MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEMI ANNUAL STATUS REPORT

INTEGRATION OF VISUAL AND MOTION CUES
FOR SIMULATOR REQUIREMENTS AND RIDE QUALITY
INVESTIGATION

NGR 22-009-701

December 1975 - June 1976

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Principal Investigator

Laurence R. Young

INTRODUCTION

The research covered by this grant is aimed at the development of practical tools which can extend the state of the art of moving base flight simulation for research and training. There are two main approaches to this research effort reported on in this progress summary:

(1) Application of the vestibular model for perception of orientation based on motion cues: optimum simulator motion controls

(2) Visual cues in landing.

Very significant progress has been made with respect to the first goal, including the completion of a Master's thesis on this subject by Mr. Joshua Borah. Experiments are underway on the second portion after initial pilot experiments which were performed during this reporting period.

In addition to the M.S. thesis, we have one paper in press and another which has been submitted for publication. These papers are appended to this progress report.

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

Application of the Ormsby Vestibular Model to Motion Requirements for a Coordinated Turn in the LINK Trainer

1 Introduction

It is often desirable to simulate the sensations of riding in or operating some vehicle without using the vehicle itself. Usually the device used for the simulation is much more tightly constrained than the actual vehicle. The most important example is probably that of aircraft simulation. Whether training a pilot, evaluating handling characteristics of a new aircraft, or trying out new instrument displays, it is preferable to make initial tests without endangering a pilot or an aircraft.

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

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The motion parameters available to a person for use in sensing motion are basically specific force and angular acceleration. These quantities can influence tactile sensors at points of body contact with the vehicle, proprioceptive sensors when muscles are stretched or compressed, and the small inertial mechanism in the inner ear known as the vestibular system. In a simulator, it is not possible to duplicate all the specific force and angular acceleration profiles attainable by the real aircraft. Often different degrees and combinations of these vectors can be generated, sometimes one to the exclusion of the other. For instance, it may be possible to duplicate the proper specific force direction only at the expense of improper angular acceleration and vice versa. A whole range of combinations varying between these extremes is usually possible. It is not always obvious which strategy will do the best job of making people feel as though they are in the real aircraft.

Very sophisticated washout designs have been developed, especially since real time digital processing has become feasible. Complex networks have been developed for coordinating attitude and translational acceleration to obtain the desired specific force direction without exceeding simulator constraints. The art has been extended by the use of non-linear adaptive filtering to present as much of a motion cue as possible.

Although physiological thresholds and sensitive frequencies are considered and are used in "tuning" these circuits, the basic attempt is still to minimize error in specific force and angular acceleration presentation. This has been the logical thing to do because these

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

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

This discussion has so far considered only the use of real motion to produce the feeling of movement. This feeling is also influenced by movement of the visual field. It seems that the peripheral visual field is especially important in creating motion sensations, and can also effect the perception of spatial orientation. Almost everybody has, at one time or another, experienced the illusion of moving by another train in a railroad car only to discover themselves at rest and the other train really the one in motion. The same illusion can be created with a field of dots for example, which move by as though the person is passing through a tunnel with dotted walls. This phenomenon is called linearvection. If the dot pattern moves in a circular fashion, as though the person were rotating inside a cylinder with dotted walls, a powerful illusion of rotational motion can be induced. This is called circularvection. If the circularvection is about a horizontal axis,

it may also induce a feeling of tilt with respect to the vertical.

These effects can be produced with many different visual patterns and by using only the peripheral portion of the visual field. An implication for aircraft simulation is that a relatively simple moving display on the cockpit side windows may help create the desired sensations of motion.

2 Analysis of a Coordinated Turn Simulation

In aircraft parlance, "coordinated" flight means that the specific force vector remains vertical with respect to the cockpit. When this is accomplished, the pilot and passengers feel no side forces, only a force of varying magnitude pushing them straight into their seats. Most pilots, especially airline pilots, always attempt to maintain coordination since their passengers are most likely to feel comfortable under these conditions.

We have attempted to simulate a coordinated turn in a three degree of freedom Link GAT-1 trainer using the Ormsby model of Human Dynamic Orientation to predict the non-visually induced sensations of a passenger during the maneuver. The model has been adapted to provide a gauge of simulation fidelity by using a simple, intuitively logical scheme for assigning penalties to incorrect perceptions. Incorrect perception is defined as any difference between perception in the simulator and in the aircraft. This penalty or cost index analysis is then used to choose a motion profile for the Link that is most likely the optimal simulation for a particular turn.

For use in the physiological model and experiments, a specific coordinated turn profile was needed. Most convenient for this work, is an idealized profile that is as simple as possible while retaining the basic elements that make coordination difficult to simulate. This is true for two reasons. The most compelling is that the only way to get a completely realistic profile is to record aircraft motions (attitude and accelerations) as a pilot flies the maneuver, and such material is not readily available. The second reason is that no two pilots will roll in and out of coordinated turns with exactly the same profile, and a single pilot will probably never fly the same profile twice. It can therefore be argued that more generalized conclusions can be drawn by studying the idealized situation.

The most important thing to note about a coordinated turn, however, is that the specific force vector rolls with the cockpit and increases in length. It may deviate slightly from cockpit vertical now and again, but to an observer in the craft it does not indicate cockpit roll angle or roll rate. In a three degree of freedom device, with only pitch, roll, and yaw motion available, it is not possible to create this situation. Even in a multi-degree-of-freedom simulator, with lateral motion capability, it is not possible to sustain a roll angle very long without allowing the specific force to realign with earth vertical. It is this aspect of the turn that should be emphasized in the idealized version to be analysed with the physiological model.

The basic parameters chosen for the idealized turn are a 30 degree bank, 85 knot, constant altitude coordinated turn, maintaining airspeed during roll-in and roll-out. This will yield a turn rate of about 7 degrees per second, considerably faster than the standard 3 degree per second turn. It is, however, by no means unreasonable and the steep bank angle will emphasize the effects of coordination. A typical roll rate in a small plane is about 10 degrees per second. The roll profile used here is shown in Figure 1 and is essentially a constant roll rate during roll in and out with tenth second ramps leading to and from the constant value. There is no doubt that a real pilot does not maintain a constant rate, but probably increases to a maximum and decreases back to zero in a more or less smooth curve. Without actually measuring this in a real situation, however, there is no way of telling whether a typical profile is more closely fit by a square wave, a trapezoid, a triangle, etc. The profile shown was chosen as the simplest. The yaw rate profile is also shown in the figure. Since, the pitch angle change in such a maneuver is very small and since a one degree change in pitch is below the resolution of the psychophysical estimates obtained for this work, the small pitch adjustment will be ignored during this simulation.

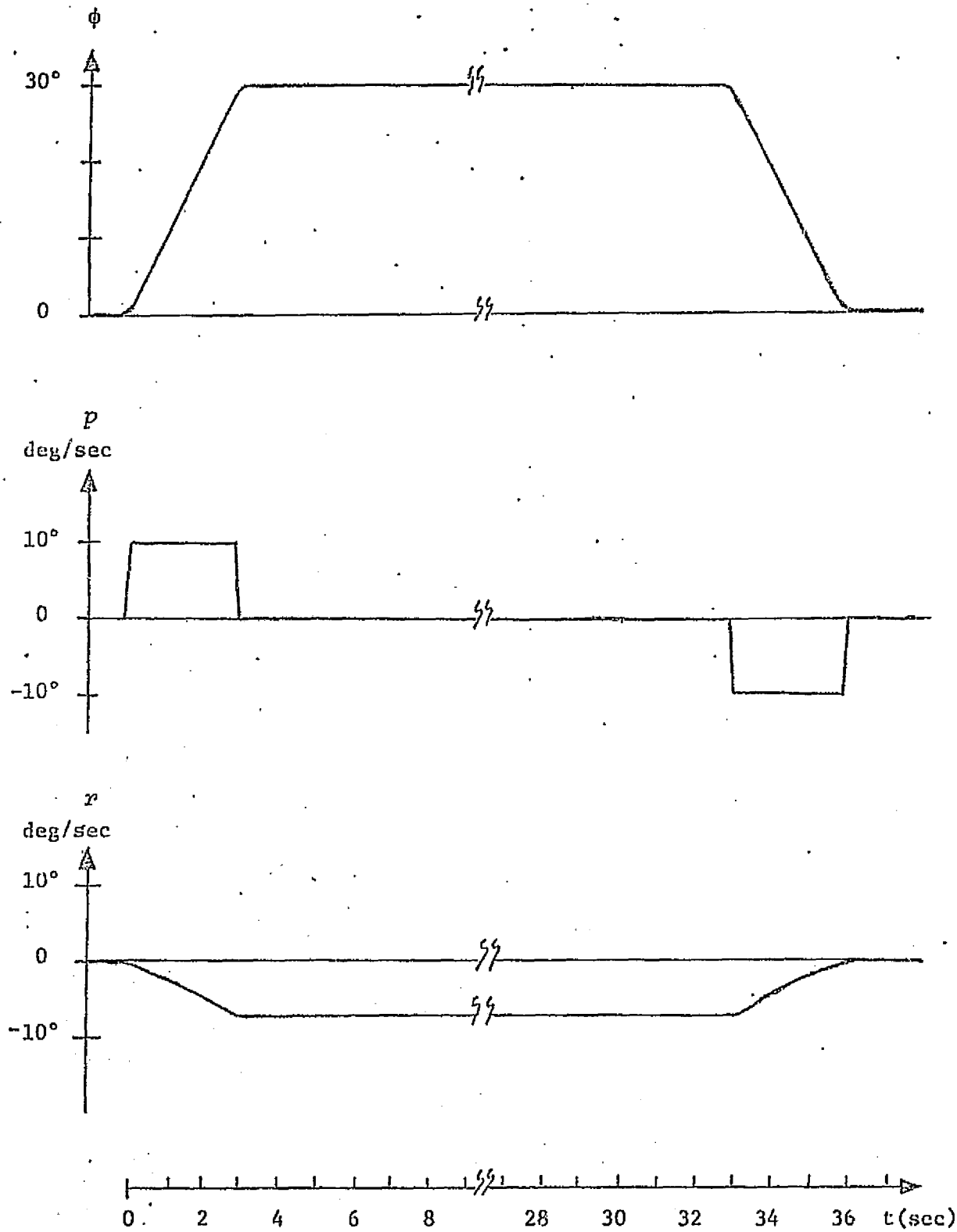

Figure 1 Idealized coordinated turn profile

3 Ormsby Model of Human Dynamic Orientation

A model for predicting perceptual responses to motion stimuli has been developed at the MIT Man-Vehicle Laboratory by Charles Ormsby. The model is based on the known mechanics of the vestibular organs. It assumes an optimal processing strategy by higher centers to obtain estimates of attitude and motion and was designed to be consistent with available neurophysiological and psychophysical data. Since much of this data is derived from experiments which necessarily include tactile and proprioceptive motion cues, it can be argued that the model is tuned to account for some of these cues. It must be regarded, however, as primarily a vestibular information and information processing model.

The vestibular system is composed of two types of sensors. The rotational motion sensor is a set of three roughly orthogonal toroids or circular canals. The canals are fluid filled and completely obstructed in one section by a gelatinous mass called the cupula. Imbedded in the cupula are hair cells which can respond to deformation in one sensitive direction. When a canal is accelerated about its axis of symmetry, the endolymph fluid lags behind the canal walls and applies a force to the cupula. The resulting deformation is transformed to an afferent firing rate and signals a rotational motion. A set of these organs, called semicircular canals, are contained in the membranous ducts within bony fluid filled labyrinths on either side of the head, behind the auditory portion of the ear.

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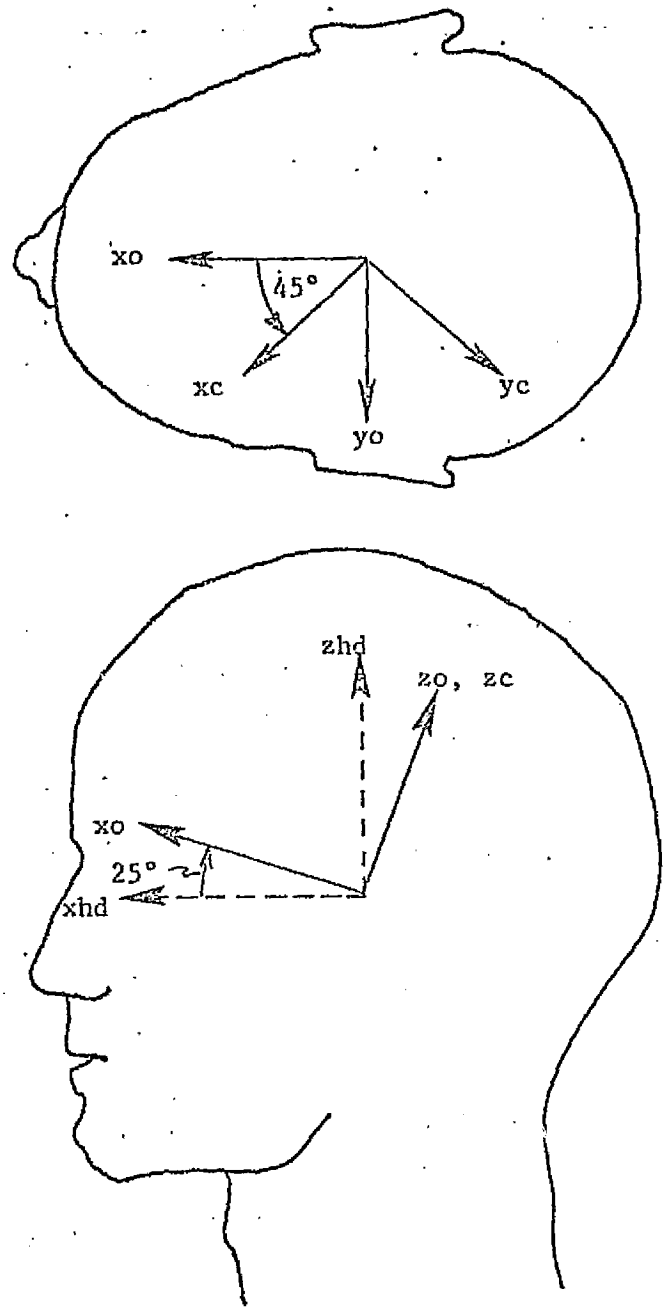
The other type of sensor, responsible for detection of specific force, is a gelatinous mass containing calcium carbonate crystals (otoconia) and supported by a bed or hair cells (maculae). This stucture is also immersed in a fluid, but since the otoconia are denser than the fluid, a chnage in specific force will cause them to move relative to the labyrinth, thus deforming the supporting hair cells. On each side of the head, occupying the same labyrinthine structure as the canals, are two such organs: the utricular and saccular otoliths. The utricular sac actually serves as both the housing for the utricular otolith and the base reservoir of the three canals.

Each canal is excited (afferents increase their firing rate over resting levels) by angular acceleration in one direction along its sensitive axis, and is asymmetrically inhibited by rotation in the opposite direction. Since the two canal sets behave with opposite polarities, a sort of push-pull system is created yielding a roughly symmetric combined response. The utricular macula contains hair cells of all orientations and is sensitive in all directions parallel to its plane. The saccule is predominantly sensitive in the direction perpendicular to the average utricular pl .

For modelling purposes, the system is simplified to one cyclopian system consisting of three canal and three otolith organs. All organs are modelled as responding symmetrically along their sensitive axes which are shown in the next two figures. These axes will be referred to as otolith and canal sensor coordinates. The



Canal coordinates ≡ (xc, yc, zc)

Otolith coordinates ≡ (xo, yo, zo)

Figure 2 Cyclopian sensor coordinates

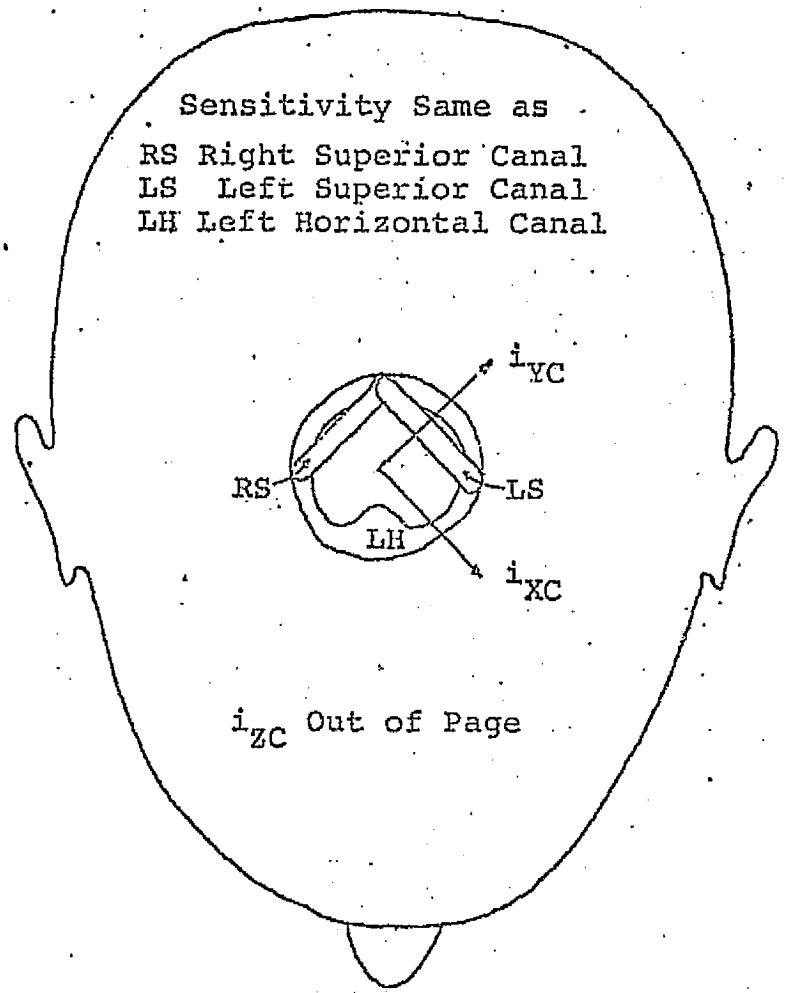


Figure 3 Sensitivity of cyclopian canal system

response of each canal along its sensitive axis is modelled as a highly overdamped torsion pendulum, with an added rate sensitivity and adaptation term presumably due to afferent processing. Although actually an angular acceleration sensor, the excess damping quality causes a response that is proportional to angular velocity for high frequencies. Indeed, the system seems to interpret canal responses as angular velocity. The model assumes, for each canal, the following transfer function for afferent response to angular acceleration.

$$\frac{FR_{cs}(s)}{\omega(s)} = (573)\underbrace{\frac{s}{(18s+1)(0.005s+1)}}_{\text{torsion pendulum}}\ \underbrace{\frac{30s}{(30s+1)}}_{\text{adaptation}}\ \underbrace{(0.01s+1)}_{\text{rate sensitivity}}$$

$FR_{cs}(s)$ = canal afferent firing rate

$\omega(s)$ = angular velocity along sensitive axis

(spontaneous firing rate neglected)

The otoliths are modelled as linear accelerometers with an added rate sensitivity term due either to mechanical properties or possibly afferent processing. The afferent dynamic response to specific force is taken as follows:

$$\frac{FR_{os}(s)}{SF(s)} = (18000)\ \underbrace{\frac{1}{(s + 0.2)(s + 200)}}_{\text{accelerometer}}\ \underbrace{(s + 0.1)}_{\text{rate sensitivity}}$$

$FR_{os}(s)$ = otolith afferent firing rate

$SF(s)$ = specific force along sensitive axis

Inputs to the Ormsby model are time histories of specific force and angular velocity vectors given in head coordinates ($\underline{SF}_{hd}(t)$ and $\underline{\omega}_{hd}(t)$). The first step in implementing the model is the transformation of these inputs to sensor coordinate axes. It is then assumed that these afferent responses are the signals available to the human nervous system processing mechanism. From this point on the model becomes very phenomenological since we do not yet approach a capability to deduce central processing algorithms from central nervous system wiring. It is assumed that central processors do something akin to a least mean squares error optimization to estimate specific force and angular velocity inputs based on afferent output. If the system has no *a priori* information about input besides an expected magnitude range and frequency bandwidth (mathematically described as a Markov process), and also expects a certain amount of measurement noise, the least mean squared error estimator is a Kalman filter. If input and measurement noise statistics are time invariant, this reduces to a steady state Kalman (or Wiener) filter. It is a steady state Kalman filter that is implemented by the model and tuned to yield $\hat{\underline{SF}}_{0s}$ and $\hat{\underline{\omega}}_{cs}$ estimates to fit available data (the hat above the two terms signifies that they are perceptual estimates and the subscripts identify them as otolith and canal estimates respectively).

In th case of the canals, the filter is "tuned" so that estimates of $\hat{\underline{\omega}}_{cs}$ are essentially the same as afferent responses. This reflects available perceptual and neurophysiological data, and suggests that little central processing is required. The otolith filters, however,

have a more dramatic effect on specific force estimates in order to fit perceptual data. This suggests either a significant amount of central processing or that a term which should be present in the afferent model is being attributed to the higher centers. The basic effect of the otolith Kalman estimator is to low pass filter the afferent signal with a time constant of about 0.7 seconds. The only difference between utricle and saccule filters is the gain, the saccule gain being half that of the utricle.

At this point, the model has generated estimates of three specific force components and three angular velocity components. The saccule component is transformed by a nonlinear input-output function, one way to account for observed attitude perception inaccuracies, and the resulting estimates are transformed back to head coordinates. These two vectors ($\underline{\hat{SF}}_{hd}(t)$ and $\underline{\hat{\omega}}_{hd}(t)$) must now be combined to yield an overall estimate of attitude, linear acceleration and angular acceleration.

