1. After launch and during main engine cut-off (MECO) did you experience any spontaneous (i.e., not induced by head motion) illusory sensations?
   a. No.
   b. Yes, but I don't recall details.
   c. Yes, I felt as though I was doing a backward summersault.
   d. Yes, I felt as though I was doing a forward summersault.
   e. Yes, I felt another sensation. Please briefly explain: ______________________________________
   f. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   g. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ___________________

2. During MECO did you experience any illusory sensations when you moved your head?
   a. No.
   b. Yes, but I don't recall details.
   c. Yes, I felt as though I was doing a backward summersault.
   d. Yes, I felt as though I was doing a forward summersault.
   e. Yes, I felt as though I was tumbling (i.e., like I was doing a continuous summersault, or experienced a sensation of a multi-axis rotation).
   f. Yes, I felt another sensation. Please briefly explain: ______________________________________
   g. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   h. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ___________________

3. During re-entry did you make any deliberate head movements to see how they felt?
   a. No.
   b. Yes.
   c. Why or why not? Please briefly explain: ____

4. Did any head movements, deliberate or not, during re-entry produce any illusory sensations? (Circle all that apply.)
   a. I experienced no illusory sensations during head movements.
   b. I recall having one or more illusory sensations when moving my head, but I don't recall details.
   c. When I pitched or rolled my head, my head seemed to tilt more than the actual motion.

d. When I pitched or rolled my head, my head seemed to tumble (i.e., like I was doing a continuous summersault, or experienced a sensation of a multi-axis rotation).
e. When I pitched or rolled my head, my head seemed to tilt less than the actual motion.
f. When I pitched or rolled my head, the tilt sensation lagged the actual motion.
g. I felt a brief translation (linear motion) in an opposite direction to my head tilt.
h. I felt a brief translation (linear motion) in the same direction as my head tilt.
i. When I yawed my head, the visual scene seemed to blur.
j. When I yawed my head, the visual scene seemed to move in the opposite direction.
k. When I yawed my head, the visual scene seemed to move in the same direction.
l. Other: ____
m. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
n. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

5. Were there any phases of flight or maneuvers where you deliberately avoided moving your head? (Circle all that apply.)
a. No.
b. Yes, but I don’t recall details.
c. TAEM turns.
d. HAC turn.
e. Intercepting the inner glide slope.
f. Landing flare.
g. Rotation to nose-wheel touchdown.
h. Rollout.
i. Other: ____

6. When the Shuttle rolled during TAEM (i.e., all maneuvers pre-HAC), did you experience any illusory sensations? (Circle all that apply.)
a. No.
b. Yes, but I don’t recall details.
c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.
f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
g. Yes, the Shuttle’s pitch rate seemed to be more than indicated on the instruments.
h. Yes, the Shuttle’s roll rate seemed to be more than indicated on the instruments.
i. Yes, the Shuttle’s pitch rate seemed to be less than indicated on the instruments.
j. Yes, the Shuttle’s roll rate seemed to be less than indicated on the instruments.
k. Other: ____
l. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
m. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

7. When transitioning from automatic flight to manual (at about Mach 1 or just before the HAC), did you experience any illusory sensations?
(Circle all that apply.)
a. No.
b. Yes, but I don’t recall details.
c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.

f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
g. Yes, the Shuttle's pitch rate seemed to be more than indicated on the instruments.
h. Yes, the Shuttle's roll rate seemed to be more than indicated on the instruments.
i. Yes, the Shuttle's pitch rate seemed to be less than indicated on the instruments.
j. Yes, the Shuttle's roll rate seemed to be less than indicated on the instruments.
k. Other: ____
l. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
m. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

8. When the Shuttle rolled during the HAC turn, did you experience any illusory sensations? (Circle all that apply.)
   a. No.
   b. Yes, but I don't recall details.
   c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
   d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
   e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.
   f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
   g. Yes, the Shuttle's pitch rate seemed to be more than indicated on the instruments.
   h. Yes, the Shuttle's roll rate seemed to be more than indicated on the instruments.
   i. Yes, the Shuttle's pitch rate seemed to be less than indicated on the instruments.
   j. Yes, the Shuttle's roll rate seemed to be less than indicated on the instruments.
   k. Other: ____
   l. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   m. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

