In summary, Systems Effectiveness, as a descriptive title of the disciplines discussed in this paper, appears to be here to stay. Careful consideration of the application of these disciplines, both by Government and contractor, is required in order that effective systems can be delivered economically and timely to the user.

REFERENCES

1. "Let's Put Reliability Testing on a Businesslike Basis", Ira G. Hedrick, Chief Technical Engineer, Grumman Aircraft Company.

2. The Utilization of Human Factors Information by Designers, David Meister and Donald E. Farr, Bunker-Romo Corporation, Technical Report.

MOTION SIMULATION FOR FLIGHT TRAINING

T. R. BRISTOW
Conductron-Missouri

Discussions concerning motion simulation in operational flight trainers generally attempt to evaluate the value of motion simulation in terms of training transfer and the amount of flight time required to bring groups trained without motion to the same performance level as those trained with motion. This paper is part of a study done to develop criteria for developing the range of motion required and the washout rules for braking the motion once it was initiated. This portion was a literature search concerning comparative studies of simulations with and without motion where the goals were not training but were usually oriented to some other goal.

The results of these simulator studies will be briefly listed, with more detailed discussion deferred to a later part of this paper. They are as follows:

1. Motion cues enable the pilot to control an unstable vehicle, whereas without motion, he loses control.
2. Motion cues enhance prompt and instinctively correct control inputs.
3. Re-stabilization of a stable vehicle after a roll-rate disturbance was twice as fast with motion cues as without them.
4. Control is better with both visual and motion cues than with visual cues alone.
5. Roll control in turbulence is very much better if motion cues are present.
6. Motion cues raise the pilot's response frequency.
7. Roll control at low frequencies is many times more accurate with motion cues than without them.
8. In controlling an unstable vehicle, the pilot uses variable control lead in accordance with sensory inputs (visual and motion).
9. Control error at higher frequencies is much less with visual and motion cues than with visual alone.
10. Motion cues are more closely coupled to the pilot than are visual cues.

The essence of these results is that the pilot's behavior in controlling the simulated vehicle is different when motion cues are available than when they are not, and incidentally, that there is interplay between visual and motion sensory inputs. If one can accept this principle, it becomes possible to approach more directly the complex question of the training value added by motion simulation. In a simulator without a motion base, a pilot is deprived of very important cues. Because these motion cues are absent, it becomes necessary for the pilot to rely on a whole new family of cues with respect to attitude and acceleration. He is forced to rely primarily on vision, both inside (IFR) and outside (contact) the cockpit. Because of the absence of kinesthetic cues, the visual task loading is overburdening to the pilot. This overburdening in the visual task area precludes optimum training, and is a non realistic situation, because he is denied an important set of stimuli which in real flight provides him with prompt and positive cues as to unanticipated changes in flight path and attitude, as well as a significant feedback path by which he adjusts and refines his responses. In a no motion simulator, he must make numerous artificial and unrealistic compensations to overcome the loss of motion cues. This situation may overstress the student and inhibit the rapid learning of many related aspects of the complex tasks of piloting an aircraft.

If a flight simulator used for training in flight characteristics and practice in flight control fails to include motion simulation, a pilot will readily perceive that the simulator does not feel or act like the real airplane.

Figure 151 is a block diagram of the pilot controlling an aircraft and receiving information back from the effects of his control inputs through his visual senses and through his kinesthetic senses. The cockpit instrumentation and the outside world supply information to his visual sense to which he responds with control action. The aircraft motions provide the stimulus for his kinesthetic senses, that is his vestibular, proprioceptive, and somatic senses. The pilot has the unique capability of adjusting his response characteristics depending on the type and quality of the information available to him, and as a function of the dynamics of the system he is attempting to control. He can, for example, compromise the information gained through his visual senses and his kinesthetic senses in favor of the visual sense, where the quality of visual information is apparently high. His kinesthetic system, however, is a reflex system as differentiated from his cognitive system and is therefore capable of operating more rapidly, and automatically. Therefore, it can supply control lead to a higher frequency. In developing this concept of the pilot as a systems component, we consider the stimulus response pattern set up in the training environment. That is, the pilot receives stimuli through visual and kinesthetic senses, responds with a control action, and then adjusts his response in accordance with feedback signals through these same senses. This concept is important when the simulated aircraft requirements are considered.