The basic premise for the next operation is that the system will depend most heavily on the otolith specific force estimate for low frequency attitude information, and will look to the canals to find out about high frequency attitude changes. The following figure diagrams this logic. Block A computes the rotation rate of $\underline{\hat{SF}}_{hd}$. Block D separates $\underline{\hat{\omega}}_{hd}$ into parts agreeing with $\underline{\hat{\omega}}^{H}_{SF}$ (called $\underline{\hat{\omega}}^{c}_{c}$) and parts contradicting $\underline{\hat{\omega}}^{H}_{SF}$ (called $\underline{\hat{\omega}}^{i}_{c}$). All other operations are clear from the diagram. The output of this system is called $\underline{\hat{DOWN}}$ and is a vector of lenght 1 g, in the direction of perceived vertical. The $\underline{\hat{DOWN}}$ vector is the model's prediction of attitude perception. Linear acceleration perception is assumed to be

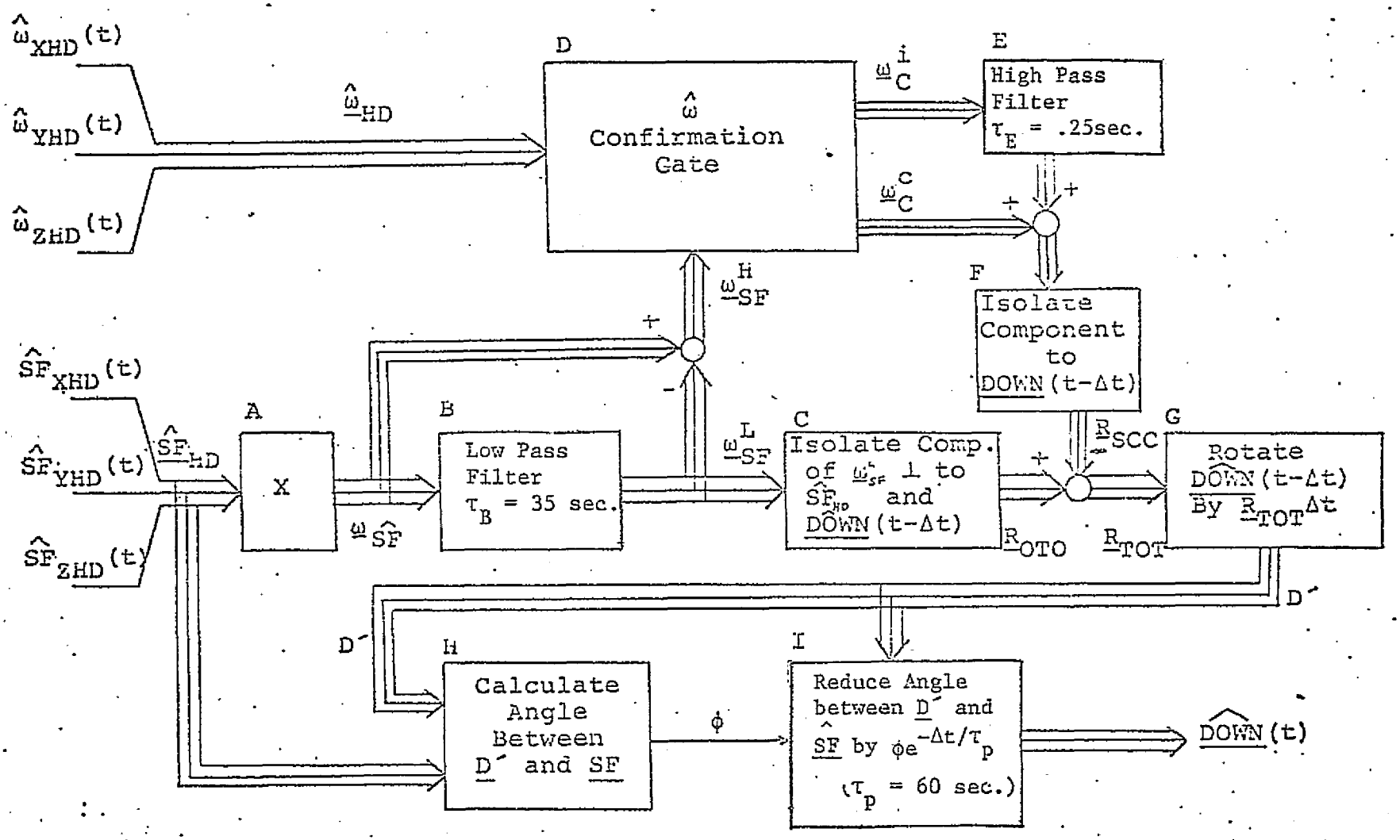


Figure 4 $\hat{DOWN}$ Estimator

$$\underline{\hat{DOWN}} - \underline{\hat{SF}}_{hd}$$

Perception of angular velocity parallel to $\underline{\hat{DOWN}}$ is simply the component of the canal estimate parallel to $\underline{\hat{DOWN}}$. Angular velocity perpendicular to $\underline{\hat{DOWN}}$ is the derivative of $\underline{\hat{DOWN}}$ ($\underline{\dot{D}}$) plus the high pass portion of any canal signal both perpendicular to $\underline{\hat{DOWN}}$ and not present in $\underline{\dot{D}}$. This is diagrammed in the figure 5, while the following figure (6) schematically summarizes the entire model.

It should be pointed out that the preceding description applies only to the model as used in this analysis. It should also be noted that the inputs $\underline{SF}$ and $\underline{\omega}$ must act on the body as a whole and derive from an outside source. Voluntary head movements are likely to involve corollary discharge of one sort or another, possibly to vestibular organs themselves, and certainly to central processors telling them what to expect. This constitutes a different situation.

The model is used in the form of a digital Fortran IV program. In the version used here, afferent responses are updated every 0.1 seconds and Kalman filter estimates are updated every second.

4 Model Predictions for the Coordinated Turn

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

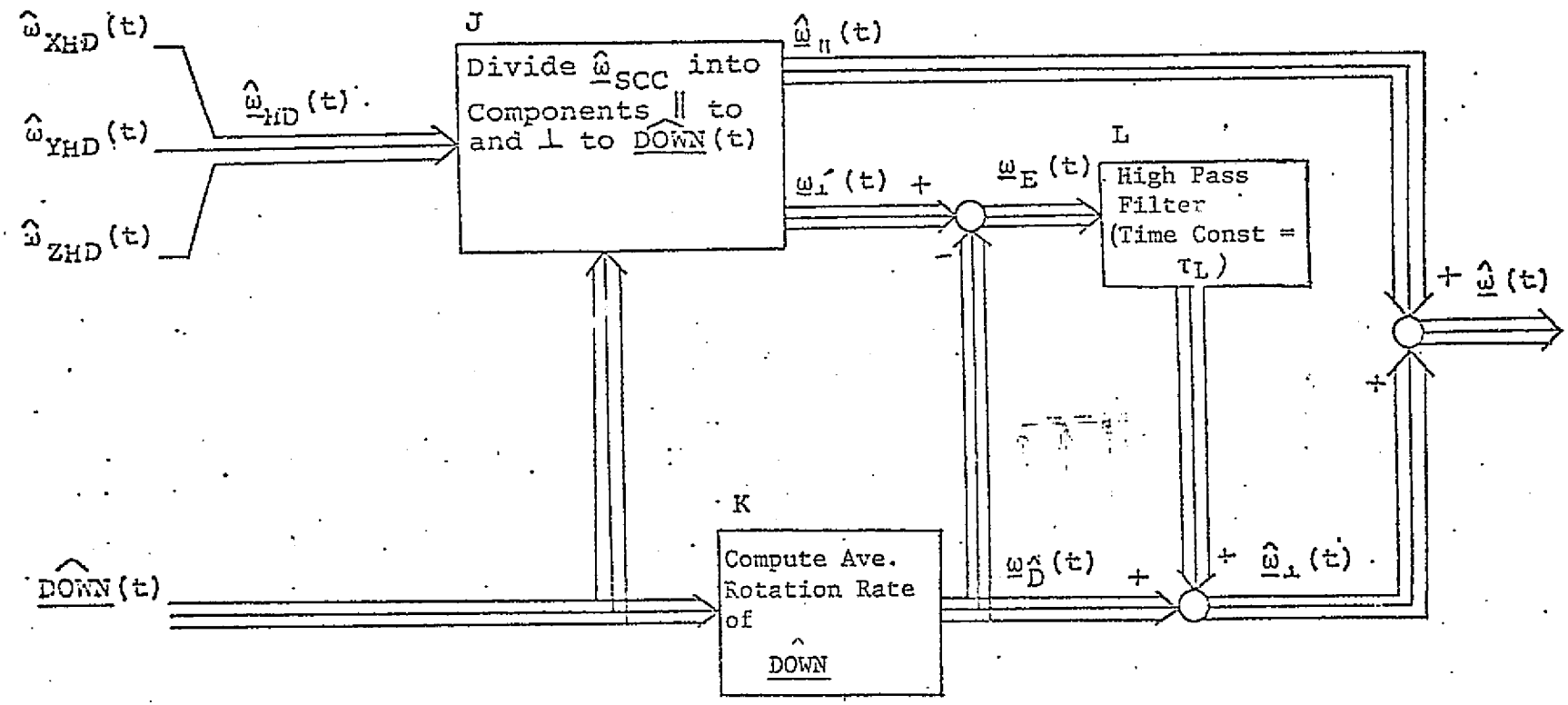

$\hat{\omega}_{XHD}(t)$
$\hat{\omega}_{YHD}(t)$
$\hat{\omega}_{ZHD}(t)$
$\hat{\underline{\omega}}_{HD}(t)$
J
Divide $\hat{\underline{\omega}}_{SCC}$ into Components $\parallel$ to and $\perp$ to $\widehat{\underline{DOWN}}(t)$
$\hat{\underline{\omega}}_{\parallel}(t)$
$\underline{\omega}_{\perp}'(t)$
+
−
$\underline{\omega}_E(t)$
L
High Pass Filter (Time Const = τ_L)
+ $\hat{\underline{\omega}}(t)$
+
$\widehat{\underline{DOWN}}(t)$
K
Compute Ave. Rotation Rate of $\hat{\underline{DOWN}}$
$\underline{\omega}_{\hat{D}}(t)$
+
+ $\hat{\underline{\omega}}_{\perp}(t)$

Figure 5

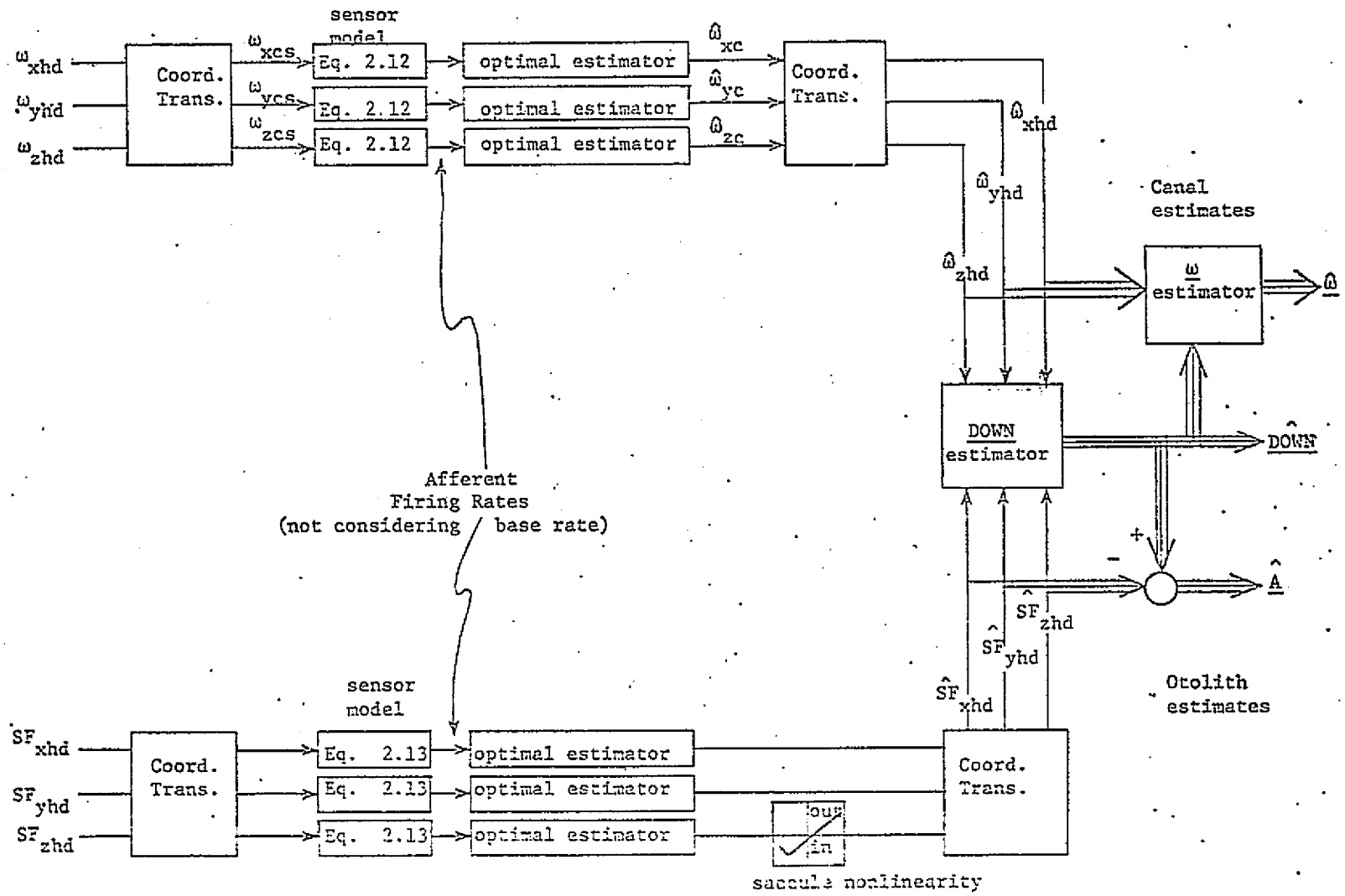


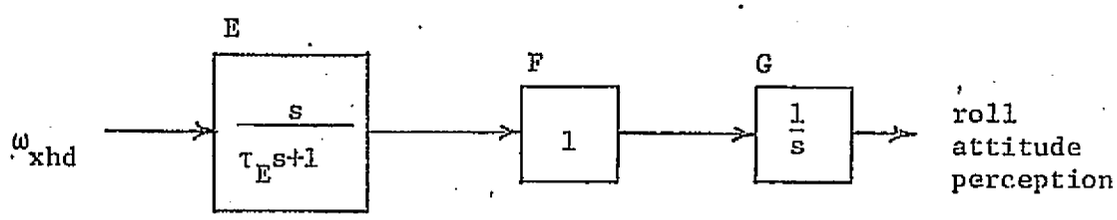
Figure 6 Schematic of Ormsby model.

attitude. Canals, on the other hand, are sensitive to the angular velocity produced by roll-in. Looking at figure 4, it can easily be seen that the only non-zero signal travels the upper loop through blocks D, E, and F.

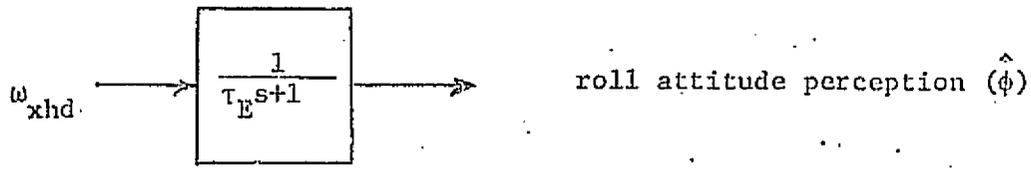
A quick idea of what to expect can be obtained by reducing the model to blocks E, F, and G of figure 4. This is shown in figure 7. Blocks H and I are dropped since they will only come into play if integration errors accumulate. Over the three seconds of roll-in, the equation for afferent response to angular acceleration will yield a response that is roughly proportional to the input. Figure 7, then, leads us to expect a roll attitude perception that looks very much like the roll rate stimulus profile.

Although the specific force vector has not been rotated, it has elongated and therefore brings into play the saccule non-linearity mentioned before. The expected result is an "elevator illusion" of being tilted backwards. Figure 8 shows the actual prediction of the computer model for the roll and pitch attitude perception during the roll-in phase of the idealized coordinated turn.

Now we must consider the perception of angular rate. If τ_L in figure 5 is 0, it can be seen that roll rate perception is just the derivative of roll attitude. If, on the other hand, τ_L is large, figure 5 says the system will "trust" the canals and will perceive a roll rate that more nearly follows the roll velocity stimulus. Note that this roll rate perception will be inconsistent with the roll attitude perception shown in figure 8. They hypothetical person



Further reduces to:



($\tau_E \simeq 0.25$ seconds)

Figure 7 $\hat{\underline{\text{DOWN}}}$ estimator reduced to approximate roll attitude during coordinated turn. Block G has been simplified to keep track of $\hat{\phi}$ instead of rotating the $\hat{\underline{\text{DOWN}}}$ vector. Block F is unity because there is only one component $\omega^i_{c_{xhd}}$ which in this case is approximately perpendicular to $\hat{\underline{\text{DOWN}}}$.

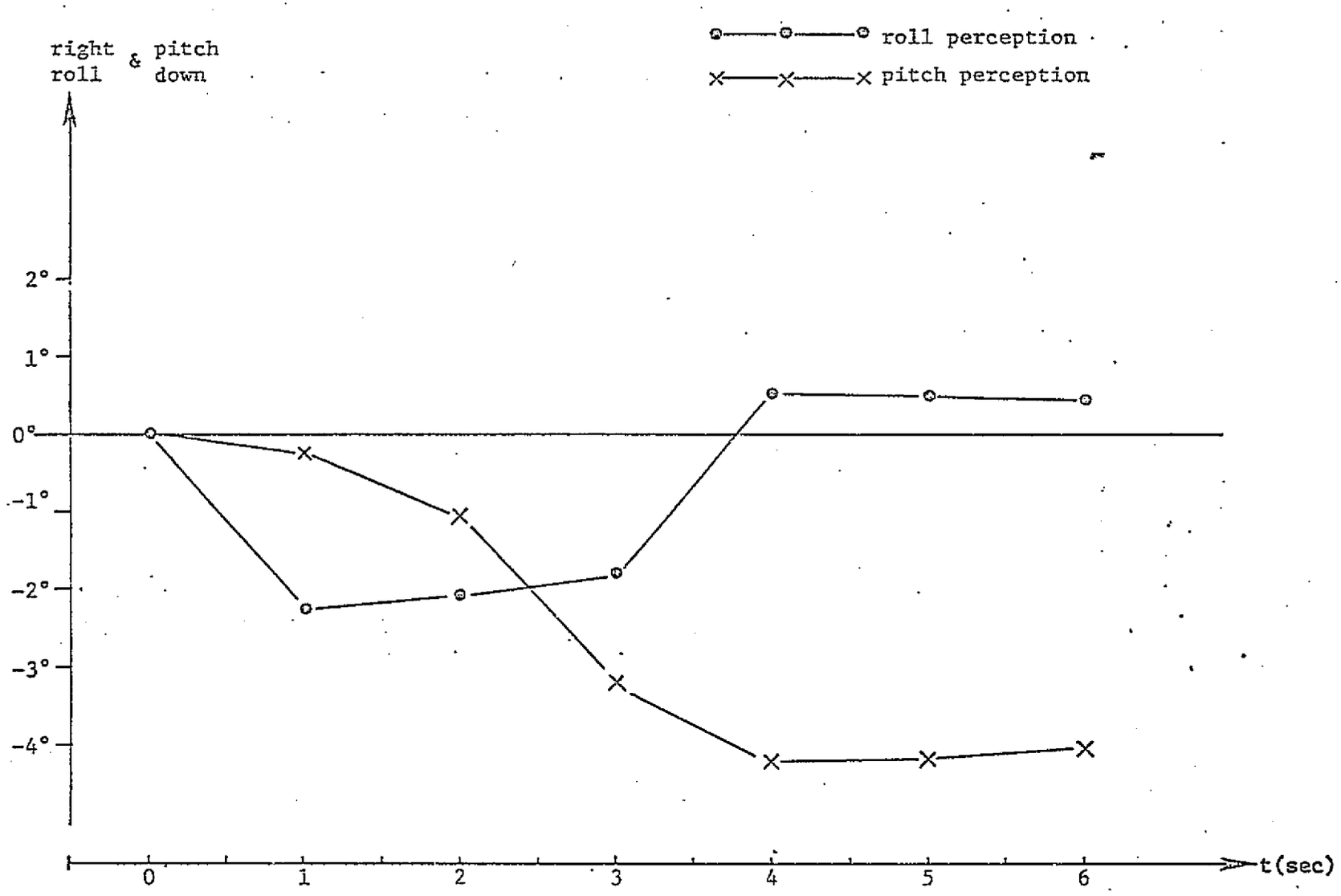


Figure 8 Model predictions for roll and pitch perception during initiation of the idealized coordinated turn.

feels a roll rate that is larger than the derivative of his attitude estimate. Contradictory sensations of a similar nature are well documented for other situations. There is a whole range of possible responses between the two examples given depending on the value of τ_L, and the proper value of τ_L is not at all clear. Ormsby made a claim for a value between 0 and 5 seconds. Figure 9 shows the model predictions for angular rate perceptions during roll in using both $\tau_L = 0$ and $\tau_L = 5$ seconds.

It should be assumed that figures 8 and 9 represent a naive subject. A pilot has prior knowledge of the maneuver, having initiated it, and has usually experienced the profile many times before. It is possible that his innate feelings are the same as those of a naive passenger, but are interpreted differently. It is also conceivable that mental set causes the pilot to experience sensations that are actually different from those of a naive person. For example, the pilot may turn up his τ_E value (in figure 4) having learned that canal estimates are all he has to go on. If τ_E is large, a person will "trust" his canals and in this case will not be far wrong in estimating roll angle during roll-in. As the turn continues at constant bank angle, blocks H and I of figure 4, which must now be considered, will cause attitude perception to gradually realign with SF. The human nervous system is amazingly plastic and the above is one of many possible conjectures that can only be verified experimentally. Such an experiment is beyond the scope of our present research. Finally, remember that figures 8 and 9 represent non-visually induced sensations.

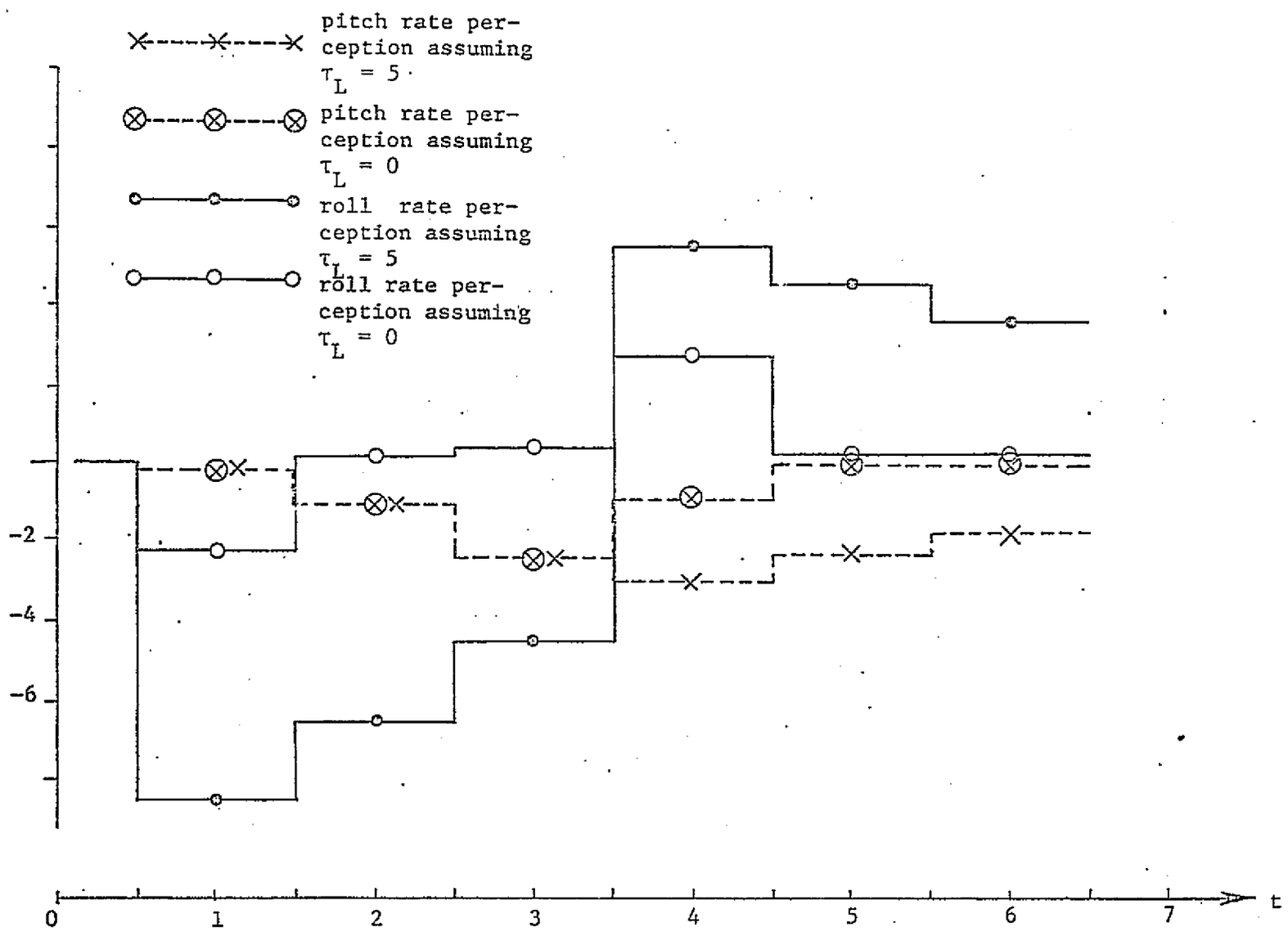


Figure 9 Model predictions for roll and pitch perception during initiation of the idealized coordinated turn. The idealized turn profile is shown in figure 1

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Although several cautions and uncertainties have been mentioned, it is highly likely that the gross predictions of the model are correct. During a coordinated turn, people will feel only a small change in roll attitude compared to their true roll, a roll rate that may be somewhat more pronounced, and a slight pitch back as specific force increases.