9. When the Shuttle intercepted the inner glide slope and decelerated, did you experience any illusory sensations? (Circle all that apply.)
   a. No.
   b. Yes, but I don't recall details.
   c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
   d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
   e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.
   f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
   g. Yes, the Shuttle's pitch rate seemed to be more than indicated on the instruments.
   h. Yes, the Shuttle's roll rate seemed to be more than indicated on the instruments.
   i. Yes, the Shuttle's pitch rate seemed to be less than indicated on the instruments.
   j. Yes, the Shuttle's roll rate seemed to be less than indicated on the instruments.
   k. Other: ____
   l. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   m. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

10. During the Shuttle's landing flare, did you experience any illusory sensations? (Circle all that apply.)
   a. No.
   b. Yes, but I don't recall details.
   c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
   d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
   e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.

f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
g. Yes, the Shuttle's pitch rate seemed to be more than indicated on the instruments.
h. Yes, the Shuttle's roll rate seemed to be more than indicated on the instruments.
i. Yes, the Shuttle's pitch rate seemed to be less than indicated on the instruments.
j. Yes, the Shuttle's roll rate seemed to be less than indicated on the instruments.
k. Yes, the Shuttle seemed higher AGL than indicated on the instruments.
l. Yes, the Shuttle seemed lower AGL than indicated on the instruments.
m. Yes, the Shuttle seemed to have a faster speed than indicated on the instruments.
n. Yes, the Shuttle seemed to have a slower speed than indicated on the instruments.
o. Other: ____________________
p. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
q. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ____________

11. During the Shuttle's rotation to nose-wheel touchdown, did you experience any illusory sensations? (Circle all that apply.)
    a. No.
    b. Yes, but I don't recall details.
    c. Yes, the Shuttle seemed to pitch more than indicated on flight instruments.
    d. Yes, the Shuttle seemed to roll more than indicated on flight instruments.
    e. Yes, the Shuttle seemed to pitch less than indicated on flight instruments.
    f. Yes, the Shuttle seemed to roll less than indicated on flight instruments.
    g. Yes, the Shuttle's pitch rate seemed to be more than indicated on the instruments.
    h. Yes, the Shuttle's roll rate seemed to be more than indicated on the instruments.
    i. Yes, the Shuttle's pitch rate seemed to be less than indicated on the instruments.
    j. Yes, the Shuttle's roll rate seemed to be less than indicated on the instruments.
    k. Other: ____________________
    l. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
    m. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ____________

12. After wheel stop, before leaving the flight deck, did head movements produce any illusory sensations? (Circle all that apply.)
    a. No.
    b. Yes, but I don't recall details.
    c. When I pitched or rolled my head, my head seemed to tilt more than the actual motion.
    d. When I pitched or rolled my head, my head seemed to tumble (i.e., like I was doing a continuous summersault, or experienced a sensation of a multi-axis rotation).
    e. When I pitched or rolled my head, my head seemed to tilt less than the actual motion.
    f. When I pitched or rolled my head, the tilt sensation lagged the actual motion.
    g. I felt a brief translation (linear motion) in an opposite direction to my head tilt.
    h. I felt a brief translation (linear motion) in the same direction as my head tilt.
    i. When I yawed my head, the visual scene seemed to blur.
    j. When I yawed my head, the visual scene seemed to move in the opposite direction.
    k. When I yawed my head, the visual scene seemed to move in the same direction.
    l. Other: ____________________
    m. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
    n. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ____________

13. During re-entry, did you experience any illusory sensations <u>unrelated</u> to a head movement? (Circle all that apply.)
    a. No.
    b. Yes, but I don't recall details.
    c. Yes, I experienced a spontaneous illusion. Please briefly describe the illusion: _______________

    d. Yes, I experienced illusory sensations due to vehicle maneuvering, deceleration, turbulence, or gusts.
    e. Yes, I experienced illusory sensations due to visual factors (e.g., cloud bank, false horizon, etc.)
    f. Other: ____
    g. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
    h. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ___________________