Figure 152 shows the pilot in a training simulator. Again he is considered as the major control element of the machine, the aim of which is to permit the same stimulus-response cycle as it occurs in the aircraft.

The pilot now receives his stimuli visually from an "out the window" display of the outside world and from cockpit instruments driven by a computer rather than by the actual aircraft systems. In order to supply the total set of stimuli available to the pilot in the aircraft, the kinesthetic senses are supplied with stimuli from a motion simulator. Establishing the goal of creating the same stimulus-response pattern in the simulator as in the aircraft, requires that we stimulate the sensory mechanisms so that the pilot adjusts his response accordingly.

By omitting any sensory channel in the simulator, we deny the pilot the corresponding stimuli upon which he acts while also reducing the amount of feedback available by which he adjusts his response. Since this represents a significant psychophysiological variation from the real life environment, there is a risk of negative training transfer and reduced task validity in certain maneuvers for proficiency checking.

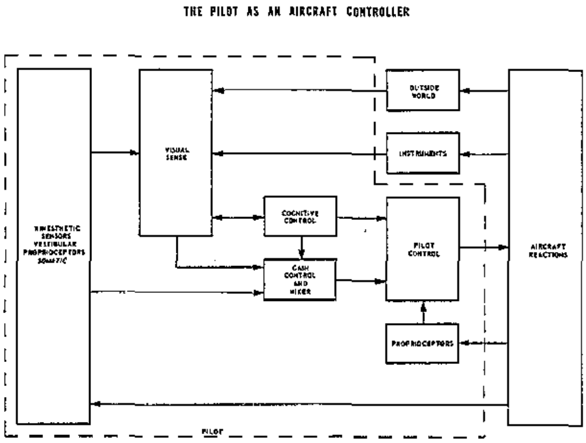

Figure 151.

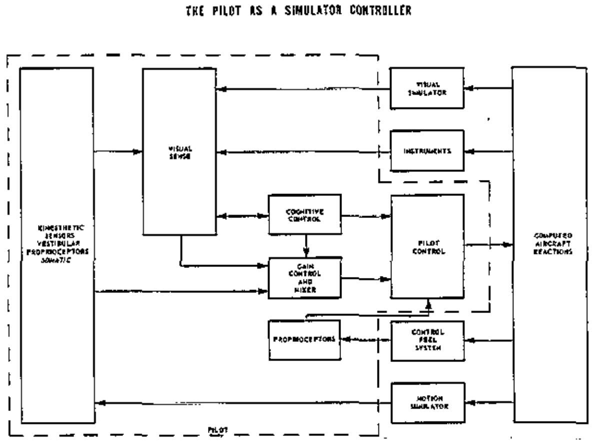

Figure 152.

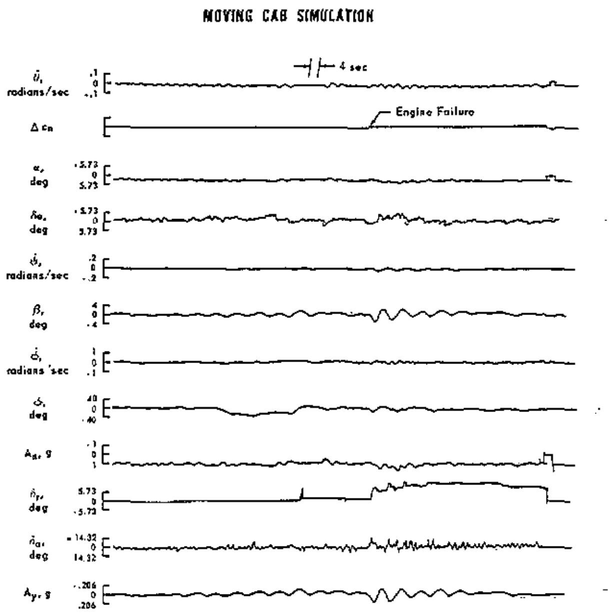

Figure 153.