5 Simulation Fidelity Analysis

If we assume that the Ormsby model is giving a meaningful estimate of human perceptions, it should be useful in gauging the effectiveness of a given simulation. It makes sense to look at some function of the difference, at each sampling instant, between model outputs for the real motion and the simulator motion. These outputs are $\hat{\underline{DOWN}}$ (attitude perception vector), $\hat{\underline{\omega}}_{hd}$ (angular velocity perception vector), and an acceleration perception vector ($\hat{\underline{A}}$) equal to $\hat{\underline{DOWN}} - \hat{\underline{SF}}$. The function shought should be dimensionless and should be proportional to the cost in "realism" of any perceptual error. There is currently no data available to indicate the quantitative loss in realism ascribed by humans to a given difference in perceptions.

It seems logical, therefore, to pick as a cost index the simplest function that makes intuitive sense. When sensations are clearly supra-threshold, the most likely candidate is just percent error, the ratio of perceptual error to the correct quantity. The computer model in the form being used here does not account for perceptual thresholds, and when sensations are in the subthreshold region, the intuitive sense of the above ratio scheme breaks down. It does not seem very

reasonable to assess a heavy penalty to an error when all quantities are probably below threshold. When the model indications for "correct" perceptions are subthreshold, it seems more reasonable to assess a large penalty for errors that are large compared to the threshold value. Costs for each of the model outputs have been computed as follows:

$$\Delta\hat{\omega}(t) = |\hat{\underline{\omega}}_{av}(t) - \hat{\underline{\omega}}_{sv}(t)|$$

$$\Delta\hat{A}(t) = |\hat{\underline{A}}_{av}(t) - \hat{\underline{A}}_{sv}(t)|$$

$$\Delta\hat{\gamma}(t) = \text{angle between } \underline{\text{DOWN}}_{av} \text{ and } \underline{\text{DOWN}}_{sv}$$

Subscripts: sv ≡ simulator vehicle; av ≡ aircraft vehicle

$$C_{\omega}(t) = \begin{cases} \dfrac{\Delta\hat{\omega}(t)}{|\hat{\underline{\omega}}_{av}(t)|} & \text{for} \quad |\hat{\underline{\omega}}_{av}(t)| > \hat{\omega}_{thr} \\[2ex] \dfrac{\Delta\hat{\omega}(t)}{\hat{\omega}_{thr}} & \text{for} \quad |\hat{\underline{\omega}}_{av}(t)| < \hat{\omega}_{thr} \end{cases}$$

$$C_{A}(t) = \begin{cases} \dfrac{\Delta\hat{A}(t)}{\hat{\underline{A}}_{av}(t)} & \text{for} \quad |\hat{\underline{A}}_{av}| > \hat{A}_{thr} \\[2ex] \dfrac{\Delta\hat{A}(t)}{\hat{A}_{thr}} & \text{for} \quad |\hat{\underline{A}}_{av}| < \hat{A}_{thr} \end{cases}$$

$$C_{\gamma}(t) = \begin{cases} \dfrac{\Delta\hat{\gamma}(t)}{|\hat{\gamma}_{av}(t)|} & \text{for} \quad |\hat{\gamma}_{av}| > \hat{\gamma}_{thr} \\[2ex] \dfrac{\Delta\hat{\gamma}(t)}{\hat{\gamma}_{thr}} & \text{for} \quad |\hat{\gamma}_{av}| < \hat{\gamma}_{thr} \end{cases}$$

Subscript: thr ≡ perceptual threshold

The individual cost indices ($C_\omega(t)$, $C_A(t)$, and $C_\gamma(t)$) are simply weighted and summed to form an overall index.

$$J(t) = C_\omega(t) + C_A(t) + C_\gamma(t)$$

No attempt was made here to mathematically minimize J. It is presented only as a simple index for comparing given simulations and, of course, can be used to pick the choice with the lowest index from among several possibilities.

For the case of the Link simulation, it is fairly easy to see what will happen once several things are realized. In the Link, which is capable only of pitch, roll and yaw motion, specific force will always line up with gravity except during transient roll and pitch accelerations (the occupant's head is above the roll and pitch axes). This is the situation that the vestibular system has evolved to handle and will not produce serious disagreement between the canals and otoliths. The only possible exception may occur if a person is subjected to large, sustained yaw rates creating the possiblitiy of Coriolis illusions, or sustained "barbecue spit" type motions causing the otoliths to signal a rotating specific force vector long after canal signals have attenuated to zero. Barbeque spit motion is not possible in the Link (pitch and roll are restricted to less than 20 degrees in either direction) and yaw will be too slow during the turn maneuver to create Coriolis problems. Therefore, we expect the Ormsby model to predict roughly accurate perceptions of roll and pitch attitude and angular rates.

The next thing to notice is that absolutely nothing can be done towards creating the model's linear acceleration perception which is in the z_{hd} direction and quite small anyway. This leaves us with the problem of minimizing the last two terms of J. Let us first consider only roll motion and momentarily neglect pitch and the component of $\underline{\omega}$ parallel to DOWN. If we do this the equation for J is reduced to only roll considerations

$$J' = \beta_\gamma \left| \frac{\hat{\phi}_{av} - \hat{\phi}_{sv}}{\hat{\phi}_{av}} \right| + \beta_\omega \left| \frac{\hat{p}_{av} - \hat{p}_{av}}{\hat{p}_{av}} \right|$$

$\hat{\phi} \equiv$ roll perception; $\hat{p} \equiv$ roll rate perception

The first term can be zeroed approximately by following the figure 8 $\hat{\phi}_{av}$ profile with the Link trainer.

Remember that in the Link trainer as opposed to the aircraft, roll rate sensation will be the derivative of roll attitude sensation regardless of τ_L.

$$\hat{\phi}_{sv}(t) = \frac{d\hat{\phi}_{sv}(t)}{dt}$$

If $\tau_L = 0$, this equation holds for the aircraft also, and both terms in the equation for J' have been zeroed. Both $\hat{p}_{sv}$ and $\hat{p}_{av}$ will follow the open circles in figure 9. If $\tau_L = 5$ seconds, $\hat{p}_{av}$ is represented by the solid circles in figure 9 while $\hat{p}_{sv}$ follows the open circles. Since $\hat{\phi}_{sv}$ is the integral of $\hat{\phi}_{sv}$, it can easily be seen that with $\beta_\omega/\beta_\gamma = 1$ any change in simulator motion decreasing the second term

of this equation will quickly be overbalanced by an increase in the first. Unless $\beta_\omega/\beta_\gamma$ is much greater than 1, J' is minimized for this case by remaining faithful to roll attitude perception. There is no reason to believe that angular rate perception should be weighted more heavily than attitude perception. Although this is all somewhat hypothetical, the conclusion is that the most likely candidate for "optimal simulation" will recreate roll *attitude* perception.

If we now consider pitch motion, the same argument will lead to the conclusion that pitch attitude perception should be duplicated at the expense, if necessary, of pitch rate perception. A good first try at duplicating pitch attitude perception is to follow, with Link motion, the figure 8 pitch curve to its maximum, sustain that value through the constant phase of the turn, then pitch-out with a mirror image of pitch-in.

We have so far considered everything except angular rate perception about z_{hd}. This can be closely duplicated by adjusting Link yaw velocity to produce a z_{hd} component equal to that in the aircraft. In other words, this should satisfy

$$r_{sv} \cos \gamma_{sv} = r_{av} \cos \gamma_{uv}$$

$$r_{sv} = r_{av} \frac{\cos \gamma_{av}}{\cos \gamma_{sv}}$$

$\gamma_{sv} \equiv$ total angle between simulator zv axis and vertical

$\gamma_{av} \equiv$ total angle between aircraft zv axis and vertical

Figure 10 shows a coordinated turn simulation profile for the Link trainer based on the above arguments. Model predictions for motion perception during these profile are shown in figures 11 and 12. Model predictions for the aircraft turn (assuming $\tau_L = 5$) are superimposed. According to the model, proper attitude perception has been virtually duplicated although there has been some expense to pitch and roll angular rate perception as anticipated. Figure 13 shows the results of cost index calculations for the simulation of figure 10. Weighting factors have been taken as 1, and τ_L has been taken as 5 seconds. Figure 14 shows the case of zero τ_L.

When flown with its own "factory" logic, the Link GAT-1 trainer employs a proportional roll and over a certain range, maintains roughly 1/6 of the imaginary aircraft roll angle. When a motion history based on this logic is input to the fidelity index program, the results are as shown in figure 15.

6 Use of Circularvection Display

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

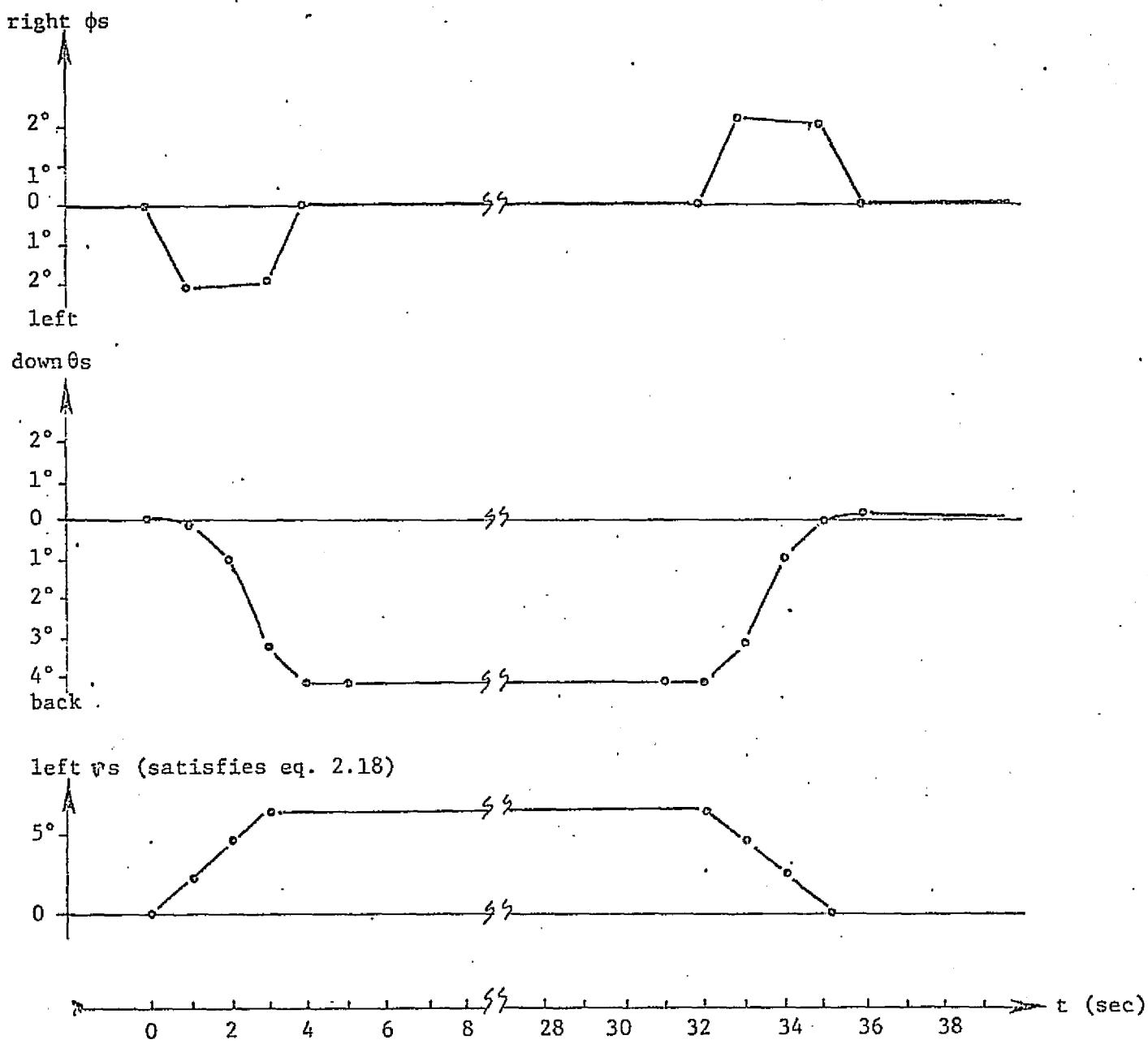

Figure 10 A coordinated turn simulation profile for the Link trainer

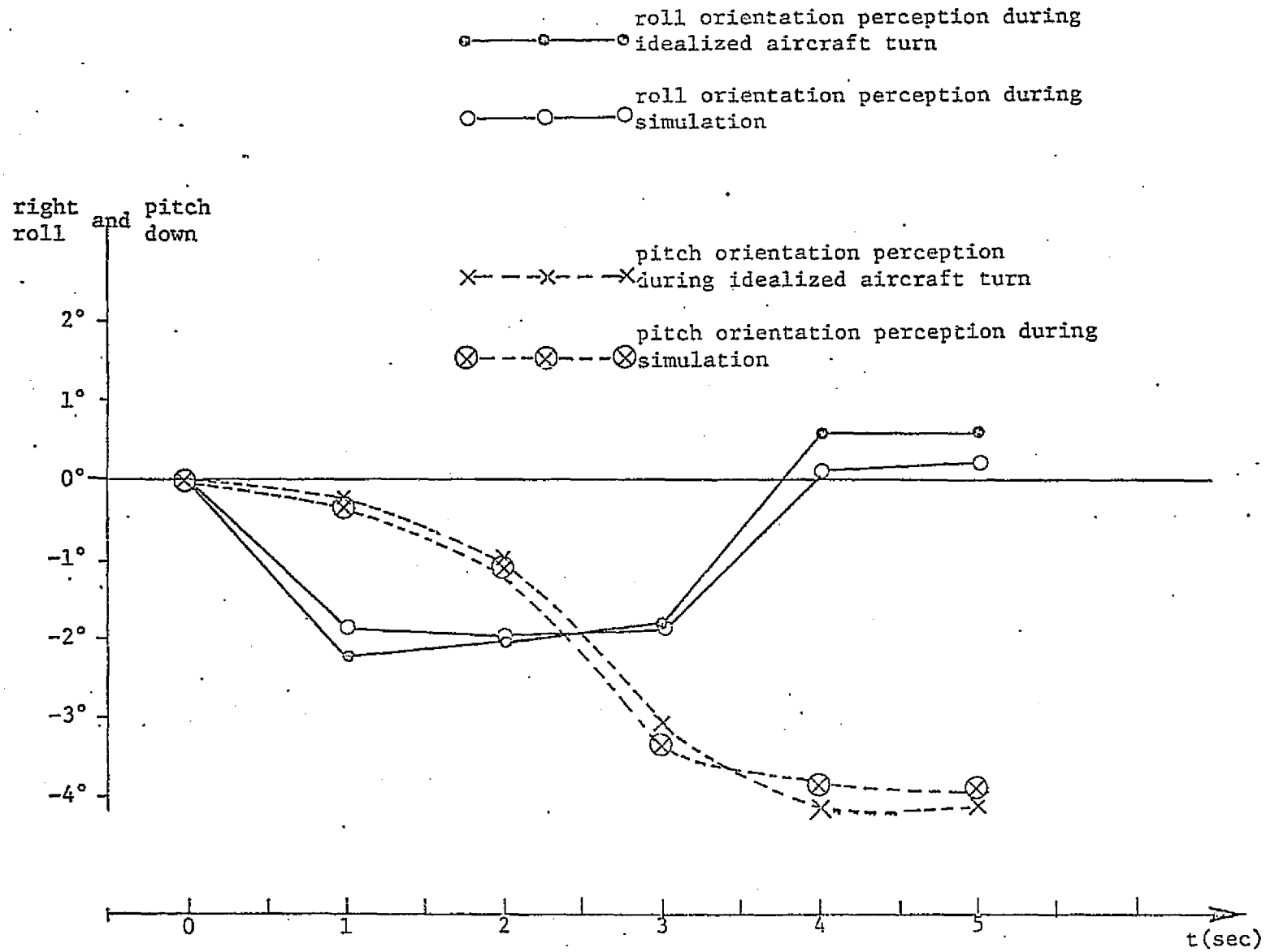

Figure 11 Pitch and roll rate perceptions during a simulation of the idealized coordinated turn. (The idealized turn profile is shown in figure 1 and the simulation profile is shown in figure 10 .)

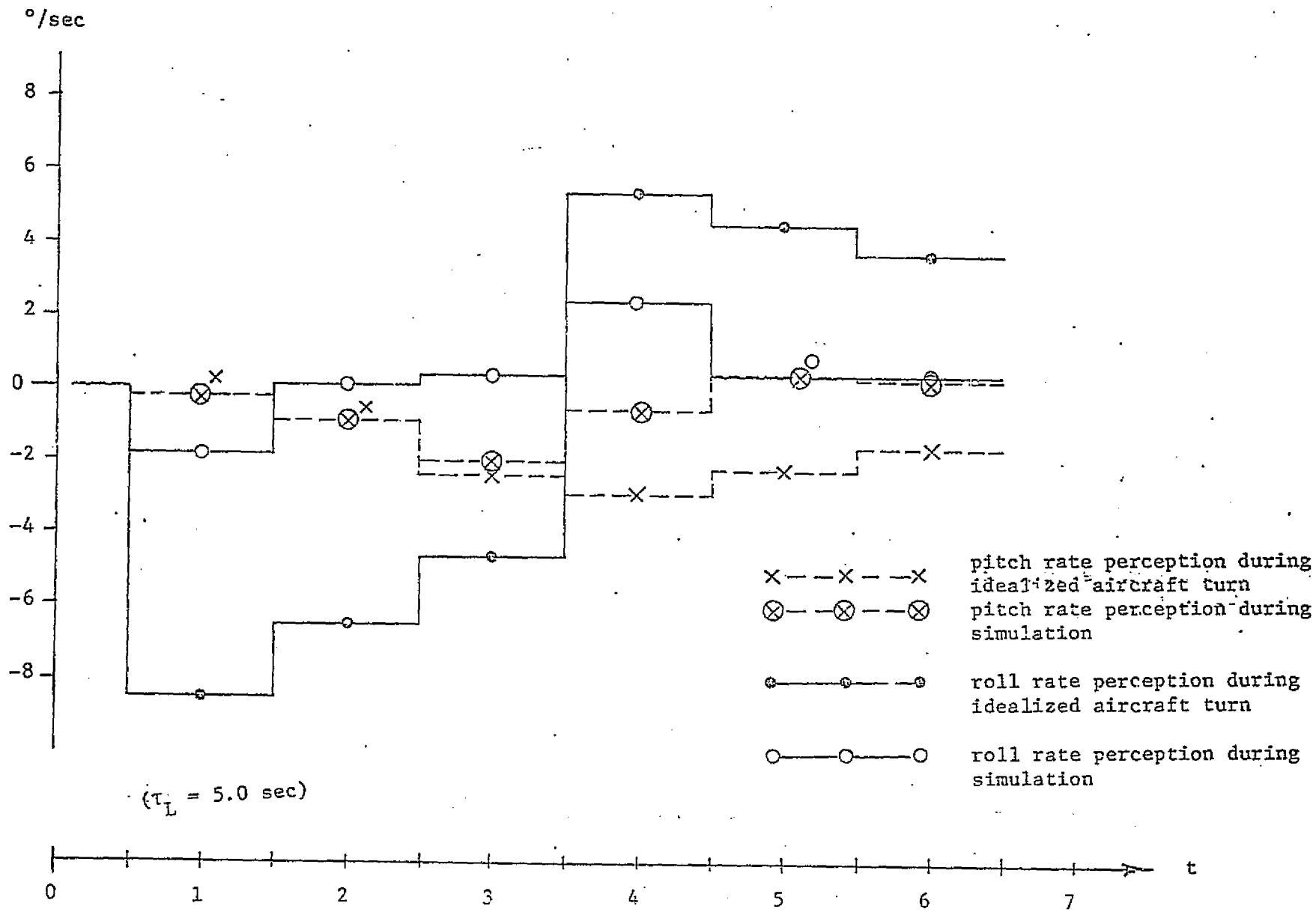

Figure 12 Pitch and roll perception during a simulation of the idealized coordinated turn. The idealized turn profile is shown in Figure 1 and the simulation profile is shown in Figure 10

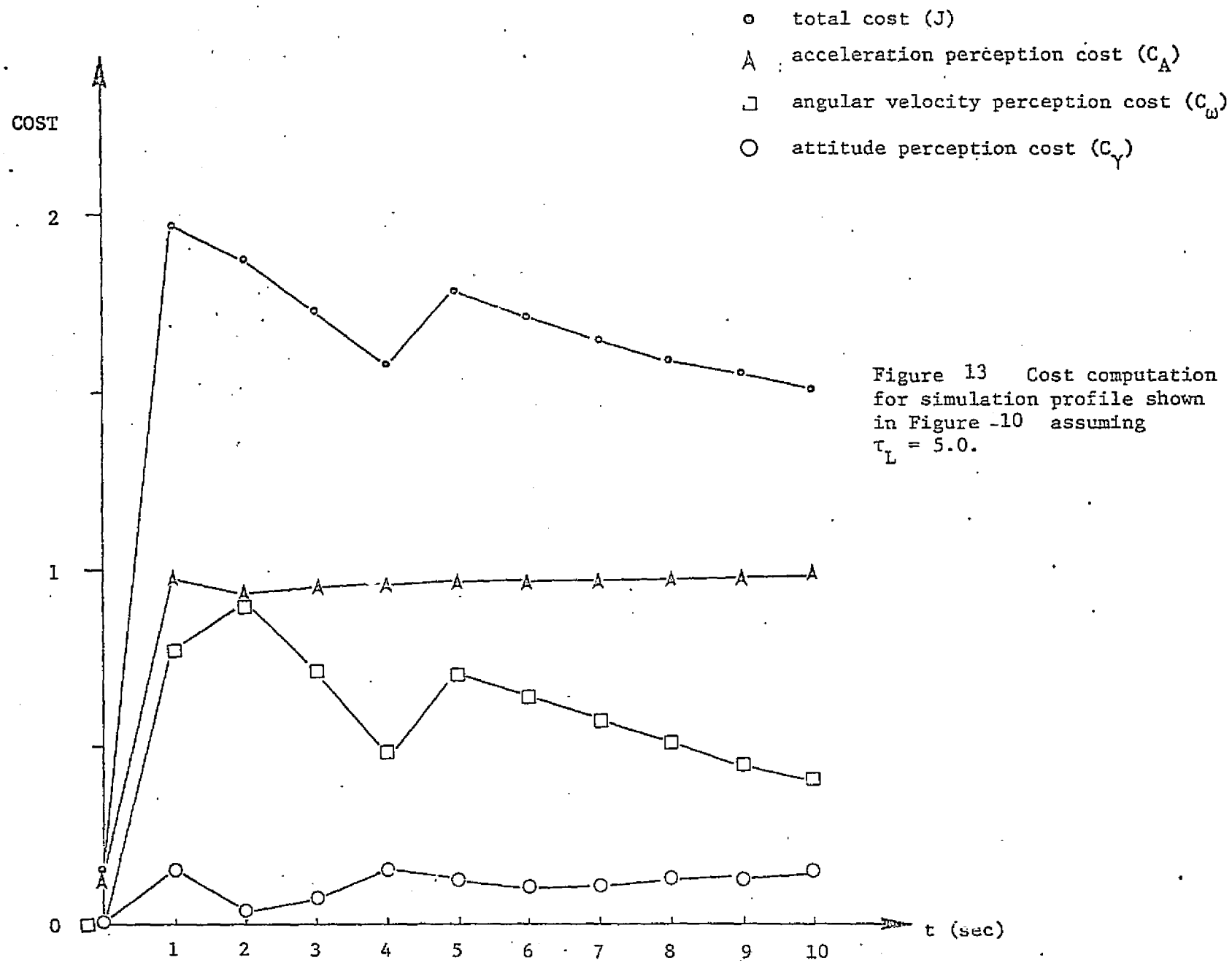

Figure 13 Cost computation for simulation profile shown in Figure 10 assuming $\tau_L = 5.0$.