14. When flying manually, did you experience any illusory sensations <u>unrelated</u> to a head movement? (Circle all that apply.)
    a. Not applicable; I did not fly manually.
    b. No, I experienced no spontaneous illusory sensation when flying manually.
    c. Yes, but I don't recall details.
    d. Yes, I experienced a spontaneous illusion. Please briefly describe the illusion: _______________

    e. Yes, I experienced illusory sensations due to vehicle maneuvering, deceleration, turbulence, or gusts.
    f. Yes, I experienced illusory sensations due to visual factors (e.g., cloud bank, false horizon, etc.).
    g. Yes, the Shuttle felt <u>more</u> <u>sensitive</u> than my training experiences suggested, so that I needed to deliberately reduce the size of my control inputs.
    h. Yes, the Shuttle felt <u>less</u> <u>sensitive</u> than my training experiences suggested, so that I tended to over-control it.
    i. Other: ____
    j. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
    k. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ___________________

15. If you experienced an illusory sensation when flying <u>manually</u>, how easy or difficult was it to "fly through"? (Circle a single answer.)
    a. Not applicable; I did not fly manually.
    b. I experienced no illusory sensation when flying manually.
    c. I don't recall the level of difficulty.
    d. Very easy.
    e. Easy.
    f. Moderate.
    g. Difficult.
    h. Very difficult.
    i. Impossible; I had to transfer control to the other pilot or use auto-flight.

16. Referring to Question #15, if you did "fly through" an illusory sensation, which technique helped you to do so? (Circle all that apply.)
    a. I experienced no illusory sensation when flying manually.
    b. I don't recall which technique I used.
    c. Concentrating on the HUD.
    d. Concentrating on other flight instruments.

Please specify which one(s): ____

e. Verbal cues; talked to myself or with the other pilot.
f. A combination of visual and verbal techniques.
   Please specify which ones: ____

g. Other: ____

17. To prevent illusory sensations and/or to improve your sense of accurate orientation, which displays, controls, procedures, and/or techniques would you enhance or add to the Shuttle? Please briefly explain your answer, if any.

18. During the post-flight walk-around, did you experience any illusory sensations? (Circle all that apply.)
   a. No.
   b. I was unable to accomplish the post-flight walk-around because of:
      i. A temporary lack of coordination.
      ii. Dizziness.
      iii. Fainting or being light-headed.
      iv. Other: ____
   c. Yes, but I don't recall details.
   d. Yes, during head movements.
   e. Yes, during body movements.
   f. If you answered Yes in d or e, please briefly explain the illusory sensation(s) you experienced:

   g. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   h. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

19. Immediately after landing (up to about 2 hours after landing), did you experience any illusory sensations related to a head movement?
   a. No.
   b. Yes, but I don't recall details.
   c. Yes. Please briefly explain: ____

   d. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   e. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

20. From about 2 to 24 hours after landing, did you experience any illusory sensations related to a head movement?
   a. No.
   b. Yes, but I don't recall details.
   c. Yes. Please briefly explain: ____

   d. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
   e. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: __________________

21. From about wheel stop to 24 hours after landing, did you experience any difficulties with your balance or ability to walk normally (e.g., around corners or up/down stairs)?
   a. No.

b. Yes, but I don't recall details.
c. Yes. Please briefly explain: ____

22. Beyond 24 hours after landing, did you experience any illusory sensations related to head movement?
    a. No.
    b. Yes, but I don't recall details.
    c. Yes. Please briefly explain: ____

    d. Yes, as indicated above, and the feeling was transient (i.e., lasted a few seconds or less).
    e. Yes, as indicated above, and the feeling was sustained. If sustained, please estimate how long the sensation lasted in seconds or minutes: ____________________

23. Beyond 24 hours after landing, did you experience any difficulties with your balance or ability to walk normally (e.g., around corners or up/down stairs)?
    a. No.
    b. Yes, but I don't recall details.
    c. Yes. Please briefly explain: ____