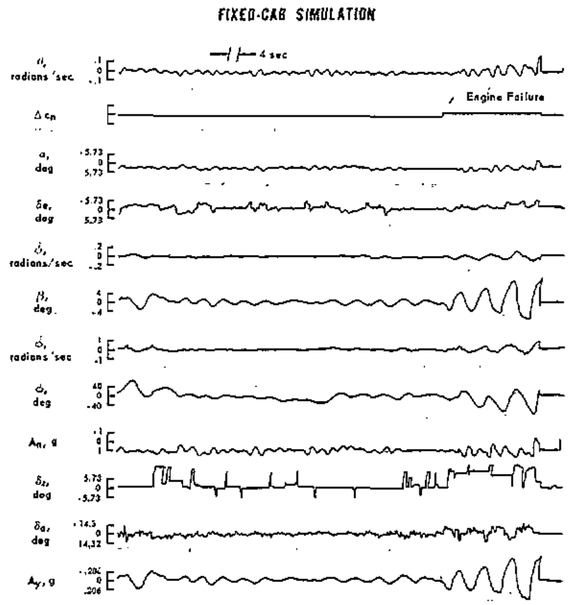

Figure 154.

With this brief background about the pilot and his dynamic interaction with the vehicle, let us examine more closely the results of the experimental work mentioned earlier.

The first of these examines an unstable aircraft simulated on a five degree of freedom motion base.

Figure 153 is a time history of a number of parameters in an SST with inoperative pitch dampers and a simulated engine failure. [1] Note that the elevator trace shows a relatively high frequency, low amplitude movement. The ailerons were handled approximately the same way. The rudder trace is exceptionally clean with very few departures from the straight line; a careful examination of the trace will show that the major rudder input is made within two seconds after the engine failure. The rudder was applied with authority and then minor adjustments were made to choose a final position for the rudder. The aircraft in this particular configuration was unstable but the resulting Dutch roll was controlled and the airplane resumed a stable situation. The purpose of the study was to examine the handling capability of the aircraft in terms of pilot control ability in an emergency situation imposed upon an existing unstable condition.

Now let us look at Figure 154 and examine this same situation with the difference that the pilot does not have motion cues. Note that even prior to the engine cut, the pilot had difficulty in controlling the problem. An examination of the elevator trace shows larger, lower frequency, control movements than were present with motion cues. The aileron trace does not show this effect as radically as the elevator. The most drastic difference is the rudder trace where relatively large inputs are made by the pilot as steps and impulses in both directions. It should also be noted that the rudder response to the engine cut was delayed approximately 3 - 4 seconds in the no-motion case as compared to 1 - 2 seconds with the moving base. The most drastic effect of the lack of motion is the difficulty of overcoming instability due to failed dampers and the total loss of control of the simulated aircraft after the engine failure.

The second item on our list relates to the interaction between motion cues and instrument readings. In the SST simulation, pilots stated that the information required to permit control where such instability exists cannot be gained from the variety of instruments present in the cockpit.

The following quotation from the report of those experiments discloses the pilot's opinion with respect to the effect of motion upon instrument interpretation:

> "Pilots' observations indicated these marked favorable effects of simulator motions were due to two factors. One was that the motions directed the pilot's attention immediately to the critical motion and to the appropriate instrument. The other was that motion cues enable the pilots to react promptly and instinctively to apply appropriate control inputs" [1]

Other experiments, informal and unpublished, indicate that the time for a pilot to apply corrective rudder in the case of a failed engine on a simulated airliner is less by 50% with motion cues added, than it is with instrument indications alone.

Item 3 demonstrates that motion also improves control of a stable aircraft. This was a blind landing simulation study of a Caravelle aircraft in a landing configuration, done at M.I.T. [2] Figure 155 shows the time required for re-stabilization of the aircraft after the introduction of roll disturbances. Note that in the fixed base simulator, approximately 12 - 16 seconds are required to restabilize the aircraft. With the motion base, an average of only 8 seconds was required to accomplish the same task. Here again it is seen that motion enhances the pilot's ability to control the aircraft, not simply as an alerting function, but as a fundamental continuing contribution.

MEDIAN ROLL-RESPONSE TIME TO STEP ROLL-RATE DISTURBANCE IN SIMULATED LANDING.

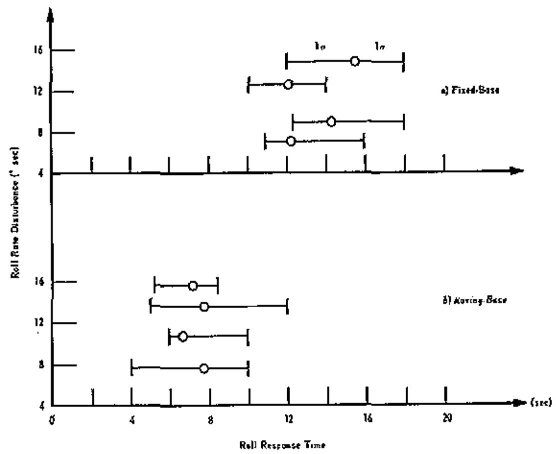

Figure 155.