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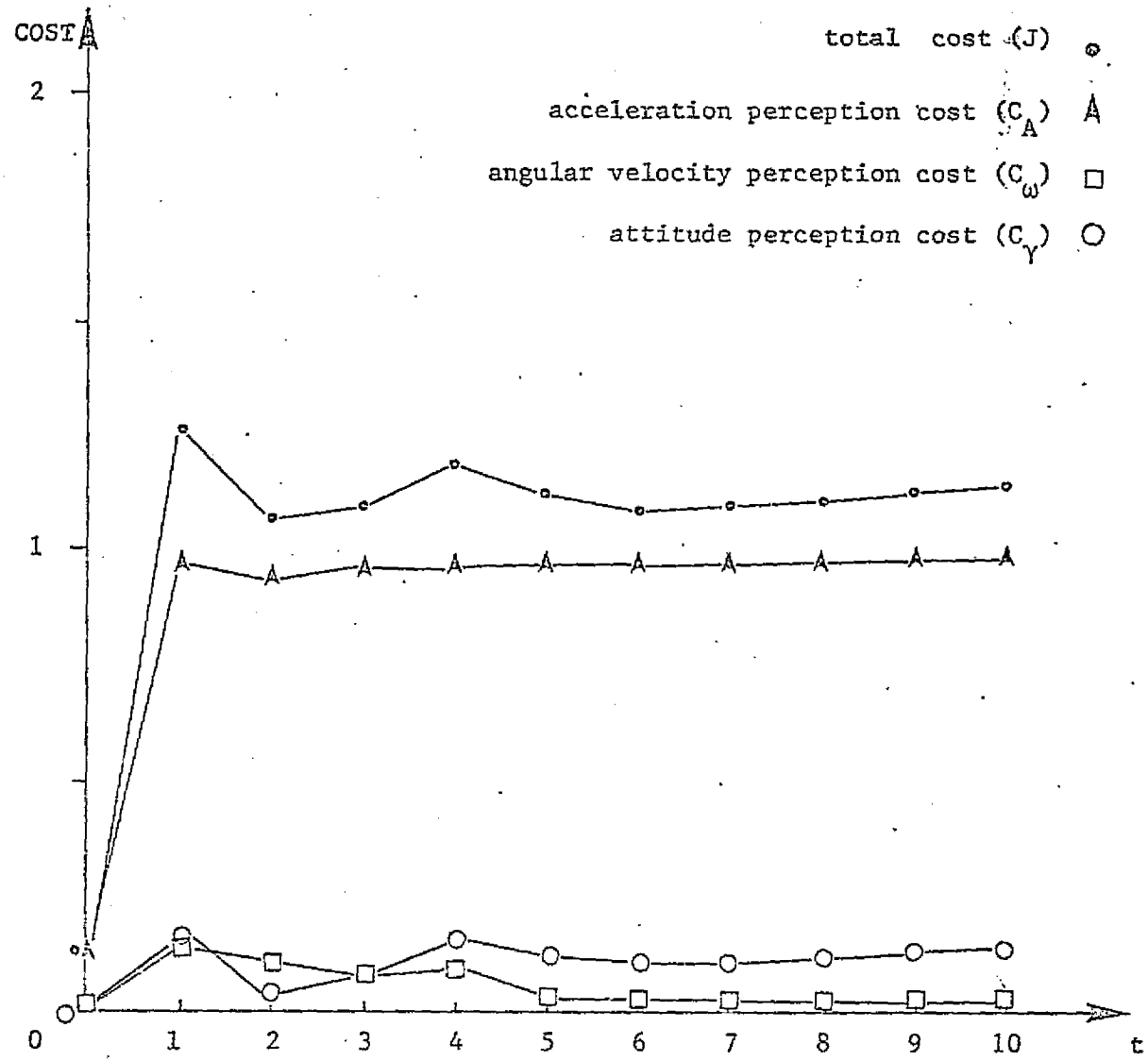

Figure 14 Cost computation for simulation profile shown in Figure 10 assuming $\tau_L = 0$.

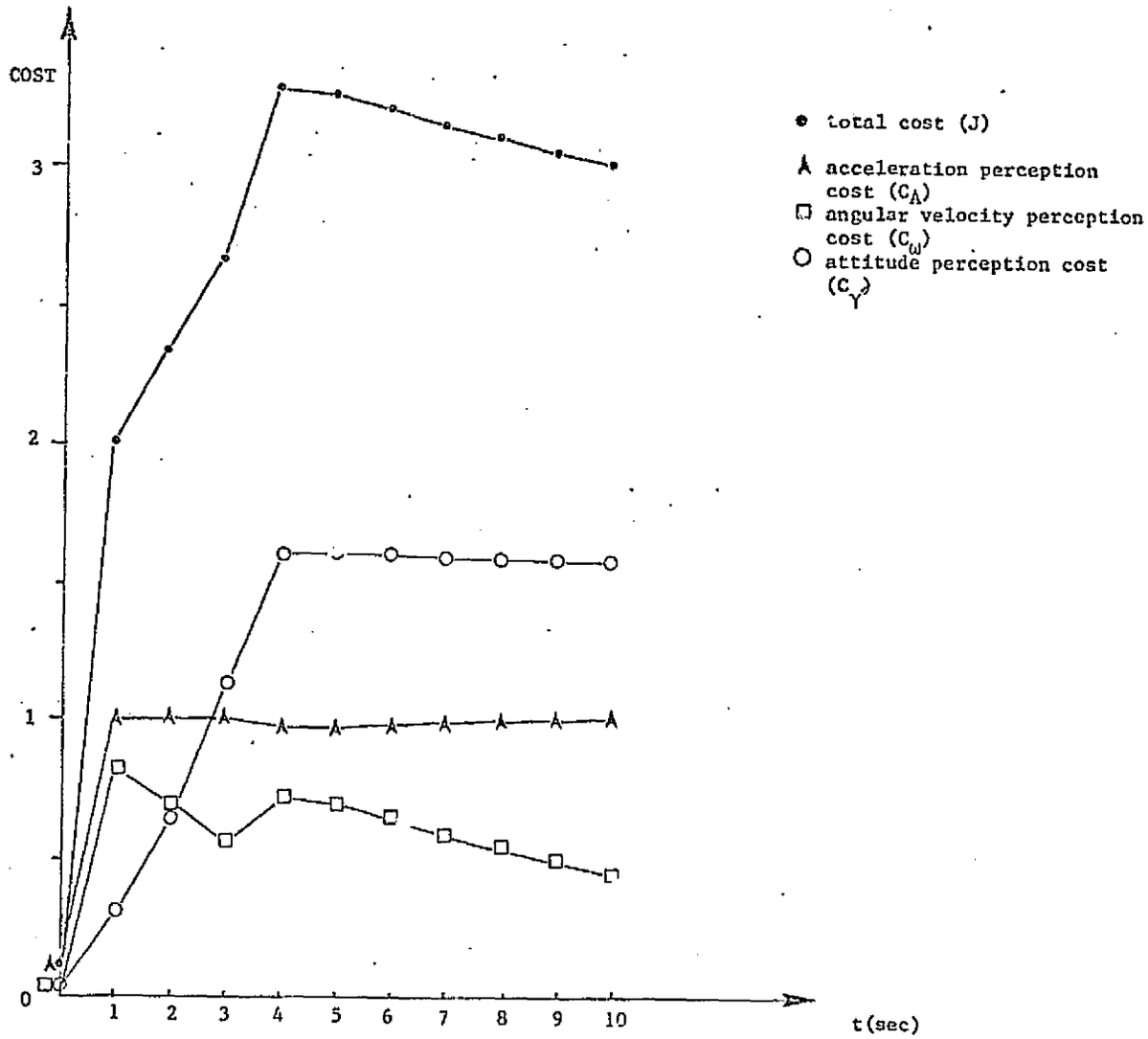

Figure 15. Cost computation for simulation profile based on proportional roll stragegy.

The Link stripes can be made to move up on one window and down on the other producing an optokinetic roll display. It has been shown that this display can produce the paradoxical illusion of constant roll velocity and a constant tilt with respect to the vertical. When the tilt illusion (using the same Link trainer and a similar visual display) was measured in previous work, it was found that subjects instructed to maintain an upright orientation tilted themselves an average of 8.5 degrees in the direction of stripe motion. Stripe speed was varied between 14 and 26 degrees per second and tilt reached steady state after an average of 17 seconds. Onset time for the constant roll velocity sensation was not measured.

For the coordinated turn simulation under discussion, the most logical display strategy is a stripe roll velocity profile that is proportional to the roll velocity profile of the actual turn (see figure 1). This may enhance the roll velocity sensation produced by onset of Link roll thereby bringing the roll rate perception closer to that of figure 9 (for $\tau_L = 5$). Previous work suggests that attitude perception will possibly be affected; however the true attitude profile can always be appropriately adjusted. The most serious problem here is that of onset time. Circularvection takes anywhere from 3 to 10 seconds to onset, and the roll into the idealized coordinated turn takes only 3 seconds.

7 Experimental Procedures

Three different types of experiments were run to test this theory. These are briefly described below:

Experiment 1: Roll rate calibration

This experiment was designed to obtain subjective magnitude estimates of angular roll velocity during a standard type of stimulus in the Link trainer. The standard stimulus was a series of constant velocity rolls with a four second pause between each one. There were no yaw or pitch motions during this experiment, but there were three different types of visual stimulation. The projected stripes were either stationary on the cockpit side windows, rolled (moved up one side and down the other) at a constant rate, or rolled at a rate proportional to the roll velocity of the Link trainer. The latter was achieved by using the roll tachometer feedback as a command signal to the film drive. There are two possible choices of sign for the proportional stripe motion. Stripe motion can be opposite that of the Link (counterrolling stripes) or can be the same as that of the Link. Both strategies were used in this experiment. Counterrolling stripes provide a motion cue that is entirely consistent with actual motion, while stripes rolling in the same direction as the Link provide a cue that is contradictory.

The subjects used a voltmeter display connected to a hand grip to indicate their perceptions of roll rate. Subjects were familiarized with this instrument by means of a series of modulus stimuli. The modulus was repeated at the beginning of each run.

Subjects were given the following set of instructions:

> "Use the head rest as a support or aid to keep your head stationary with respect to the cockpit. Keep your gaze on the meter. The meter needle can be moved by rolling the hand grip and will maintain a position proportional to the hand grip roll angle. When the experiment begins, concentrate on your sensation of roll *rate* or *velocity*. You will be given a motion called the modulus and your maximum sensation of *roll rate* during this motion should correspond to 5 on the meter. Subsequent motions should be rated proportionately; for example, a roll rate that feels twice as fast as the modulus should be a 10 on the meter. The modulus will be administered 8 times initially and then 4 times before every run. During each run, attempt to continuously track your roll rate with the meter needle. The first two runs will be practice. You will be asked to switch off your earphones at the start of each run. The experimenter will still be able to hear you, so if your hand slips or you make an involuntary indication for some other reason, simply report the mistake verbally. The green signal light will indicate that the run is over and you may stop tracking and turn on your head set. Remember to concentrate on your innate feeling of roll velocity and do not attempt to outguess the experiment. Indicate any roll rate sensation you feel even if you can logically deduce that the feeling is illusory."

Feedback from the Link roll and pitch position potentiometers, Link roll and yaw tachometers, stripe speed tachometer, and the hand grip roll position potentiometer (indicating meter needle position) were recorded on digital tape. All outputs except pitch position and yaw rate were also recorded on the four channel strip chart.

Experiment 2: Roll rate estimation during turn simulation

Experiment 2 was an attempt to obtain roll rate magnitude estimates during the three possible coordinated turn profiles. One profile is that developed in the previous section and will be referred to as SIM1. Another simply multiplies the SIM1 profile by a factor of 2 and will be called SIM2. The third profile, SIM3, is the proportional roll strategy that would be followed if the Link were using its own analog logic cards to simulate the motion history of figure 1. The SIM1 and SIM2 motion profiles were combind with stationary stripes (SS), stripes following the aircraft profile of figure 1 (SA1), stripes following the aircraft profile of figure 1 times a factor of 4 (SA4).

The modulus routines were administered twice before each session and once before every experimental run. Instructions to the subject were the same as those given in experiment 1.

Experiment 3: Vertical tracking task

Experiment 3 was designed to obtain subjective estimates of spatial orientation during coordinated turn simulations and during standardized pitch and roll stimuli. The simulation profiles used were the same as those used in Experiment 2 except that only the SS and SA4 stripe motions were used. The standardized pitch and roll stimuli were taken from the calibration routines and presented one third administered on the roll axis alone, one third on the pitch axis alone, and one third on the pitch and roll axes simultaneously.

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The hand grip indicator was outfitted with a pointer and the face of the meter was covered. The subjects were given the following instructions:

> "Use the head rest as a support or guide to keep your head stationary in the cockpit. Keep your gaze near the top of the pointer. During each run, keep the pointer aligned with what you perceive as the vertical with respect to the room. You will be asked to switch off your earphones at the start of each run. The experimenter will still be able to hear you, so if your hand slips or you make an involuntary indication for some other reason, simply report the mistake verbally. The green signal light will indicate that the run is over and you may stop tracking and switch your earphones on. Remember to concentrate on your perception of vertical and continuously track this direction with the pointer. Do not try to outguess the experiment and indicate your feeling of vertical even if you can logically deduce that it must be incorrect".

Feedback from the Link roll and pitch potentiometers, the tachometer, and the handgrip position potentiometers were recorded on data tape. Hand grip outputs and the two Link position outputs were also recorded on the four channel strip chart.

Subjects

Four naive subjects (non-pilots) and one pilot went through all three experiments. Twelve subjects in all participated, but only these five underwent the entire series of experiments.

Two pilots were asked to rate seven turn simulations on the basis of realism. The pilots were presented with seven different simulations consisting of combinations used and order presented as shown in figure 16. It was suggested that they imagine themselves as copilot or a

SUBJECT	RUN	LINK MOTION PROFILE	STRIPE MOTION PROFILE
10p	1	SIM2.	SS
	2	SIM1	SA1
	3	SIM3	SS
	4	SIM2	SA4
	5	SIM1	SS
	6	SIM2	SA1
	7	SIM1	SA4
11p	1	SIM1	SS
	2	SIM3	SS
	3	SIM 2	SA4
	4	SIM1	SA1
	5	SIM1	SA4
	6	SIM2	SA1
	7	SIM2	SS

Figure 16 Simulation profiles and order of presentation for pilot fidelity ratings.

passenger in a small aircraft, during zero visibility conditions.

The series of seven runs was presented twice. The first time, the subject was instructed to simply concentrate on his sensations as compared with those he would expect in a real aircraft. During the second presentation which followed the same order as the first, the subject was told to mark his rating for each run on the form shown in Figure 17.

Each line of the form has 10 bins representing increasing "realism" from left to right. An indication at the far left means "not at all realistic" while an indication at the far right means "extremely realistic". Subjects were told to place an x in the appropriate bin after each run using a new line each time.

The two subjects who participated in this phase of the study were (1) a single engine, commercial instrument rating pilot with 500 hours experience; and (2) a pilot with a multiengine rating and over 1000 hours as an airforce instructor.

8 Tabulation of Data and Statistical Analysis

Experiment 1: Roll rate calibration

Experiment 1 required subjects to track their roll rate sensation during a series of constant velocity rolls plus a low level of random noise. Between runs subjects were given several 5°/sec roll stimuli (the modulus) and were told that this corresponded to a 5 on the response scale. During runs, subjects were instructed to use a

Realism

not at all realistic — highly realistic

1

2

3

4

5

6

7

8

9

Figure 17 Simulation rating form

meter needle (controlled by a moving hand grip device) to continuously indicate their sensations proportional to the modulus. The stripe display was stationary during some runs (SS), moved at different constant velocities during other runs (SC), and moved with roll rates proportional to the Link roll rate during some runs (SP).

Figure 18 shows a typical continuous strip chart recording of a run from Experiment 1. The first step in data reduction was to find the peak roll rate stimulus and peak response indication for each stimulus period. A stimulus period was taken as the time from the onset of a link roll movement command to the onset of the next movement command.

Stimulus and response peaks were computed directly from the data tape by a PDP-8 program. In order to eliminate unwanted spikes, the computer algorithm defin-s a peak as the maximum value remaining equal to or less than the signal for longer than 0.2 seconds. The computer identifies peak absolute values du: ng each stimulus period but outputs the values with their proper signs. Stimulus peaks are computed from the Link tachometer signal, and response peaks from the hand grip roll potentiometer signal.

If each stimulus response pair is considered a data point, each subject contributed 31 data points in the stationary stripe category, 7-8 data points for each of the gains used in the proportional stripe motion category, and 7-8 data points for each value of constant stripe motion. The latter case must be broken down further, since during a given run, some Link motions were in the same direction as the stripe motion and some were in the opposite direction. Thus within each constant stripe motion category, 3-4 data points represent contradictory

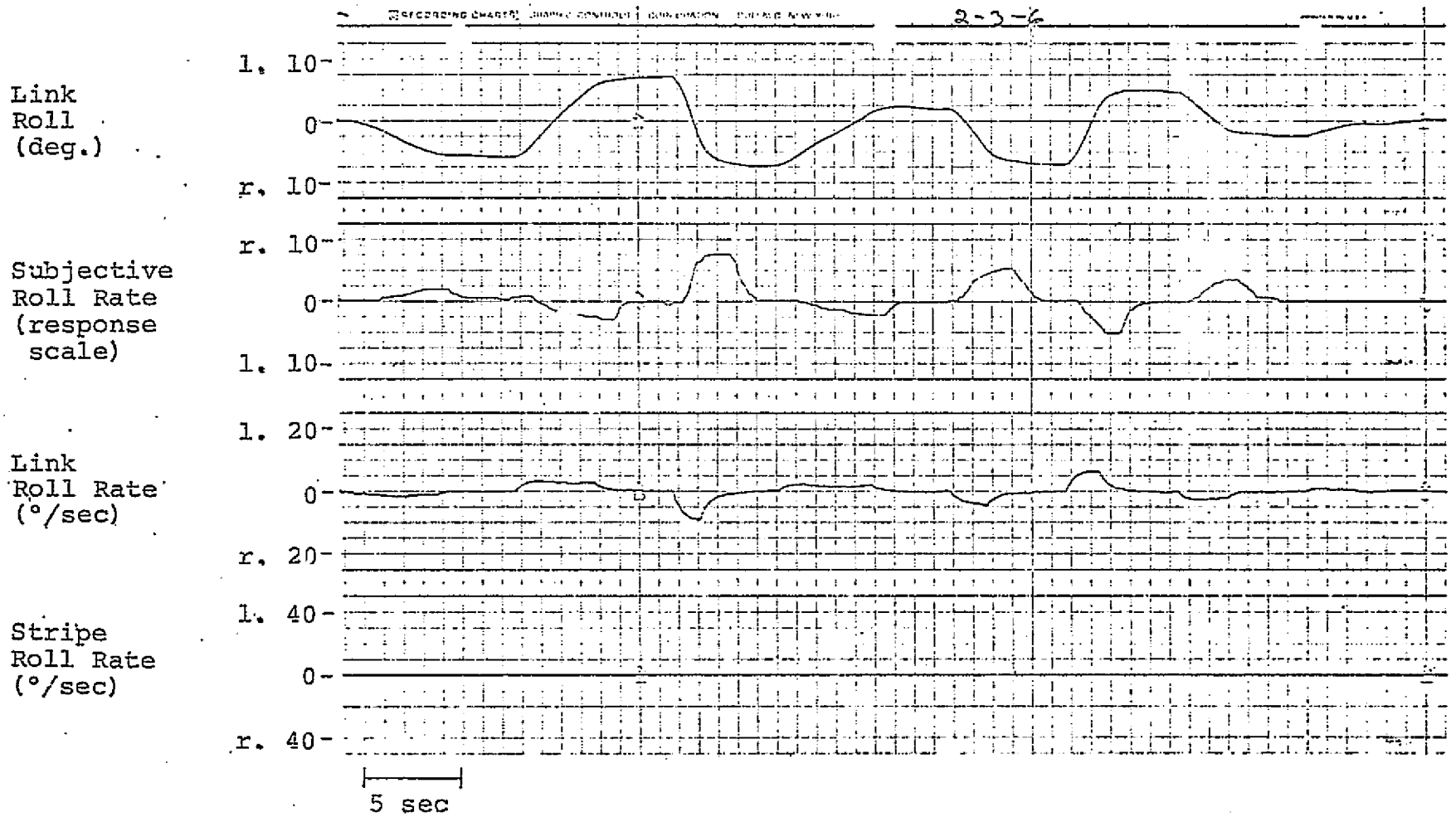

Figure 18 Typical Strip Chart Recording of Roll Rate Magnitude Estimation During Experiment 1. The motion profile is CAL2 (see figure 4.1), and the stripe display remained stationary with respect to the cockpit (SS) during this run. Subject 2, session 3, run 6.

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motion cues. The specific numbers vary slightly because two of the motion profiles have uneven numbers of left and right rolls.

Data points were deleted only when the subject verbally indicated a slip of the hand or some similar error during the stimulus. There were only two such data points in all of Experiment 1.

In the stationary stripe category, there was a very strong correlation between stimulus and response points for all subjects. Correlation coefficients range from 0.96 to 0.98. Transformation of one or both variables with a log operator results in lower correlation, and linear regressions in all cases are significant at $\alpha = 0.001$.

When response is taken as the dependent variable, the model is

$$RESP = B_0 + B_1(STIM)$$

The estimate computed from the data is

$$\hat{RESP} = b_0 + b_1(STIM)$$

where RESP is peak subjective angular rate indication during a stimulus period, and STIM is peak Link roll rate during the same period.

At a criterion level, $\alpha = 0.01$, b_1 is not significantly different from 1.0 for any of the subjects nor is b_0 significantly different from zero. At the less stringent level of $\alpha = 0.1$, one subject shows a significant intercept and two other subjects show slopes significantly different from 1. The statistic used to test the coefficient b_1 is

$$t_0 = (b_1 - 1)/(\hat{V}(b_0))^{1/2}$$

and the test statistic for the intercept is

$$t_0 = b_0/(\hat{V}(b_0))^{1/2}$$

The mean value (± standard deviation) for b_1 across subjects is 0.96 ± 0.056. For b_0, the mean value is 0.21 ± 0.23. Mean variance of the estimate is 1.29 ± 0.44.

A similar regression analysis was performed on the proportional stipe motion (SP) runs. During SP runs, stripes move at rates proportional to Link roll rate with proportionality constants of 1, 2, 4, -1, and -4 (abbreviated SP1, SP2, SP4, -SP1, and -SP4). The sign of the gain refers to the direction of the visual motion cue with respect to Link motion. Positive gains indicate stripes providing a motion cue of the same direction as Link motion, while negative gains cause cues opposite to true roll direction. SP1 implies stripes that remain stationary in inertial space.

Figure 19 shows a typical SP run. Out of a total of 30 such runs, only 5 show regression slopes that differ significantly from the SS case for that subject at the $\alpha = 0.05$ level. Of these 5, three cases have greater slopes and two have smaller slopes than in the SS case. Furthermore, there is no discernable pattern relating slope to proportional stripe gain. This is demonstrated in figure 20.