24. In future vehicles, how do you think cockpits should be changed to improve the astronaut pilot's ability to reduce, minimize or eliminate the chances of experiencing illusory sensations (i.e., to maintain accurate spatial orientation)? (Circle all that apply.)
    a. No changes needed.
    b. Bright, large-format, high-contrast displays (including HUDs).
    c. Layouts that minimize the need for head movements.
    d. Larger, wider artificial horizon displays.
    e. Larger windows.
    f. Alternative head restraints; please suggest one or more: ____________________________________

    g. Other procedures or techniques; please explain: ____

    h. Other: ____

25. Do you have any other experiences or ideas related to spatial orientation issues during space operations that you'd like to describe? If so, please use the space below.

Thank you, again, for taking the time to complete our *Survey!*

Please return the *Survey* and signed *Consent Form* (with Your Personal Shuttle Spaceflight History and birth date) in the envelope provided.

Appendix B. N-SEEV Pseudo-code

Countermeasure Assessor with N-SEEV

```
If aircraft state == recovered,
        then set all countermeasures to OFF
        and set SDConfidenceLevel == None
        and set NSEEV to OFF
        and return to SDAT code that called the CountermeasureAssessor
ELSE if aircraft state == imminent crash, and aircraft type == fighter
        then set auto-ejection == ON, and set all other countermeasures to OFF
        if other aircraft type (lunar lander, either helicopter, 737, space shuttle, V-22 Osprey, Other/Cessna)
                then set auto-recovery == ON and set all other countermeasures to OFF
                and set tickRate == eightHertz          //to check state more frequently
ELSE if aircraft state == impending crash
                then set auto-recovery == ON
                and set tickRate == eightHertz          //to check state more frequently
ELSE if aircraft state == unusual attitude (confirmed or suspected – if these modifiers still apply)
        then set audio and tactile commands to ON
                unless auditory workload (data set column AG) > 6.00, then set audio command to OFF
        and set audio cue, tactile cue, and olfactory cue to OFF
        and set CountermeasureLevel == High
ELSE if Moderate SD Confidence
        then set audio and tactile cues to ON
                unless auditory workload (data set column AG) > 6.00, then set audio cue to OFF
        and set CountermeasureLevel == Medium
ELSE if Low SD Confidence
        then set SD_Icon == ON
        and set CountermeasureLevel == Low
Call N-SEEV function.
```

```
//Now for the N-SEEV logic in N-SEEV function:
If CountermeasureLevel == High, do nothing; it's as high as it can get due to N-SEEV logic.  Exit this function.
If CountermeasureLevel == Medium
        do random draw from Pearson 6 (4,5,6)
                if randomdraw > 5.00
                then wait from current time (data set column A) to current time + 5.00 seconds
                        do nothing until current time + 5.00 seconds, then
                                if CountermeasureLevel is still Medium     //was not elevated by previous steps
                                then set audio and tactile commands to ON
                                        unless auditory workload  > 6.00, then set audio command to OFF
                                and set CountermeasureLevel == High
        exit N-SEEV function
ELSE if CountermeasureLevel == Low
        do random draw from Pearson 6 (4,5,6)
                if randomdraw > 7.00
                then wait from current time (data set column A) to current time + 7.00 seconds
                        do nothing until current time + 7.00 seconds, then
                                if CountermeasureLevel is still Low        //was not elevated by previous steps
                                then set audio and tactile cues to ON
                                        unless auditory workload  > 6.00, then set audio cue to OFF
                                and set CountermeasureLevel == Medium
        exit N-SEEV function
```

Appendix C. Venkatesan Thesis Abstract

Multisensory Models for Human Spatial Orientation Including Threshold Effects
by
Raghav Venkatesan