CONTROL OF AIRCRAFT RESPONSE TO A STEP SIDE GUST WITH DIFFERENT SIMULATION CUES

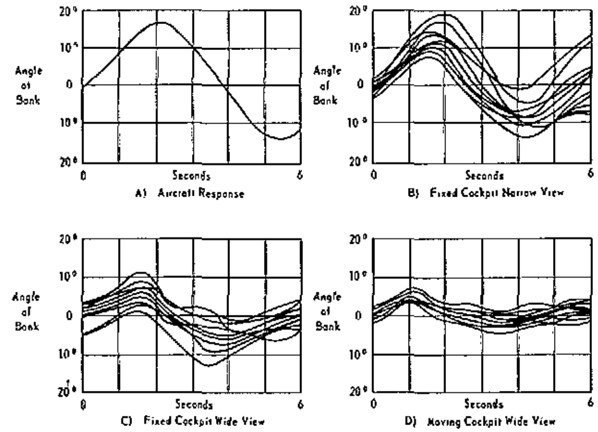

Figure 156.

EFFECT OF COCKPIT MOVEMENT ON CONTROL IN TURBULENCE

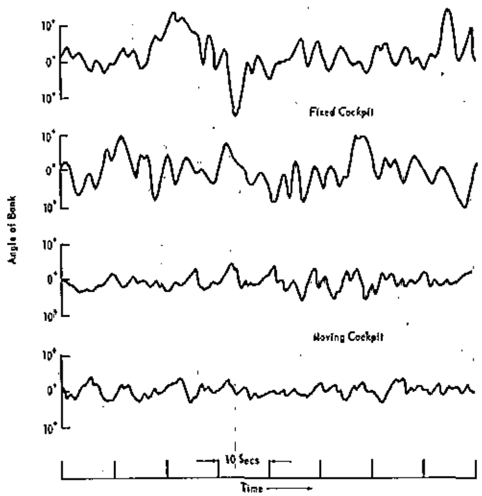

Figure 157.

ANALYSIS OF CONTROL ANGLES IN FIXED AND MOVING SIMULATION

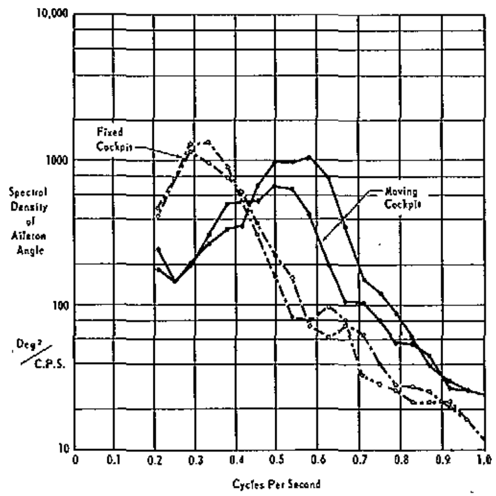

Figure 158.

ANALYSIS OF BANK ANGLES IN FIXED AND MOVING SIMULATION

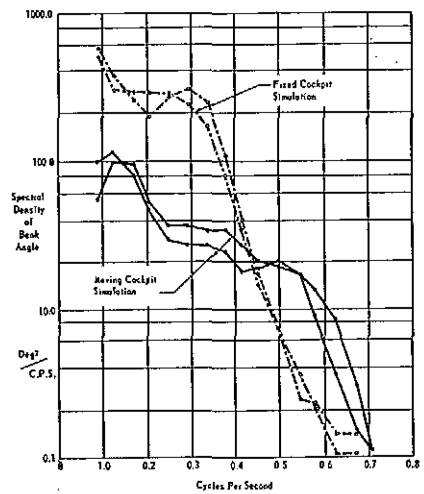

Figure 159.

Item 4, a contribution of the Royal Aeronautical Society in England, [5] demonstrates the interdependence of motion cues and outside visual scenes, both wide and narrow, in controlling the simulated aircraft in a side gust.