Since stimuli of both signs (directions) are involved, any relation between intercept and proportional stripe gain would indicate some sort of visual, directional bias. Figure 20 shows no obvious intercept-gain relation. Figure 20 also contains a plot of

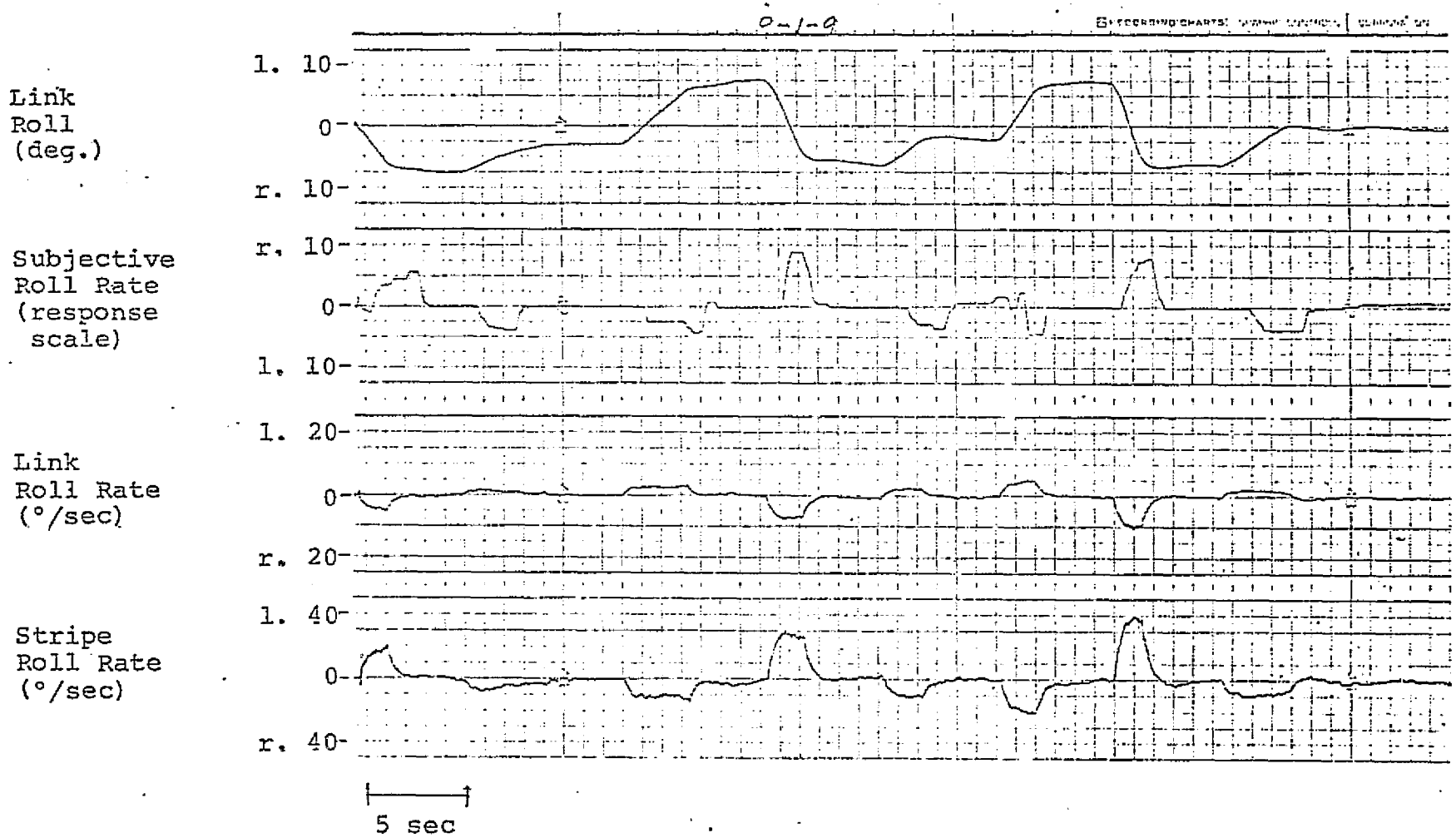

Figure 19 Typical Strip Chart Recording of Roll Rate Magnitude Estimation With SP4 Stripe Motion. The stripe roll rate is proportional to Link roll rate, but 4 times as fast and in a counter rolling direction. Subject 9, session 1, run 9.

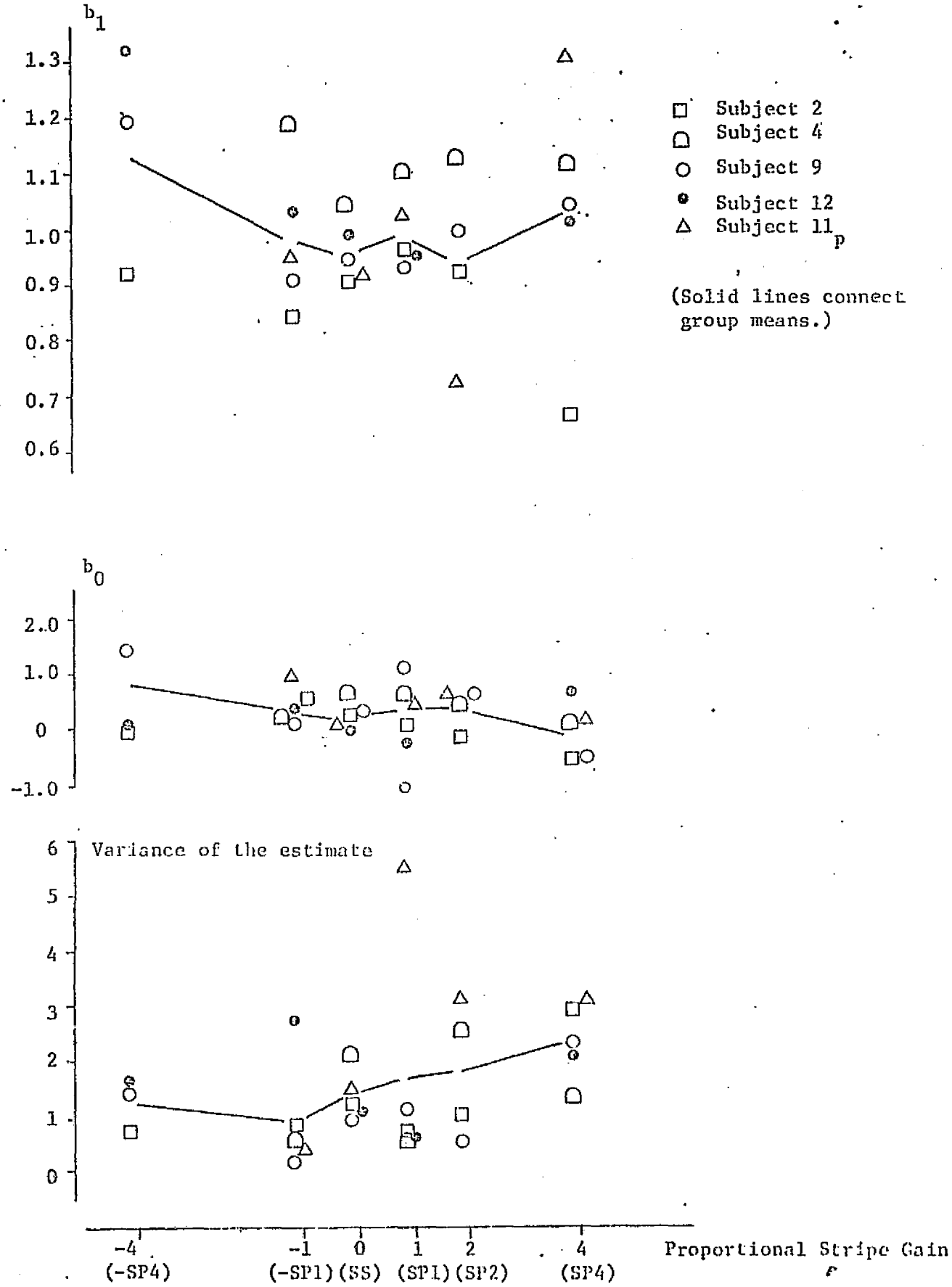

Figure 20 Slope, Intercept, and Variance for proportional (SP) and stationary (SS) stripe regressions. Independent regression variable is peak Link roll rate, and dependent regression variable is peak, subjective roll rate estimate.

"variance of the estimate" for each regression line against proportional stripe gain. Once again, there is no clear relation with stripe gain, although six of the individual points differ significantly from the SS case at the $\alpha = 0.05$ level.

The above comparisons between proportional and stationary stripe cases contain the underlying assumption that SP cases, as well as SS cases, can be modelled by the equation given before. As mentioned earlier, some residual plots show a slight tendency for repsonses to have greater magnitude than the regression estimates over low stimulus magnitudes. The same tendency sometimes appears in SP runs, and is, perhaps, more pronounced. An attempt was made to test for this without having to propose a specific model for SP. The appropriate technique is to test for differences in mean responses over the different conditions at a particular value of the stimulus. Because of the random noise input, there is never more than one sample at any precise stimulus value, so a small stimulus interval must be used instead. An interval of 1 deg/sec was chosen as the smallest value that can be filled with enough samples and the largest value that is still well below the resolution of the response data (standard error the estimate was typically just over 1.0 on the SS regressions). Even so, the only way to obtain enough samples is to rectify the data

and then either pool different SP gains within subjects or pool all the subjects. In order to minimize subject and sign (direction) effects, response data points for each subject were transformed by the SS case, stimulus dependent regression. When stimulus is taken as the dependent variable, the regression is a least squares estimate of the stimulus, given the response value. By employing this estimate, each response, for all stripe motion cases, can be transformed into the stimulus value most likely to have produced the response had the stripes been stationary. The effect of this is to remove any directional bias or non-unity gain characteristics of a particular subject. In other words, the stationary stripe regressions were used as calibration curves. Figure 21 shows a plot of stimulus versus transformed response for one subject during SP1, SP2 and SP4 runs. Note that the SS regression line is represented by a line of unity slope passing through the origin (the solid line in the figure). The dotted line forms a 90% confidence interval taken from the original SS curve. The particular stimulus bin chosen was the interval from 2 to 3 deg/sec. This interval contains the largest sample density across the population and is near the region where the phenomenon in question is observed. The test statistic is

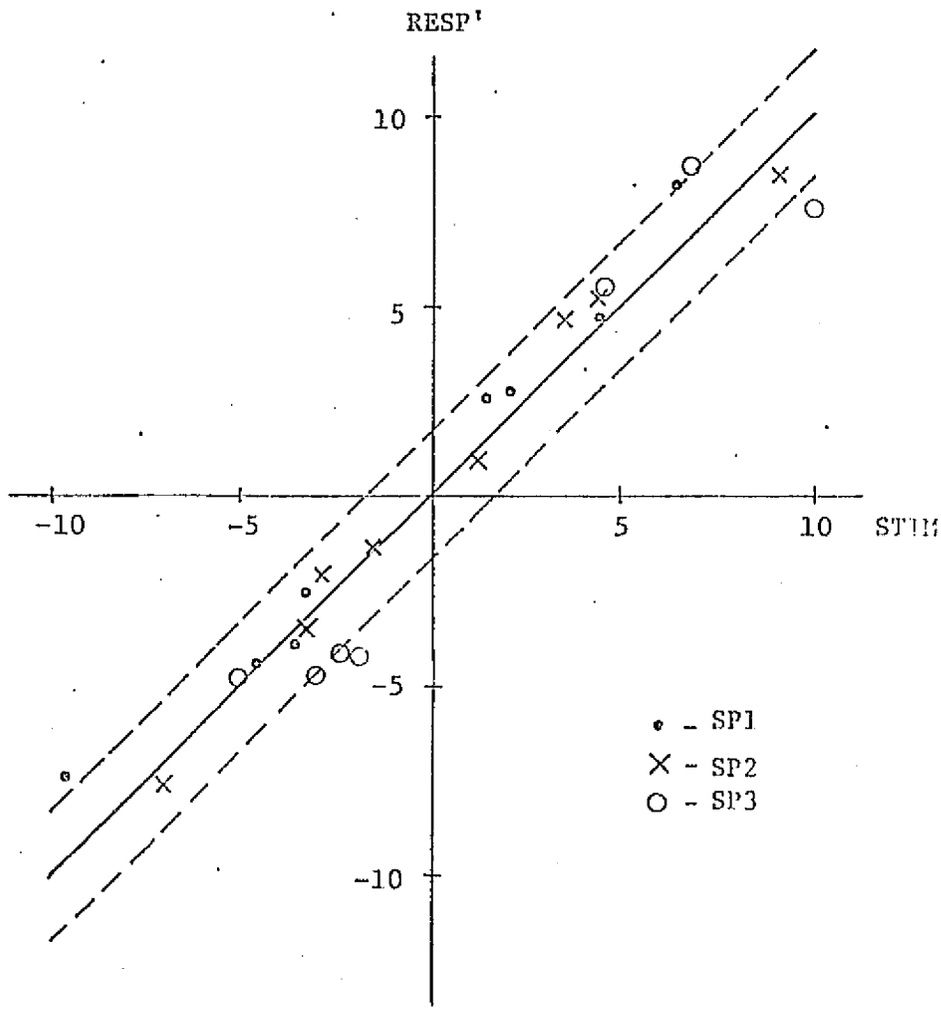

Figure 21 STIM versus RESP' for SP1, SP2, and SP4 data points, subject 9. RESP' is peak, subjective, roll rate estimate transformed by the stationary stripe calibration regressions. The stationary stripe regression line is represented by STIM = RESP'.

$$t_0 = (\overline{RESP'}_{SP} - \overline{RESP'}_{SS})/s_p(1/n_{SP} + 1/n_{SS})^{1/2}$$

where s_p is the pooled variance, n is sample size and $\overline{RESP'}$ is the mean transformed, rectified response. The null hypothesis is

$$H_0: \overline{RESP'}_{SP} = \overline{RESP'}_{SS}$$

The test was tried in two ways. Each subject was tested individually by pooling SP1, SP2, and SP3. Each of the preceding stripe motion categories (SP1, SP2, and SP3) was tested individually by pooling all subjects. Use of pooled variance implies that the true variances of the underlying distributions are equal. A test for difference in variance is insignificant on all cases at the $\alpha = 0.1$ level.

Only one subject showed a significant difference, at the $\alpha = 0.1$ level, between SS and SP stripe motions. When subjects are pooled, $\overline{RESP'}_{SP4}$ is greater than $\overline{RESP'}_{SS}$ at a significance level of $\alpha = 0.025$. SP1 and SP2 categories show longer mean responses than SS although not significantly so, even at the $\alpha = 0.1$ level.

Evaluation of the constant stripe motion (SC) data was seriously hampered by the small number of available data points in each category. Figure 22 shows a typical SC run. Regression

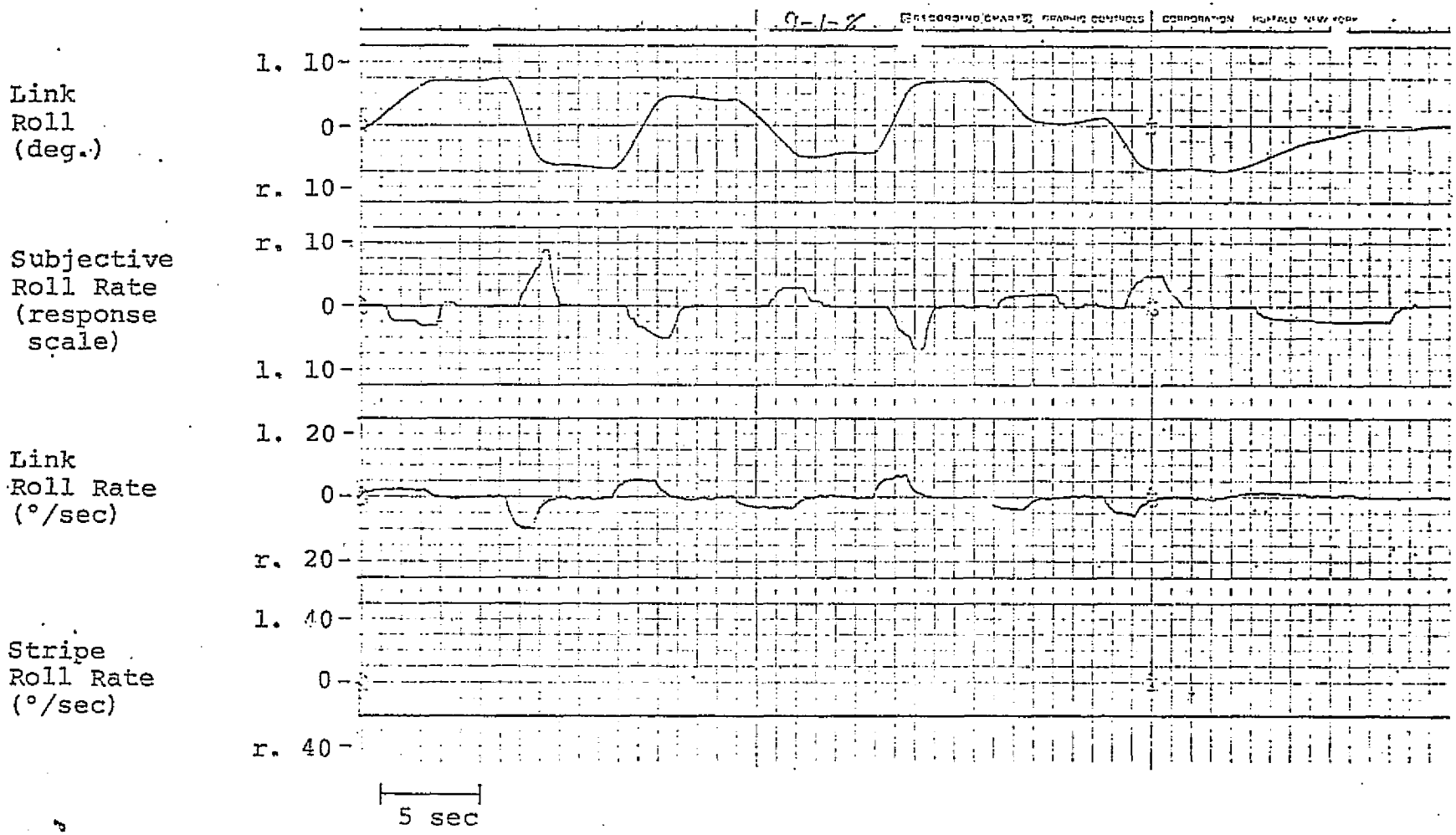

Figure 22 Typical Strip Chart Recording of Roll Rate Magnitude Estimation During SC20 Stripe Motion. Stripe display rolls at 20°/sec to the right throughout the run. Subject 9 session 1, run 8.

lines, in many instances have no statistical significance, and those that do pass a statistical test must still be viewed with an understanding that they depend on only four data points. The constant stripe motion was always to the right with respect to the Link cockpit, so Link rolls to the left (negative stimulus values) provide complementary vestibular and visual cues, while rolls to the right (positive stimulus values) presented contradictory vestibular cues. The word "complementary" is used to indicate that visual motion cues are in the same direction as actual Link motion, "contradictory" implies the opposite. Positive and negative (right and left) stimulus values were therefore worked up as separate regressions. Intercept, slope and variance of the estimate values are presented in Figure 23 only for those regressions showing statistical significance. (Numbers following the "SC" abbreviation refer to the constant stripe velocity in degrees per second.)

The figure does show a tendency towards lower (more negative) intercept values during "complementary" constant stripe motion and during 40 deg/sec "contradictory" constant stripe motion than in the SS case. The magnitudes involved are on the order of 1 deg/sec which is rather small. Slopes tend to be smaller in all three complementary SC categories than in SS.

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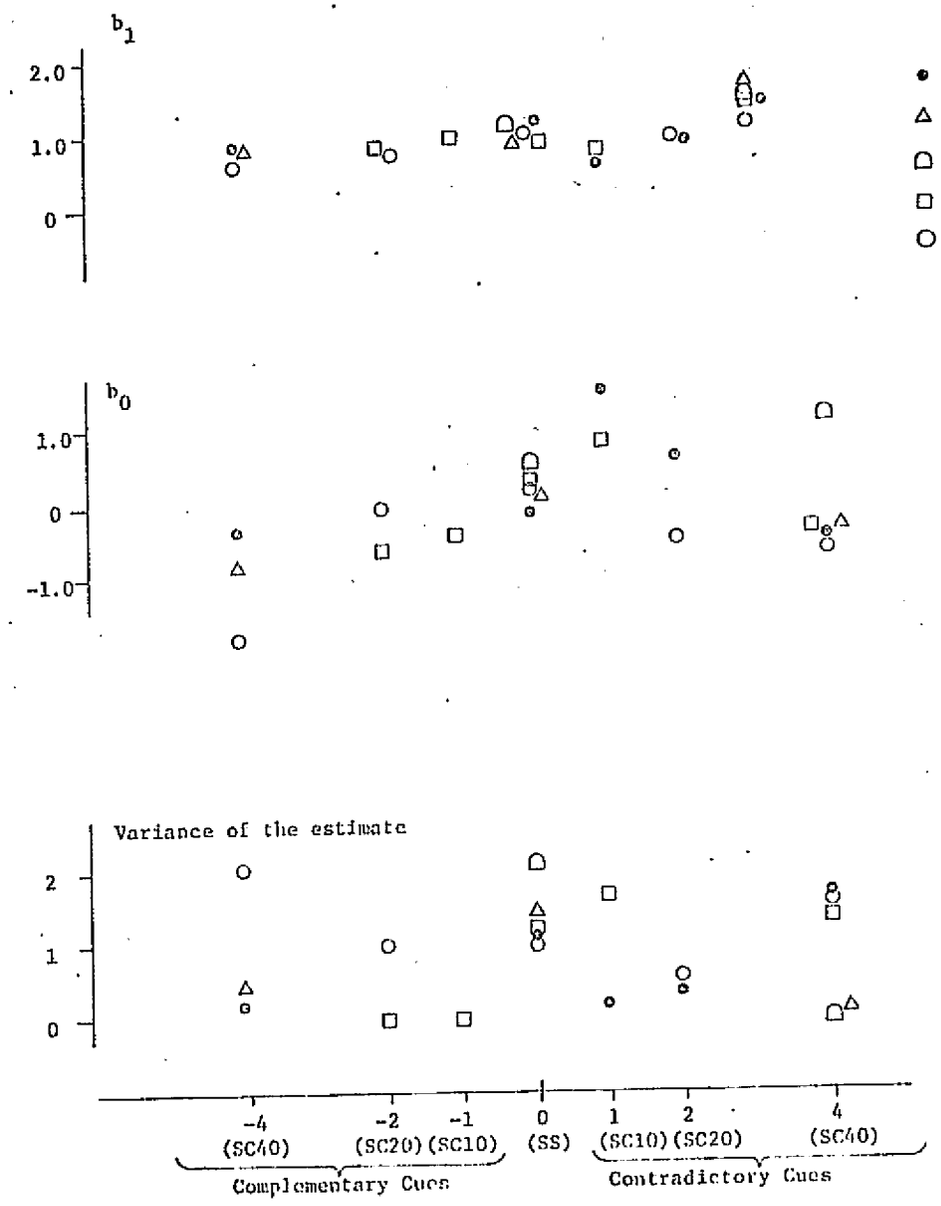

Figure 23. Slope intercept and variance for constant velocity (SC) and stationary stripe (SS) regressions. Peak response is the dependent variable. "Complementary refers to data points during left Link rolls consistent in direction with the visual cue. "Contradictory" refers to right roll data points, contradicted by the visual cue.

Slopes are smaller than SS in the contradictory 10 deg/sec and 20 deg/sec stripe categories, but tend to be larger in the contradictory 40 deg/sec case. For SC10 and SC20, differences from SS can be explained by the small non-linear trend discussed earlier in terms of residual plots. It can be expected to show up in the SC regressions since each includes stimulus values on only one side of the origin. The SC40 data, on the other hand, may show a real response bias caused by the stripes, especially at low stimulus values. In order to check this without the linearity assumptions implied by the regression analysis, the SC data was transformed and tested under the same procedures described for the SP data. The only difference was that individual subjects could not be tested. Only by pooling subjects are enough data points available. The results show larger $RESP'_{SC}$ than $RESP'_{SS}$, but differences are not significant for either the individual stripe speeds or when all speeds are pooled.

Experiment 2: Roll rate estimation during turn simulation

During experiment 2, subjects performed the same roll rate estimation task as in experiment 1, but the stimulus profiles included three variations of a coordinated turn simulation in combination with three different moving stripe profiles. One simulation profile is the profile found to produce nearly the same model estimate of attitude perception as the idealized aircraft turn, and is abbreviated SIM1.