E-Observer, a stand-alone executable version of the *Observer* model developed by Newman and Oman (2009), was developed. The complicated structure of the *Observer* model and its parameters made this conversion challenging. The resulting Windows PC executable uses a publically available library (MATLAB component runtime v7.10). *E-Observer* parameters are limited to the preset choices in *Observer*. A hypothetical example of the use of *E-Observer* to analyze an aircraft accident radar trajectory data is discussed. Like many other dynamic models for human spatial orientation, *Observer* does not incorporate perception thresholds, which limits its use to relatively large stimuli and hence cannot be used for investigation of certain accidents and flight simulator design, which involve sub-threshold motions. The literature on motion thresholds is reviewed which suggests that vestibular perception thresholds are not mechanical thresholds, but are due to signal-in-noise phenomenon. As a first step towards incorporating thresholds in *Observer*, modeling yaw perception thresholds was attempted and two detection models are proposed – a Matched Filter model and a Two-Threshold model. The Matched Filter detector model matches the noisy perception with a noise-free stimulus template and evaluates how much they correlate. Based on the correlation, the model finally decides if the signal is present or not. However, this model applies only in cases where the subject is in an experiment, and knows the expected stimulus waveform. Grabherr et al. (2008) proposed a high pass filter model for direction recognition thresholds based on their recognition data. This thesis explores an alternative modeling approach assuming that the CNS samples the angular velocity estimate and its derivative, and applies thresholds to both. Whether the motion stimulus is detected or not depends on how many of these samples cross the threshold level. The performance of both models was compared against the Grabherr et al. data. It was found that both models are able to approximate the 79.4% detection criterion for thresholds determined in Grabherr's study. However, the two threshold model does not assume that the subject knows the stimulus waveform. Supported by Project SA1302 by the National Space Biomedical Research Institute through NASA NCC 9-58.

Appendix D. Biological Cybernetics Article Abstract

Relationships between Observer and Kalman filter models for human dynamic spatial orientation
by
Pierre Selva and Charles M. Oman

How does the central nervous system (CNS) combine sensory information from semicircular canal, otolith, and visual systems into perceptions of rotation, translation and tilt? Over the past four decades, a variety of input-output ("black box") mathematical models have been proposed to predict human dynamic spatial orientation perception and eye movements. The models have proved useful in vestibular diagnosis, aircraft accident investigation, and flight simulator design. Experimental refinement continues. We review the history of these models, distinguishing two widely known model families, the linear "Kalman Filter" and the nonlinear "Observer." We derive simple 1-D and 3-D examples of each model for vestibular inputs, and show why – despite apparently different structure and assumptions – the models' predictions are dynamically equivalent when model free parameters are adjusted to fit the same empirical data, and perceived head orientation remains near upright. We introduce the idea that the motion disturbance and sensor noise spectra employed in the 1-D Kalman Filter formulation may reflect human perceptual thresholds and prior motion exposure history, and thus justify the interpretation that the CNS cue blending scheme minimizes perceptual errors.

Appendix E. Acronyms

1-D	one-dimensional
3-D	three-dimensional
AFRL	Air Force Research Laboratory
ASEM	*Aviation, Space and Environmental Medicine*
AsMA	Aerospace Medical Association
cm	centimeter(s)
CNS	central nervous system
COTR	contracting officer's technical representative
deg	degree(s)
FAST	Function Allocation Simulation Tool
FORT	frame of reference transformation
g	acceleration due to gravity; 1-g at the Earth's surface
GUI	graphical user interface
HAC	heading alignment circle
HFES	Human Factors and Ergonomics Society
HUD	head-up display
IRB	Institutional Review Board
ISS	International Space Station
MECO	main engine cut-off
MIDAS	Man-Machine Integration Design and Analysis System
MIT	Massachusetts Institute of Technology
MVL	Man Vehicle Lab
NASA	National Aeronautics and Space Administration
NSBRI	National Space Biomedical Research Institute
N-SEEV	attention model (noticing - salience, effort, expectancy, value)
OTTR	otolith tilt-translation reinterpretation
PhD	doctor of philosophy degree
R&D	research and development
SA	sensorimotor adaptation
SCC	semi-circular canal
SD	spatial disorientation
SDAT	Alion's spatial disorientation analysis tool
sec	second(s)
SM	science master's degree
SOAS	Alion's spatial orientation aiding system
TAEM	terminal area energy management
VAC	SDAT's vestibular attitude calculator
VLV	vertical landing vehicle
VMS	NASA Ames' vertical motion simulator