The upper left hand graph of Figure 156 presents the response of the aircraft when the pilot takes absolutely no corrective action. The period of the aircraft is roughly 8 seconds. When the pilot attempted to control the aircraft in response to this gust input, with visual cues from a narrow angle visual system, the control inputs sometimes made the situation actually worse than no control whatsoever. The lower left hand curves show that the response was slightly better with the wide angle visual system and no motion. Note that in the lower right hand graph, both the amplitude of the cockpit deviation and the spread from pilot to pilot was dramatically narrowed. In addition to this, the peak deviation occurs sooner, from approximately a second and a half in the case of visual only to a point of one second in the presence of motion and visual. The test indicated that measured time lags for the pilot response were reduced from 17 seconds to .4 seconds in the presence of the motion cues.

Item 5 pertains to aircraft control in turbulence. In Figure 157, the plots [5] show the sampling of time histories of bank angle in the presence of rough air with both the fixed cockpit simulation and the moving cockpit simulation. The importnat thing to note here, as in the case of the SST, is that the basic frequencies involved in the time history are lower and the deviations are larger on the fixed base simulation than on the motion base simulation. Said another way, the pilot's reactions are slower and less accurate in the absence of motion cues.

Items 6 and 7 relate to the frequency response of the pilot, and we see why motion cueing produces some important improvement in the pilot's ability to cope with varying dynamic situations. Figures 158 and 159 are spectral analyses of time history curves in Figures 156 and 157. In Figure 158, the pilot in a fixed cockpit appears as a bank pass filter with the center frequency of his control at approximately .3 cycles per second. With a motion base, his center frequency is between .5 and .6 cycles per second, approximately one octave improvement. This is an indication that a definite quantitative difference can be measured in the pilot't control technique, with and without motion cueing. Note that this cueing phenomenon is a continuous one, not merely an alerting process in which the pilot is reminded to refer to his instrumentation for more specific information. The succession of motion cues makes him more aware of the requirements for control inputs and also more aware of the consequences of his control inputs. He therefore responds more rapidly, acts with more authority and accomplishes a more precise maneuver with motion than without.

Figure 159 shows that, in addition to increasing the pilot's response frequency as in Figure 158, motion cueing improves his control accuracy at very low frequencies by a very considerable amount.

Items 8 and 9, results of a study at M.I.T.[6], supplied some quantitative data. The human controller in a dynamic situation applies variable lead compensation as a function of the sensory channels available to him, and the relative difficulty of the control task. In this case, the task was to control a basically unstable inverted pendulum under three circumstances; visual cues alone, motion cues alone, and with combined visual and motion cues. Figure 160 shows the quantitative results of this study.

Note that man's ability to control the dynamic situation visually, rapidly deteriorated as the natural frequency of the system was increased beyond 1 - 1½ radians per second. Note that the same control problem, handled with motion cues alone, allowed man to extend the controlled frequency range significantly past that which he could handle visually. With both the motion system and visual references, the error was reduced further because of the operator's ability to handle the dynamics problem and then adjust the system more precisely to the visual references. The basic equipment, in this experiment, was a cockpit-like structure driven in roll through a control stick. For the visual task, the operator was seated behind the cockpit and asked to hold the cockpit vertical in the presence of a reference mark. For the motion only task, the operator was seated in the cockpit with neither visual reference nor instrumentation. In the case of the combined system, the man was in the cab and the room was lighted so that he could use the room as a visual reference. As can be seen, this type of visual system is a relatively idealized situation much more closely coupled to the problem than an outside visual scene would be in the aircraft, and much more sensitive than an instrument which might be present in the cockpit. It should also be noted that this was a single task problem, indicating that these results are probably near the upper limit of man's capability in visual control. It is anticipated that in a multimode control task with less ideal references, man's frequency response capability would be significantly less.

Item 10 is one explanation of why the visual sense is less dependable and slower in determining motion than the motion senses themselves. This is because the visual scene, whether of cockpit instruments or an outside view, is loosely coupled to the pilot, whereas motions sensed kinesthetically act quickly and directly upon his body.

The sketches of Figure 161 illustrate two cases of the changing viewpoint and the mechanism through which we sense motion in this environment. On the right is an illustration of the sensation of motion looking perpendicular to the direction of movement. In this particular example, the subject is concentrating on a point F some distance out in the visual field while moving to the left. Note that all points closer to the subject than the point of interest move in the same direction as the observer. The illustration on the left is intended to illustrate a concept of flow where the observer is moving in the direction he is looking, as on the glideslope at some distance from the ground. In this particular case, a person's velocity sense is dependent very strongly on the proximity of a visual reference. This is basically an angular phenomena, so that the magnitude of the effect is dependent on the rate at which points depart from their instantaneous position. This means that in the air the visual scene is loosely coupled to the pilot, and the consequences of any control action taken by the pilot requires a significant time period to become apparent.