SIM2 has a roll profile proportional to SIM 1 but with twice the magnitude, and the profile abbreviated SIM3 has a roll profile proportional to aircraft roll (proportionality constant = 1/6). The three stripe display conditions are stationary stripes (SS), and stripe roll rates proportional to true aircraft roll rate (SA). Proportionality constants of 1 (SA1) and 4 (SA4) were used. Two calibration runs (CAL) with stripes stationary were also administered during the course of each experiment 2 session.

Figures 24 and 25 show two typical responses to SIM1. Note that in the former, the subject has responded to all the stimuli, while in the latter, there is a response only to the two rolls away from zero (the first and third roll motions). Figures 26 and 27 show responses to SIM2 and SIM3 respectively.

The missed responses observed in figure 25 are of interest because they were not anticipated. For tabulation purposes, a missed response was defined to be a response to stimulus period 2 or 4 (STIM2 or STIM4) (STIM1 and STIM3 were never "missed") either less than 10% of that subject's average STIM1 and STIM3 response magnitude or of a sign opposite to the stimulus. The latter condition usually indicates that the response from STIM1 did not quite return to zero by the time STIM2 began. The total miss ratio (number of misses divided by number of possible responses) over all subjects and stripe profiles is just over 2/3. Note that if a subject were responding to the visual cue as opposed to vestibular or tactile cues, the Figure 25 response profile would be expected during SA1 and SA4 runs.

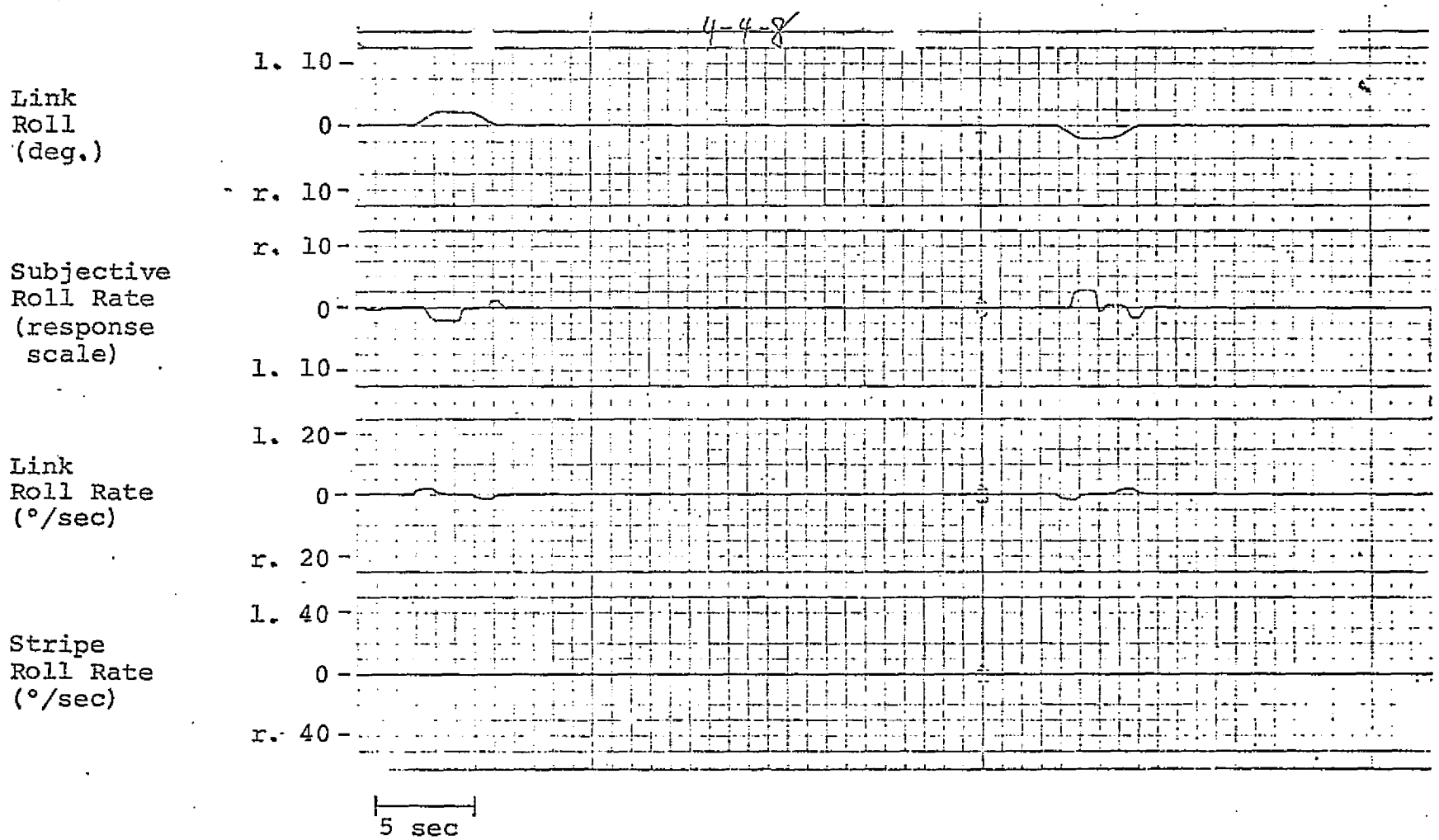

Figure 24 Strip Chart Recording of Roll Rate Magnitude Estimation During SIM1 Turn Simulation Profile. SIM1 is the profile found to produce nearly the same model estimate of attitude perception as the idealized aircraft turn. Subject 4, session 4, run 8.

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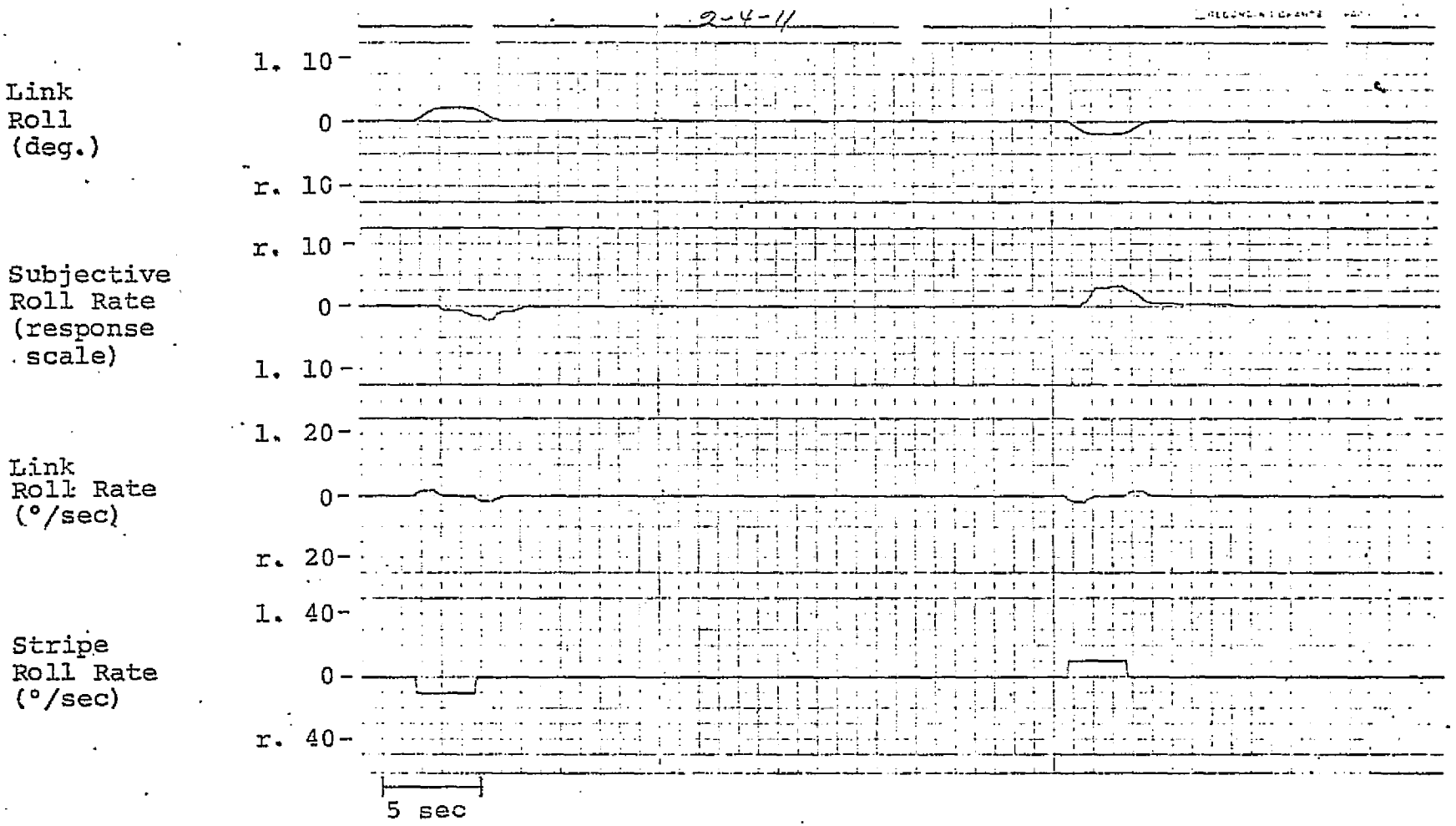

Figure 25 Strip Chart Recording of Roll Rate Magnitude Estimation During SIM1. Comparison of Link roll rate (channel 3) and subjective response (channel 2) shows no response to the second and fourth stimuli. Subject 2, session 4, run 11.

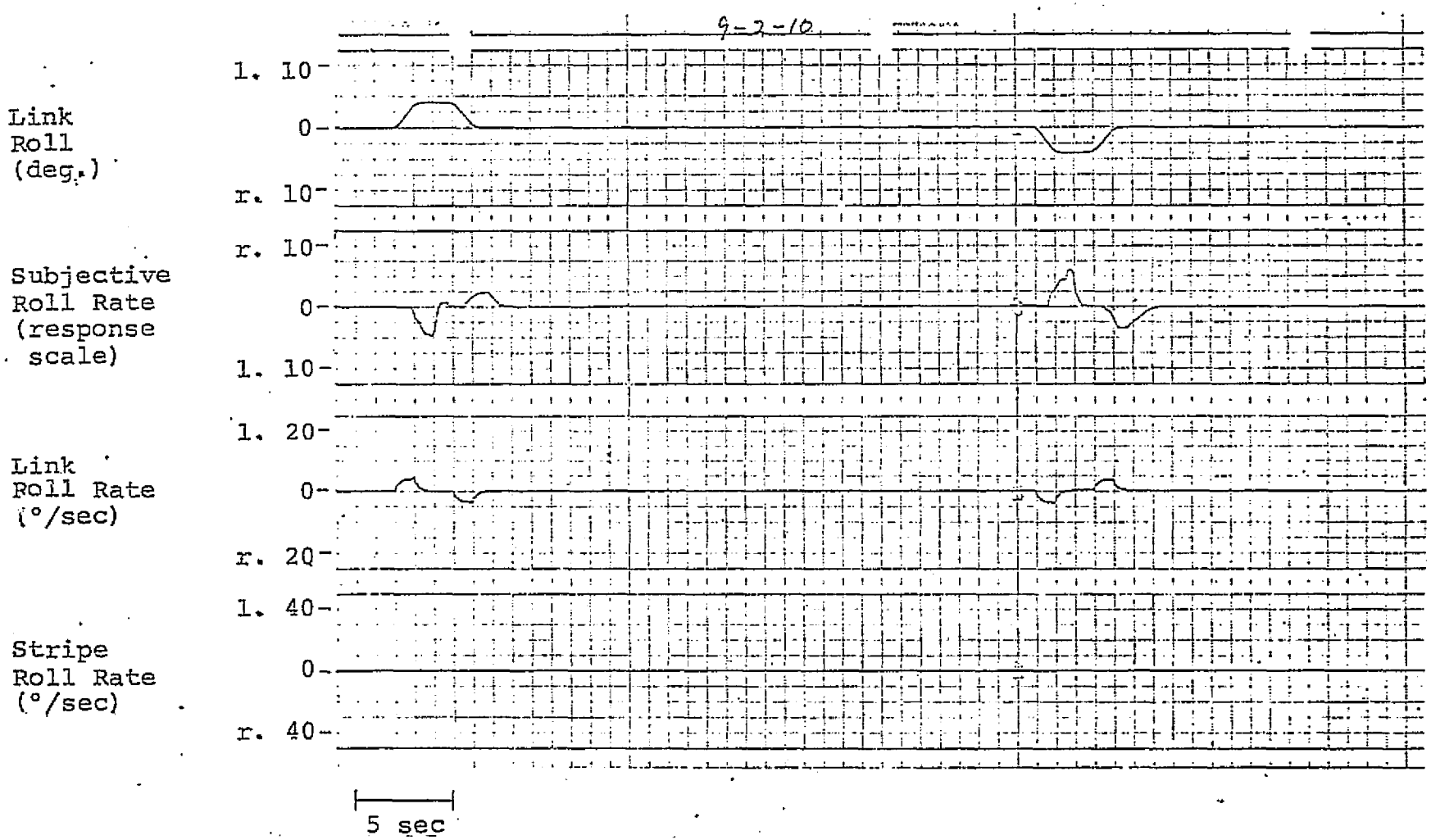

Figure 26 Strip Chart Recording of Roll Rate Magnitude Estimation During SIM2 Turn Simulation Profile. Roll magnitudes are twice those of SIM1. Subject 9, session 2, run 10.

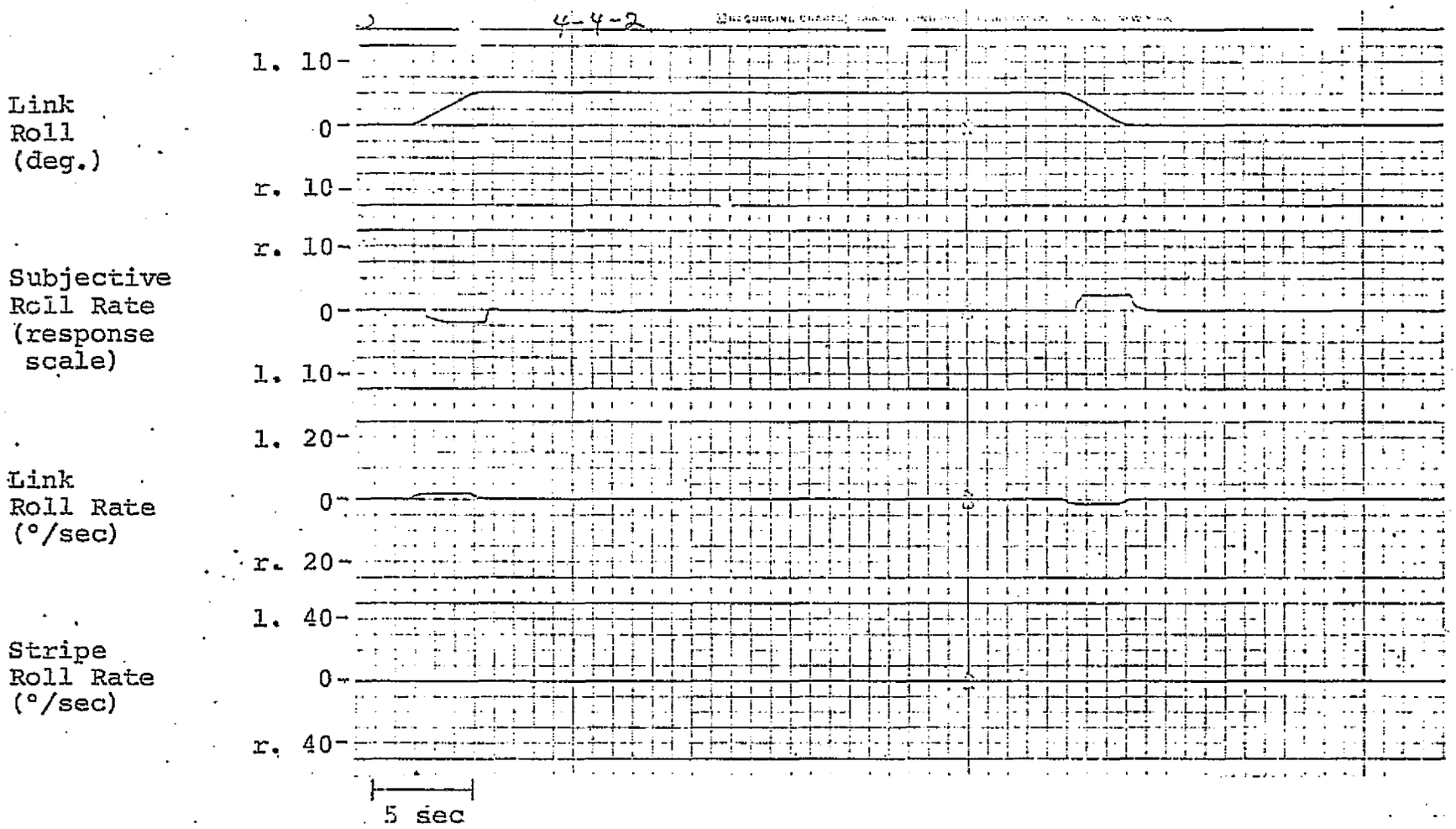

Figure 27 Strip Chart Recording of Roll Rate Magnitude Estimation During SIM3. SIM3 is the proportional roll simulation strategy applied to the idealized turn of section 2.1. Subject 4, session 4, run 2.

A contingency table was set up for SIM2 and SIM4 responses with two columns, "responded" and "missed"; and three rows, SS, SA1 and SA4. Data for the table was pooled from all subjects. A χ^2 test indicates that the null hypothesis of independence between columns and rows cannot be rejected. Therefore, although a slightly higher miss rate was recorded during the moving stripe runs, the optokinetic stimulus had no statistically significant effect on the phenomoneon.

During SIM2 runs, misses of STIM2 and STIM4 were not as frequent but still occurred. The total miss rate is 1/3 as opposed to 2/3 for SIM1. A χ^2 contingency test is significant at the $\alpha = 0.1$ level, but not if a more stringent criterion is used. SA stripe profiles may contribute to missed responses during SIM2 runs; however, the low significance of the results coupled with the lack of significance for the same tests in the SIM1 case, suggests that a cautious interpretation is appropriate.

STIM1 and STIM3 response magnitudes show no statistical relation to the stripe motion profile for either SIM1 or SIM2. During SIM1 runs, these responses did tend to be slightly larger than predicted on the basis of SS calibration runs. The effect is significant at the $\alpha = 0.05$ level for three of the subjects. The two calibration runs during the experiment 2 sessions are not significantly different from those obtained during experiment 1 for any of the subjects.

Experiment 3: Vertical tracking task

Experiment 3 employed both the calibration (CAL) and turn simulation (SIM1, SIM2, and SIM3) profiles, but the subjective task was to continuously estimate earth vertical, not roll velocity as in experiments 1 and 2. Subjects attempted to align a pointer, mounted on the hand grip indicator with their estimate of earth vertical.

Figure 28 is a typical strip chart recording made during a CAL profile run in experiment 3. Note that the quantities output on the chart are slightly different from those shown in experiments 1 and 2. The first channel still carries the Link roll position, but channel 2 is now scaled to indicate hand grip roll angle instead of meter divisions. Channels 3 and 4 contain Link and hand grip pitch position, while the Link roll and film strip tachometer signals are no longer displayed at all.

Having to track both a roll and a pitch motion simultaneously does not seem to hamper accuracy significantly during this experiment, although it does cause slightly slower responses. There does not seem to be any trend among subjects regarding differences between pitch and roll response. Some subjects show a more accurate response to roll stimuli while others show a more accurate pitch response (lower RMS percent error). This is a little bit surprising considering that subjects must rely to some extent on depth perception to gauge the pitch position of the hand grip pointer. It was, thus, expected that pitch judgements would be consistently less accurate. Three subjects tended to overestimate and indicate larger pitch and roll deviations

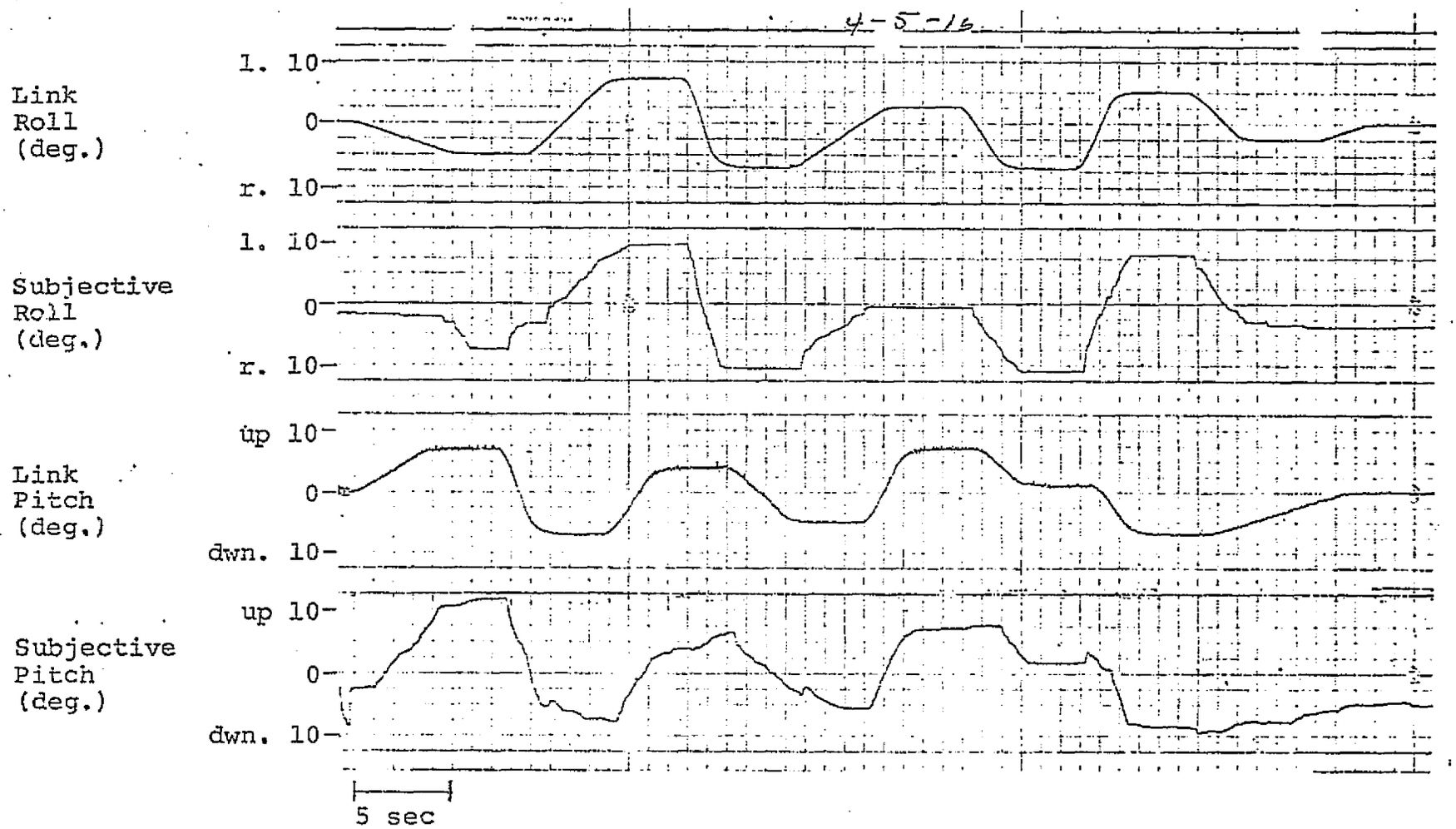

Figure 28 Typical Strip Chart Record of Two Axis Vertical Tracking Task With Calibration Profiles on Both Roll and Pitch Axes. The roll Profile is CAL2 and the pitch profile is CAL3 (see figure 4.1). Subject 4, session 5, run 16.

than the true stimuli, while one subject tended to overestimate pitch changes and underestimate roll changes, and another to underestimate the change in both roll and pitch angle.