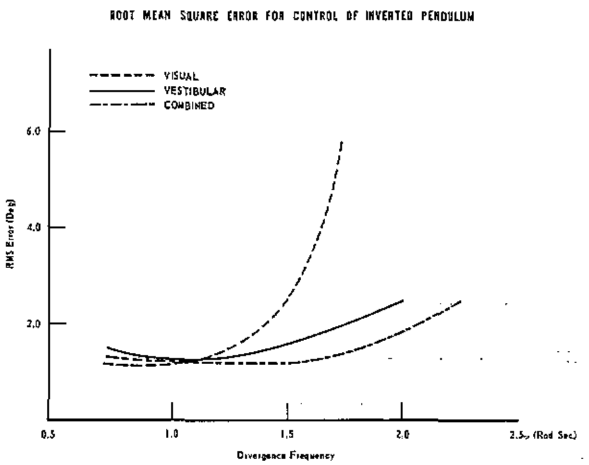

Figure 160.

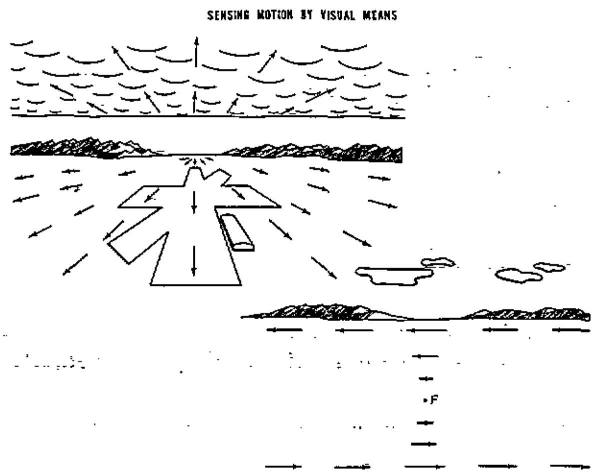

Figure 161.

CONCLUSION

These experiments, while not proving conclusively the value of motion simulation in flight training simulation, do present objective and measured results. More significantly, they point out some striking differences in man's control behavior as a function of whether motion is present or not. Since man's ability to act as an element in a control loop appears to be greatly influenced by motion cues, I think the question of overstressing the student in the absence of motion, thus inhibiting his ability to learn, should be considered rather than simply trying to determine if training without motion transfers.

BIBLIOGRAPHY

1. M. Sadof and C. W. Harper - NASA Ames "A Critical Review of Piloted Flight Simulator Research" 1962
2. L. R. Young - M.I.T. "Some Effects of Motion Cues on Manual Tracking" J. Spacecraft Oct. 1967
3. J. Douvillier, H. Turner, J. McLean, D. Heinle "Effects of Flight Simulator Motion on Pilots' Performance of Tracking Tasks" pg. 13 NASA TN D143 1960
4. J. Ruocco, P. Vitale, R. Benfari "Kinetic Cueing in Simulated Carrier Landings" pg. 75 NAVTRADEVCEN 1432-1 1965
5. D. H. Perry, J. M. Naish "Flight Simulation for Research" J. Royal Aero. Soc. Oct. 1964
6. L. R. Young and J. L. Meiry - M.I.T. "Manual Control of Unstable System with Visual and Motion Cues"
7. "The Perception of the Visual World" - J. J. Gibson - Houghton Mifflin 1950
8. B. Clark and J. D. Stewart "Perception of Angular Acceleration About Yaw Axis of Flight Simulator" Aerospace Med. Dec. 1962
9. Bioastronautics Data Book NASA - SP - 3006
10. B. Clark and J. D. Stewart "Magnitude Estimates of Rotational Velocity During and Following Prolonged Increasing, Constant and Zero Angular Acceleration" NASA Ames
11. J. L. Meiry "The Vestibular System and Human Dynamic Space Orientation" - M.I.T. Thesis - 1965
12. "Biotechnology" L. G. Fogel page 150
13. F. M. Henry "Dynamic Kinesthetic Perception and Adjustment" Univ. of Calif. - Research Quarterly