Figures 29 and 30 show two strip chart recordings of a SIM1 run. Figure 29 is typical of most subjects in that first and third roll motions are clearly indicated, while second and fourth barely receive any indication at all. The phenomenon is essentially the same as that discussed before, except that the perception of roll attitude instead of roll rate is involved.

Pilot rating of simulations

Seven different combinations of simulation motion profiles and stripe display profiles were presented to two pilots for evaluations as turn simulations (see Figure 16). Table 1 shows the ratings assigned each simulation profile by the two pilots. Markings on the rating forms were scored by assigning numbers 1 through 10 to the bins from left to right. A "10" indicates that the simulation felt very realistic, while a "1" indicates that it did not feel at all realistic. Both pilots preferred the SIM1 profile (the profile shown by the Ormsby model to closely match the attitude sensations in a real aircraft) over the other two choices. There is some conflict between the two pilots concerning the stripe profile preferred, and, in fact, neither pilot is very self-consistent in this aspect. The ratings suggest that the motion profiles were more important to the pilots than the stripe cue, although one of the pilots did comment afterwards that he preferred the "slow stripes" (SA1).

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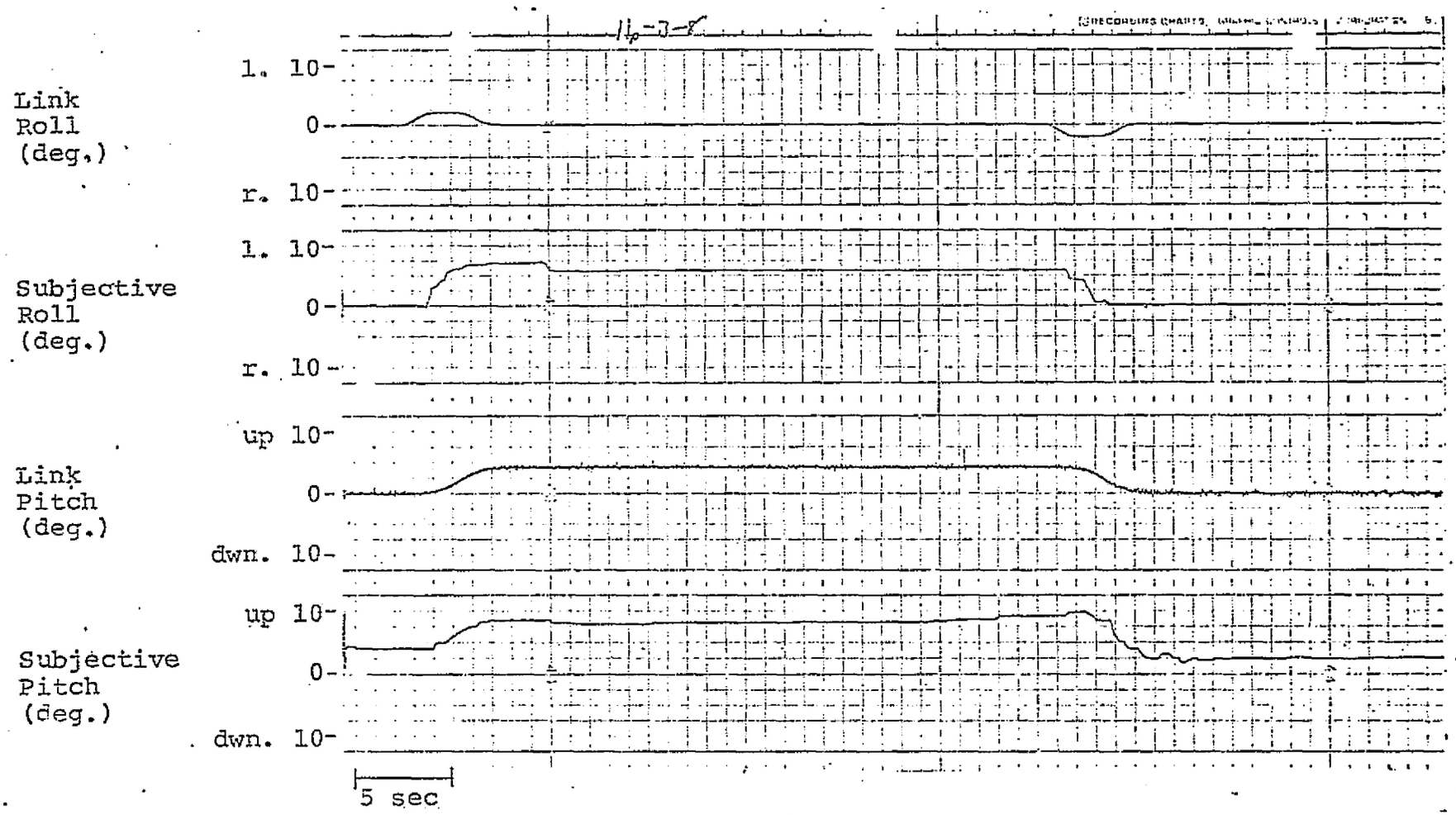

Figure 29 Strip Chart Record of Two Axis Vertical Tracking Task During SIM1 Turn Simulation Profile. Notice that the subjective roll response does not follow the shape of the Link roll profile. There seems to be no response corresponding to the two rolls back to vertical. Subject 11_p, session 3, run 8.

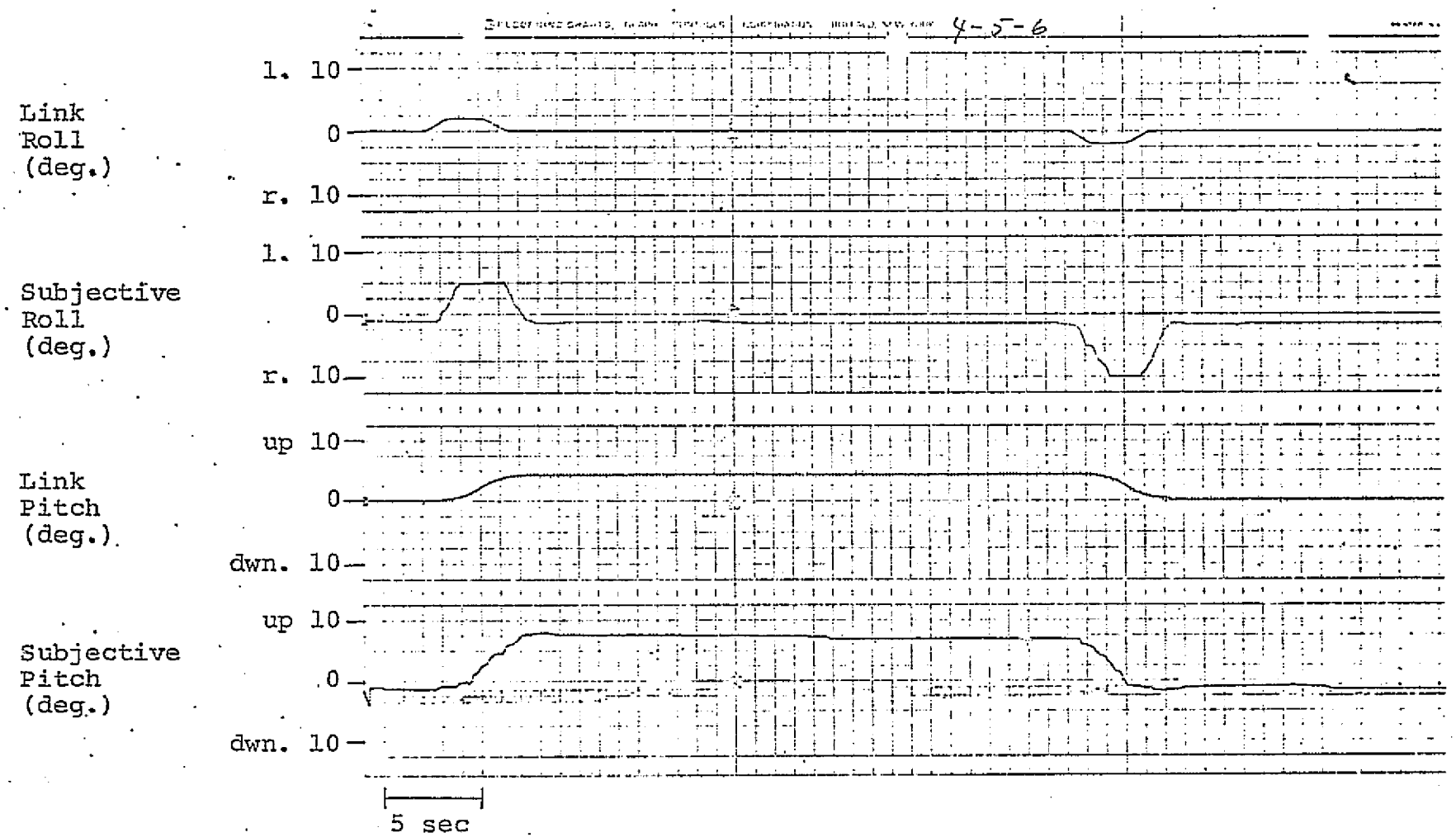

Figure 30 Strip Chart Record of Two Axis Vertical Tracking Task During SIM1 Turn Simulation Profile. This subject has vigorously responded to all 4 roll motions although he has overestimated the roll angles. Subject 4, session 5, run 6.

MOTION PROFILE	STRIPE PROFILE	PILOT RATING	
		SUBJECT 10_p	SUBJECT 11_p
SIM1	SS	6	8
	SA1	5	9
	SA4	6	8
SIM2	SS	3	7
	SA1	4	6
	SA4	2	8
SIM3	SS	3	3

Table 1 Pilot ratings of simulation profiles. "10" is the highest "realism" rating (extremely realistic) and "1" is the lowest (not at all realistic).

SIM3, the proportional roll strategy, received a relatively low rating from both pilots. In this profile, a roll angle is maintained throughout the body of the turn. One pilot commented that he felt a "side force" during this run, and the other said that the maneuver felt like a "slipping spiral". Comments from both pilots about SIM1 and SIM2 emphasized that the motions were too "jerky", "mechanical", "bumpy" or "abrupt". There are two factors besides the simulation strategy that probably contribute to this. Pitch and roll motion in our Link trainer is characterized by a certain bumpiness that is a combination of mechanical vibrations and position pontentiometers that have a tendency to become dirty and a bit noisy. The coordinated turn profile being simulated is an unusually mechanical maneuver itself. Roll in and roll out of this idealized turn are far more abrupt than a turn initiated by a real pilot. It is not surprising for this to be reflected by the simulations.

9 Discussion of results

General observations on roll rate magnitude estimation task.

During a series of constant velocity rolls between 1 and 10 degrees per second, between 2.5 and 14 degree excursion, and in the presence of a superimposed low level noise (±1 deg/sec), subjects are able to produce continuous magnitude estimates, the peaks of which correlate very highly with stimulus velocities. Input-output functions

appear to be linear relations, in most cases not significantly different from

$$RESP = B_1(STIM)$$

By setting a 5 response equal to 5 deg/sec as a modulus for this experiment, B_1 was effectively set to 1. Accuracy of the subjective data, defined by a 90% confidence interval, is about ± 2 deg/sec.

The proportional relationship above is somewhat surprising since psychological scaling laws are commonly log functions or power laws. The data may represent a small segment of a much larger log or power curve, or may be a reflection of the response scale and modulus employed. Psychological estimates are very sensitive to the precise layout of the response task. The modulus was defined midway along both the response scale and stimulus range, and stimuli were distributed over a range that corresponded closely to the range of numbers on the response scale. If subjects simply tend to use the entire response range available to them, a linear function would be the result. Whatever the reason, the proportional response function is very convenient and useful as a calibration device. It is important to note that the modulus was repeated several times before every run during the roll rate magnitude estimation experiments.

There is evidence of a slight breakdown of the linear response at low stimulus values for two subjects. It seems reasonable to assume that the response magnitude will tend to level off as stimulus threshold is approached, but this work did not attempt to carefully investigate threshold phenomena.

General observations on two-axis vertical tracking

There is considerable variance among subjects in the gain with which they estimate their orientation using the continuous vertical tracking task. For excursions ranging from 2.5 to 14 degrees, some subjects consistently overestimated their roll and pitch angles, in one case by as much as 100%, while others consistently underestimated these angles. Subjects are quite self-consistent, however, and within subjects, changes in indicated orientation angles correlate highly with true attitude changes. Simultaneously tracking different profiles on the pitch and roll axes (as opposed to motion in only one axis) does not significantly affect performance during the relatively simple low frequency stimuli used in experiment 3. As seen in figure 29, the response follows the shape of the profile rather faithfully. The lag factor (time for the response to reach a value equal to the stimulus velocity minus the time for the stimulus to reach that value) ranged from roughly 1 to 2 seconds and is not significantly dependent on stimulus velocity. With system dynamics as predicted by the Ormsby model, the lag factor is several tenths of a second. This implies that there is a 1 to 2 second response lag inherent in the task. It must be assumed that most of this delay is not due to the perceptual mechanism but to transferral of perceptions to the appropriate response.

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

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if the response task is modelled as a transport lag of 1 second plus a first order dynamic lag with a time constant of 0.55 seconds, the resulting lag factor is 1.5 seconds for a stimulus like the standardized rolls and pitches of experiment 3. Other combinations of transport delay and dynamic lag would also be consistent with the data, but any reasonable combination leads to an effective bandwidth of under 0.25 Hz after which the subject could not be expected to track effectively. It would be useful to try the vertical tracking task over a range of higher frequencies than those used to verify this.

Optokinetic display and visual effects

The moving stripe display had little if any effect on either roll orientation or roll velocity estimates during the experiments described before, with two possible exceptions. When data from all subjects is pooled, roll rate magnitude estimates during 2 - 3 degree per second stimuli in experiment 1 show a mean that is 0.82 degrees per second higher for SP4 stripe motion than for stationary stripes. SP4 means that the horizontal stripes "rolled" on the cockpit side windows at a rate four times the cockpit roll rate and in a direction opposite to the cockpit, thus providing a visual cue consistent in direction with true cockpit motion. Although the effect is significant, it is very small and represents a bias that is below the standard deviation of the responses. Proportional stripe motion with smaller gains produced no such effect. It might be interesting to try the same profiles using still higher stripe gains.

In the case of the simulation profiles, one of which employed roll velocities of the same magnitude involved in the above discussion, the stripes had no effect on response magnitude. They may, however, have contributed to the frequent failure of subjects to detect two of the stimuli during SIM2 (turn simulation with a roll profile proportional to that predicted as optimum by the Ormsby model, but twice the magnitude). The result does make sense because during the two stimuli in question, the optokinetic cue contradicts cockpit roll direction; but the significance of the result is very low. The effect cannot be demonstrated at all for SIM1 (turn profile as predicted by the Ormsby model) perhaps because the detection failure occurred so often even without the stripes. The lack of dramatic stripe effects on response magnitudes, while disappointing, is not at all surprising. Most studies have shown that any sort of vection illusion takes at least 5 to 10 seconds to build and most of the stripe rotation periods of these experiments are of shorter duration.

In the case of circularvection about a vertical axis, there is evidence that a complementary yaw motion reduces circularvection onset time and it was hoped that this would be the case for horizontal circularvection also. However, roll and pitch rotations bring the otoliths as well as the canals into play, creating a somewhat different situation. Because of the otoliths, the vestibular system has a much stronger low frequency contribution to pitch and roll orientation perception than is the case for yaw. It is very difficult to completely disorient a person with respect to vertical in a normal 1 g environment.

An unintentional, but unavoidable, factor introduced by having an illuminated cockpit is the visual frame effect. It has been shown that some people have a very strong tendency to align their perceived vertical with any reference frame visible in their environment. The differences in our experiment are that the subject is rotated along with the frame (the cockpit) and the cockpit does not provide such a readily definable frame as was used in these perception experiments.

If the frame effect were to manifest itself during the Link experiment, it would be expected to attenuate responses by encouraging the subjects to keep the hand grip aligned with the cockpit vertical. Although one subject did consistently underestimate orientation angles, other subjects consistently overestimated them and there was no way to tell whether the frame effect played a part. It was definitely exhibited by one phenomenon which does not show up in the data tabulation. Often during experiment 3, when the experimenter flashed the signal light indicating the end of a run, a roll or pitch indication that had been sitting 3 or 4 degrees off vertical would suddenly snap back. Subjects realized that at the finish of a run, the cockpit was probably level and they took the opportunity to realign their indication using the cockpit as a reference.

No extensive attempt was made to eliminate cockpit reference frames. They are certainly present in the real aircraft and simulator cockpits towards which the results of this work are aimed, and it was felt that any such effects might as well be included in the data.

The fact that roll vertical alignment responses do not show any strong tendency to be more accurate than pitch responses across subjects

is a little surprising since depth perception is involved in the pitch task. One subject actually complained about the pitch task saying he was very unsure of the pointer's pitch alignment. Interestingly, his data shows a greater accuracy in pitch than in roll response. There are two possible interpretations of this result. One is that depth perception is more accurate than other elements of the task causing its effect to be buried in the noise. The other possibility is that vision is not terribly important to the performance of the task. A series of runs in a completely dark cockpit would help clarify this.

Implications for the Ormsby model

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

The small dynamic effects predicted by the model are probably overshadowed by the dynamics of the conscious control task and the manual control dynamics involved in quickly moving the meter needle to its target position. It may be useful to look at the calibration profiles with a stochastic version of the Ormsby model. Variances could be compared to the subjective data nad if the model is assumed correct, it may be possible to separate the noise introduced by the response task from that inherent in the perceptions themselves.

The high stimulus-response correlation in the vertical tracking data is also supportive of the model. The variance across subjects is certainly noteworthy but the model cannot be expected to predict this. Ideally, the model should represent the population norm or mean. As mentioned previously, the responses usually follow the shape of the calibration profiles more or less faithfully (see figure 29), but beyond this the model predicts no dynamic effects of a large enough magnitude to be seen through the noise of the data.

The only finding that is decidedly contrary to the Ormsby model predictions is the frequent failure to detect the two roll motions towards vertical during SIM1 and SIM2. During SIM1 roll rate estimation responses, this failure was observed in over 2/3 of 58 possible responses. The effect is also apparent in the vertical tracking data. There are several possible explanations. Perhaps a threshold effect is being observed. The computer model used here does not consider thresholds. The motion involved (>2 degrees of tilt and >2 deg/sec^2 angular acceleration) are

above generally accepted threshold values. Otolith threshold is often quoted as about 0.005 g = 0.3 degrees tilt and the bulk of the data on canal angular acceleration threshold varies roughly between 0.1 degree and 1.5 degree/sec^2, although there are some figures outside this range. These threshold values are usually applied to deviations from zero, under optimum detection conditions, and often employ longer duration accelerations than are used here. If, for instance, the stochastic threshold model discussed by Ormsby is employed, it is conceivable that the results observed during SIM1 will be predicted since the dynamics of the first motion (away from vertical) will affect threshold to the second (back to vertical). SIM2, on the other hand, employs large enough roll angles (greater than 4 degrees) and accelerations (greater than 4 degrees/second^2) to make this seem unlikely as a complete explanation.

Another possible explanation is a blocking effect in which the second pair of motions is not being observed due to the nature of the response task. Note that there is only a two second interval between the first and second motions of each pair. This is shorter than the four second intervals used between stimuli in the calibration profiles and on the order of the response lag discussed before. Remember that even if the response task is modelled as a transport delay and dynamic lag, this pathway involves a conscious evaluation of sensations by the subject and transferal to an open loop manual task. It is reasonable to assume that the period from onset of a stimulus until the subject has settled on an indicator position

requires increased concentration and attention on the part of the subject. If onset of each rolling motion is thought of as a detection problem it can be assumed that if a subject's attention is still focussed on a response to the first stimulus of a pair, he has a higher probability of missing the second. Furthermore, it is also reasonable to assume that this probability will be inversely related to the stimulus magnitude. SIM2 then, having the same roll profile but with twice the magnitude of SIM1, would be expected to exhibit a lower incidence of detection failures.

Still another possibility is that there is some difference inherent in detecting roll towards vertical as opposed to roll away from vertical. This sounds like a rather unlikely explanation since total deviations from vertical are so small (2° for SIM1 and 4° for SIM2).

The final possibility is that the Ormsby model dynamics should be revised to account for this result. It could be done by adding lag somewhere to make the system behave more like an integrator of the short duration roll stimuli in SIM1 and SIM2; however, this would contradict responses observed during the calibration profiles and duirng SIM3. It would mean responses to these stimuli should be more gradual than those observed. In fact if the response to SIM1 is compared to the response to SIM3, it can be seen that they are nearly identical in time course. It is very difficult to see how this could be explained by manipulating the model dynamics. The most probable explanation then, is a combination of the detection

threshold inherent in perception, perhaps as modelled by Ormsby's stochastic threshold model, and an added probability of detection failure introduced by the response task itself.

During the roll angle tracking task, once subjects have correctly indicated a roll away from vertical they can most often be observed to maintain their correct roll angle indication until the next stimulus occurs. Occasionally they will drift slowly towards zero or make a sudden shift back towards zero after from 5 to 30 seconds. There is evidence that once people commit themselves to a decision they will stick with it until it becomes obviously untenable. If a subject begins to feel that his roll angle indication is incorrect, but has noticed no motion, it seems likely that he will exhibit a tendency to stick by his indication as long as possible.

Two Ormsby model time constants have been discussed at length in relation to predicted sensations during the aircraft coordinated turn. One constant, τ_E (see Figure 4), is used to highpass filter unconfirmed canal estimates for the DOWN estimator. The other, τ_L (see Figure 5), is used to high pass filter canal estimates of rotation velocity perpendicular to $\hat{\underline{DOWN}}$, but not reflected by the angular velocity of $\hat{\underline{DOWN}}$. The latter constant is responsible for the paradoxical discrepancy between attitude and angular rate sensations predicted by the model. It was mentioned that the values of these constants are known only within rather vague limits. They cannot be evaluated from the data presented here since they only come into play when the specific force direction history is inconsistent with head attitude history (SF does not remain earth vertical). They might be illuminated, however, by using the subjective response

tasks developed here during real aircraft turns.

The data presented here does not allow any distinction between effects of vestibular and tactile or proprioceptive cues and must be assumed to represent some unknown combination of these. It is also not clear what the relations between these effects are in the Ormsby model. It might be interesting to try a similar set of experiments using a very soft seat designed to distribute pressure as evenly as possible over the body.

Implications for simulation

When subjects experience the Link trainer motion profile considered most likely, on the basis of the Ormsby model, to be the optimum simulation of a coordinated turn maneuver, their responses often differ somewhat from the attitude and angular rate perceptions predicted by the Ormsby model. These differences have already been discussed and it was concluded that the discrepancy can probably be explained by viewing it as a threshold detection problem and considering the workload imposed by the task. At least this seems like a far more likely explanation than any of the ready alternatives. If the computer model used in this thesis represents a signal that is idealized (no random noise) and simply farther back along the pathway than the observed output, then it is a useful tool for gauging simulator fidelity. Unfortunately, the experiments performed so far are not sufficient in themselves

to unambiguiously answer this question. If the discrepancies observed are attributable exclusively to the operation of the assigned response task, we would expect to get nearly the same attitude estimate resposnes if the vertical tracking task is performed in a real aircraft during a turn similar to the one modelled here. The Ormsby model makes the same predictions for altitude perception in both cases and the same deviation of response output from that prediction should result. For the case of roll rate perception, the model predicts a different response in the aircraft than in the simulation. Subject responses to the roll rate magnitude estimation task in the simulator, however, were often more like model predictions for aircraft sensations although of a smaller magnitude. It is therefore not clear what to expect of responses to this task in the aircraft, but it would be extremely interesting to find out.

A possible approach to such an experiment is to put a subject in an aircraft copilot or passenger seat, outfitted with a handgrip device like the one used in this work, and installed in a similar position with respect to the subject. An IFR training visor or some other method would be necessary to restrict the subject from seeing through the windows or seeing the pilot's instruments. It will be impossible for even a talented pilot to precisely reproduce a specified turn profile, but if an inertial package is used to record the actual motion history (attitude, angular rate, and acceleration) any deviations can be taken into account. Turns can probably be made close enough to the idealized profile of Figure 1 to allow meaningful comparisons of subjective vertical tracking task and roll rate estimation data with that presented here. Ormsby model predictions for

both the aircraft and the simulation are shown in Figures 10 and 11. Examples of subjective responses to the predicted optimum simulation profile appear in Figures 24, 25, 29, and 30.

Experimental results indicate that an optokinetic display probably will not contribute much to innate sensations of roll motion in a simulator unless, perhaps, the display is of considerably more compelling nature than the moving stripes used in this work. As discussed before, this result is not surprising in light of the short durations of the roll motions used. This does not imply that the stripe display, or something similar, is not of potential use in simulation. Even if it does not "fool" a pilot with illusory roll motion, it may be used as a cue by pilots and contribute to performance.

The "canned" or predetermined motion profiles used in the experiments here were not really designed for pilot rating of the simulations. Idealization of the turn profile may have an insignificant effect on perceptual quantities when compared to the effects of coordination (maintenance of the specific force vector in vertical alignment with respect to the cockpit), but these small differences may be very important when a pilot is asked to compare his feelings with those he remembers from real flight. It should be expected that the idealized version would feel too mechanical and in fact this was the observation emphasized by the two pilots when asked to evaluate the simulation profiles. Pilots can much more reliably evaluate the realism of a simulation when

they can "fly" the simulator as opposed to being passive observers. It was felt, however, that while the experiment was in operation, there was certainly nothing to be lost by asking pilots to rate the simulation profiles using a very simple "realism" scale. The results do show a definite preference for the profile predicted as best by perception model considerations, but there were only three basic choices. There are many alternative simulation profiles that were not represented. The results do help verify the conclusion that stripe display has very little effect on feelings or sensations of motion during the turn simulation runs. The rating task data can be considered supportive of conclusions drawn from the Ormsby model, but for the reasons cited above and because only two pilots were used, the significance of this support must be considered quite low.

There are two obvious avenues for extension of this work towards motion simulation applications. One is to have subjects perform the vertical tracking and roll rate estimation tasks in an aircraft during the real coordinated turn maneuver. This would be valuable both for comparison with model predictions and with subjective results obtained during various ground based simulations.

The other obvious extension is to convert the Ormsby model predictions into a motion logic system for the Link trainer. The simplest approach is to fit linear dynamics to Ormsby model predictions of optimum simulator profiles for some specific maneuvers such as the coordinated turn discussed here. If this logic were implemented, pilots could actually "fly" the trainer and rate the simulation. Such experiments would aid in determining the validity of the fidelity prediction scheme developed in this work.

10 Summary

The work described in the previous sections is summarized in the thesis of Joshua Borah which was completed by Mr. Borah in June of 1976. This document is undergoing final preparation for reproduction and will be sent separately. It represents a major contribution to the goals of this grant.

VISUAL CUES IN LANDING

1 Background

The aim of this effort is the investigation of the pilot's visual perception of aircraft position and flight path during landing approaches with the ultimate objective of determining the relative importance of various visual cues. The method which is currently being used is to present the subject with a recorded television image of different landing approaches and record his magnitude estimations of deviation from an ideal flight path.

Video tapes of landing approaches were made under the supervision of Dr. Queijo with the Langley Landing Terrain Scene Generator. The approaches were made with random variations in distance, glideslope, and flightpath angle to be appropriate for psychophysical testing. Approximately 10 seconds of each apprach at each distance was recorded. The tapes start with a set of 21 scaling runs to help the subject calibrate his magnitude estimation scale for both glide slope and flight path at each of the three distances. Then follows 81 presentations of the factorial combinations of three glide slopes, three flight paths and three distances, with three replications each.

Preliminary tests were run with the Amphicon 260 video projector set up without the simulator cockpit. Ten subjects of varying flight experience were tested to refine the experimental procedure and provide data to help indicate a better configuration of the video tapes. A data analysis of their responses was performed to check the experimental design.

The following observations have been made from these preliminary experiments:

1. The exposure time of 10 seconds is too long for the short distance (the optical probe is on the runway before the run is over).
2. The closest distance should be shown first during the scaling runs, so that the nominal aim point is well defined.
3. To provide a global view of the scene, we suggest making a complete approach and then running it backwards to provide the subject with the appropriate set.
4. Because there are only three distances, altitude cues could be obtained from the contents of the lower portion of the field of view,

e.g. if a house was visible at a particular distance it meant that the flight path was lower than usual. This can be remedied by taking the nominal distance plus a small perturbation.

5 It would be advantageous to have less time between runs and have the run announced while the screen is blank.

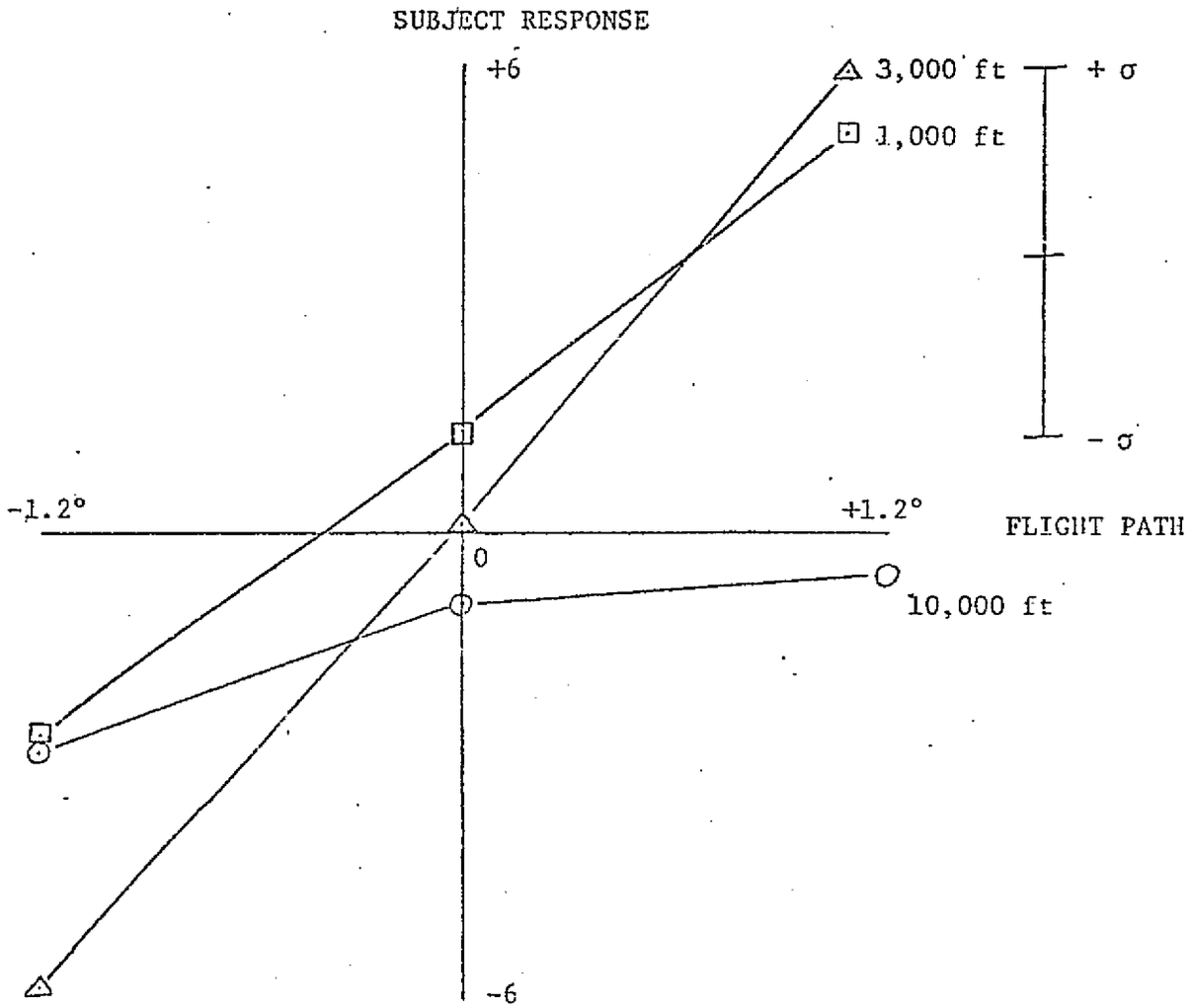
6 One subject complained of the use of a ± 10 scale for magnitude estimates, and felt that the use of glide slope deviation in dots would be more apropos for the experienced airline pilot. However, there still remains the problem of assigning scale values to flight path deviations. (Preliminary results of our experiments indicate that this may not be a problem; the observers seem to respond to flight path *angle* deviation rather than *linear* displacement.)

The magnitude estimates of one subject were processed by an analysis of variance program which simultaneously generates

the functional relation of the dependent variable (glide slope estimate and flight path estimate) as a function of the independent variables. The data for all three distances was pooled for this analysis. The results for the magnitude estimation of flight path are shown in the figure.

It was determined that the magnitude estimate of the flight path angle deviation was significantly affected by distance and flight path only. The psychophysical function is shown in the figure and indicates that the sensitivity of response is approximately the same for 1000 and 3000 foot distances, but is significantly lower at the far distance (10,000 feet). We feel that this is due to the very low angluar velocity or weak streamer effects at these far distances, and the low sensitivity indicates that the pilot is not perceiving the same angular flight path error that he does at the nearer distance.

For the magnitude estimation of the deviation of the glide slope from normal, the main effect appears to be due to the glide slope deviation itself; there was no interaction between the glide slope deviation and the other variables. However, there were strong and significant interactions between the distance and flight path, i.e. they strongly influenced the glide slope estimates.



MAGNITUDE ESTIMATE OF FLIGHT PATH ANGLE DEVIATION

The suggested changes in the experimental procedure and in the stimuli are listed below.

Experimental Procedure

1. Shorter sessions (less than one hour)
2. One estimate per landing (either glide slope or flight path, but not both)
3. Verbal estimates (no manual tasks)
4. Cleaner tapes (less noise between runs and more impersonal audio narration)

The combination of (1) and (2) requires two test sessions of moderate length rather than a single long session.

Stimuli Changes

1. Full length reverse and normal approach at the beginning of the session to establish a reference normal approach.
2. Fix only two points on the magnitude scaling runs (no repetition of normal approaches during the scaling runs)
3. Three replications of four stimulus levels (two positive and two negative), distributed randomly.

4 Distribute stimuli corresponding to normal approaches throughout runs to check for subject's scaling drift.

2 New Experiments

A new set of tapes was recorded during the spring at Langley Research Center under the supervision of Mr. C.W. Acree. This set incorporates the following changes.

1 Two initial approach distances: 3000 ft and 6000 ft.

2 Three degree normal glideslope with ± 0.5° and ± 1.0° deviation stimuli, and ± 1.5° scaling stimuli.

3 Three degree normal flightpath (zero deviation from glideslope), with ± 0.6° and ± 1.2° deviation stimuli, and ± 1.8° scaling stimuli.

4 Three replications of each of four levels of two types of stimuli (flightpath and glideslope) at each of two distances (96 runs), plus eight initial scaling runs distributed throughout each set of replications for a total of 128 runs.

5 Run times computed to keep changes in glide slope within one standard deviation of normal subject responses on worst case runs, or 5.33 seconds at 3000 foot approach distance and 10.65 seconds at 6000 foot.

A five second delay in taping was made at the beginning of each run to reduce recorded start-up transients of the simulator. This eliminated some of the tape noise between runs, but most of the noise, start-up trasients, and jumps and wiggles ofthe image were due to the video recorder (which cannot be controlled by the simulator computer). Nevertheless, the tapes represent an improvement and are suitable for full scale testing.

3 Equipment

An attempt was made to record a computer-generated runway image and display it on the Amphicon projector by viewing the computer's CRT with a TV camera. The combination of the low sensitivity Sony camera with the moderate brightness of the ADAGE CRT resulted in poor picture quality. Improvement may be possible by using simpler programs to increase display speed and brightness, and by reducing the amount of background light to improve contrast

during filming and projecting. The use of a higher sensitivity camera might also be tried.

Modeification of the simulator to allow out-the-window visual simulation is proceeding. The simulator room has been rearranged to make room for the large rear projection screen, and the screen frame has been modified to allow it to fit under some low-hanging light fixtures. The Amphicon projector head has been installed in the ceiling to provide the longest possible optical path using a reflecting mirror. A window shade will be installed to reduce the amount of background light.

A brief test was made to check the projector installation and screen location. The available mirror was considerably undersized, so the image brightness was much lower than it normally would be, but the image was reasonably good. The presence of large amounts of background light adversely affected the image contrast, but this will be eliminated by the installation of a window shade for the room.

After the window shade is installed, the projector performance will be checked again before ordering a proper full-size mirror. The simulator cockpit display electronics will need to be remounted on smaller racks before the cockpit can be fully utilized for out-the-window displays.

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INTEGRATION OF SEMICIRCULAR CANAL AND OTOLITH INFORMATION FOR MULTI-SENSORY ORIENTATION STIMULI†

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Definition of Symbols

Specific Variables

$\underline{A}$	Translational Acceleration of Head (g's)
$\underline{G}$	Gravitational Acceleration Vector (1 g)
$\underline{SF}$	Specific Force Vector ($\underline{G} - \underline{A}$) (g's)
$\underline{DOWN}$	Unit Vector Pointing Toward the Earth's Center
Ψ	Azimuth Orientation of the Head
$\underline{V}$	Translational Velocity of the Head
$\underline{X}$	Position of the Head
$\underline{\omega}_c(t)$	Rotation Information Available to the "DOWN" Estimator from the Semicircular Canals
$\underline{i}_{xc}, \underline{i}_{yc}, \underline{i}_{zc}$	Orthonormal Unit Vectors Aligned with Sensitive Axes of Semicircular Canals
$\underline{i}_x, \underline{i}_y, \underline{i}_z$	Orthonormal Unit Vectors Aligned with the Head's Roll, Pitch and Yaw Axes Respectively
$\underline{i}_{x_0}, \underline{i}_{y_0}$	Orthogonal Unit Vectors in Average Plane of the Utricular Macula
$\underline{i}_{z_0}$	Unit Vector Perpendicular to Average Plane of the Utricular Macula
$\underline{\omega}(t)$	Angular Velocity of Head with Respect to Inertial Space
$\underline{\omega}_{HD}(t)$	$\underline{\omega}_c(t)$ Transformed to Head Coordinates ($\underline{i}_x, \underline{i}_y, \underline{i}_z$)
$\underline{SF}_{HD}$	Specific Force Vector in Head Coordinates

$\hat{SF}$	Specific Force Information Available from Otolith Sensors
$\underline{\tilde{SF}}$	Subjective Estimate of Specific Force Vector in $\underline{i}_{xo}$, $\underline{i}_{yo}$, $\underline{i}_{zo}$ Coordinates
$\underline{\omega}_D$	Bodily angular rate consistent with the rate of change of $\underline{\hat{DOWN}}$
$\underline{\omega}^H_{SF}$	High Frequency Portion of $\underline{\omega}_{\hat{SF}}$
$\underline{\omega}^L_{SF}$	Low Frequency Portion of $\underline{\omega}_{\hat{SF}}$
$\underline{\omega}^c_c$	Portion of $\underline{\omega}^H_{SF}$ which is Consistent with Rotation Rate Indicated by the Canal System
$\underline{\omega}^i_c$	Portion of $\underline{\omega}^H_{SF}$ which is Inconsistent with Rotation Rate Indicated by the Canal System
$\underline{\hat{\omega}}_{\parallel}$	Subjective Sensation (Estimate) of Rotation Rate Parallel to $\underline{\hat{DOWN}}$
$\underline{\hat{\omega}}_{\perp}$	Subjective Sensation (Estimate) of Rotation Rate About a Horizontal Axis (Perpendicular to $\underline{\hat{DOWN}}$)
$\underline{\hat{\omega}} = \underline{\hat{\omega}}_{\parallel} + \underline{\hat{\omega}}_{\perp}$	Subjective Estimate of Rotation Rate of Head with Respect to Inertial Space

General

$\hat{X}(t)$	Subjective Sensation (i.e., Estimate) of $\underline{X}(t)$
$X(s)$	Laplace Transform of $X(t)$
$\underline{X}$	Underscore denotes vector quantity

Introduction

In this paper the subjective responses to multisensory stimuli (those stimuli which simultaneously excite the semicircular canals and otoliths) are modelled and the predictions of this model compared to the appropriate experimental data. Previous quantitative models have dealt almost exclusively with the response to noninteracting stimuli (those stimuli which excite either the semicircular canals [19, 22, 26, 28] or the otoliths [13, 27] but not both). When the stimulus class is generalized to include any combination of rotational acceleration and translational acceleration in three axes a number of significant problems arise. After these problems are discussed a mathematical model is developed of the perception of dynamic orientation which results from the combined effect of arbitrary angular and translation accelerations. To illustrate the usefulness of the model for the conceptual understanding of responses to multisensory stimuli, three examples of the qualitative applications of the model are given. The paper concludes by presenting the quantitative predictions of the model along with the model's frequnecy response for small pitch and roll angle oscillations.

Discussion of Modelling Problems and Philosophy

Before discussing any of the problems associated with the integration of sensory information from the semicircular

canals and otoliths it is important to clarify what the important perceptual outputs of the model should be. Certainly we would be interested in estimating the following quantities:

1. Orientation of the head with respect to the gravitational vertical
2. Rate of rotation of the head about its three principle axes
3. The translational acceleration of the head with respect to its three principle axes

and 4. Additional quantities which are dervied from the preceeding (e.g., azimuth, translational velocities, and translational positions).

The most important of these is the determination of orientation with respect to the vertical. Strictly speaking, there is no way of using information which is derived only from the otoliths to determine the direction of the gravitational vertical if there is no a priori information regarding the expected variations in orientation or translational acceleration. The principle of equivalence in general relativity precludes such a separation based purely on measurements taken from linear accelerometers. How then are we capable of distinguishing a change in orientation with respect to the gravitational vertical from a change in acceleration? The answer to this question has two parts. First, we are not restricted to the use of

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linear accelerometers (otoliths) since we also have angular velocity transducers (the semicircular canals) which indicate with reasonable accuracy the rate of change of the head's orientation for rotational rates in the frequency range from 0.1 rad/sec to 10 rad/sec. Roughly speaking, for changes in the direction of specific force which occur in this frequency range (as determined from otolith information) the distinction between a change in orientation with respect to the gravitational vertical and a translational acceleration (or some combination of the two) can be made by noting the output of the semicircular canals. As the frequency of the variations in the direction of the specific force vector decreases below .1 rad/sec, information from the canals becomes less and less useful. In fact as the frequency of these variations approaches zero the system becomes incapable of determining the true gravitational vertical. The second part of the answer therefore is that for lower frequency variations the system cannot concern itself with the true gravitational vertical but must be content to estimate an "effective gravitational vertical" which can serve as the practical reference for man's normal activities. The phenomenon of associating the gravitational vertical with the perceived direction of specific force for very low frequency (essentially static) stimuli was discussed in detail in a previous paper [18].

Once the direction of the gravitational vertical is estimated, the other perceptual quantities can be dervied.

The sensation of rotation about an axis parallel to the perceived gravitational vertical ($\hat{\underline{\omega}}_{\parallel}$) will reflect exclusively the dynamic response of the semicircular canals. The perception of rotation about an axis perpendicular to the perceived vertical ($\hat{\underline{\omega}}_{\perp}$) should reflect the information available from the canals and the otoliths. Since the otoliths are capable of sensing a constantly changing orientation with respect to the gravitational vertical the perception of constant rotation about a horizontal axis should persist indefinitely. Benson and Bodin [1] and Guedry [12] confirm that the perception of rotation does indeed persist for prolonged rotations about a horizontal cephalocaudal axis.

The estimate of translational acceleration is essentially determined once the direction of gravity is estimated since

$$\underline{A} = \underline{G} - \underline{SF} \qquad (1)$$

where $\underline{A}$ = translational acceleration (g's)

$\underline{G}$ = gravitational vector (normally 1 g)

and $\underline{SF}$ = net specific force vector or gravito-inertial reaction force (g's)

The only change needed in equation 1 is the replacement of each term by its estimate (e.g., $\underline{A}$ by $\hat{\underline{A}}$, etc.). To maintain the notation used in the previous paper on static orientation [18] the estimate of $\underline{G}$ will be denoted by $\hat{\underline{DOWN}}$ since this is more descriptive of its perceptual meaning. The remaining perceptual quantities (azimuth, translational

velocity and translational position) are obtained by integration as follows:

$$\hat{\Psi}(t) = \hat{\Psi}(t_0) + \int_{t_0}^{t} |\hat{\underline{\omega}}_{\parallel}(\eta)| d\eta \qquad (2)$$

$$\hat{\underline{V}}(t) = \hat{\underline{V}}(t_0 + \int_{t_0}^{t} \hat{\underline{A}}(\eta) d\eta \qquad (3)$$

$$\hat{\underline{X}}(t) = \hat{\underline{X}}(t_0) + \int_{t_0}^{t} \hat{\underline{V}}(\eta) d\eta \qquad (4)$$

where $\hat{\Psi}$ is the estimated angle between the projection of the head's roll axis (i_x) in the earth's horizontal plane and some fixed direction in that plane (e.g., a vector pointing toward true north).

$\hat{\underline{\omega}}_{\parallel}$ is the perception of rotation about an axis parallel to $\hat{\underline{DOWN}}$

$\hat{\underline{V}}$ is the perception of linear velocity

and $\hat{\underline{X}}$ is the perception of spatial position.

In all, the model should be capable of predicting 15 quantities (3 associated with $\hat{\underline{\omega}}$, 3 associated with $\hat{\underline{A}}$, 3 associated with $\hat{\underline{V}}$, 3 associated with $\hat{\underline{X}}$, 2 associated with the direction of $\hat{\underline{DOWN}}$, and 1 associated with $\hat{\Psi}$). Of these 15, the 2 associated with the direction of $\hat{\underline{DOWN}}$ are by far the most difficult to model quantitatively and for this reason the model developed in this paper is referred to as the "down" estimator. Equations 1-4 determine the quantities $\hat{\underline{A}}$, $\hat{\underline{\Psi}}$, $\hat{V}$, and $\hat{\underline{X}}$ as a function of $\hat{\underline{DOWN}}$ and $\hat{\underline{\omega}}_{\parallel}$ (since $\hat{\underline{\omega}}_{\parallel}$ is the portion of $\hat{\underline{\omega}}$ parallel to $\hat{\underline{DOWN}}$.)

Before considering these estimators (for $\underline{DOWN}$ and $\underline{\omega}=\underline{\omega}_{\parallel}+\underline{\omega}_{\perp}$) in detail, several problems require consideration. The

first of these is the problem of reconciling what may seem to be contradictory information from the canals and otoliths. Three examples can be cited for which there exists corresponding data. The first of these involves an abrupt change in the direction of the specific force vector relative to the head ("rotation information" from the otoliths) without any corresponding indication of rotation from the canals (e.g., aircraft catapult launch [6], or a change in the direction of specific force due to rotation on a centrifuge [9]). A second example of such a conflict would arise in the case of a constant rotation about a horizontal axis which would lead to a continuously rotating specific force vector but a zero steady state output from the canals (e.g., a barbecue-spit experiment [1, 2, 12]). Finally, situations may arise in which the canals indicate an abrupt rotation about a horizontal axis but the otoliths indicate no change in the direction of specific force (e.g., a coordinated aircraft turn or the abrupt cessation of rotation in a barbecue-spit experiment [1, 2, 12]). Since several of these examples will be treated in detail in the remaining sections of this paper it is unnecessary at this point to give a full accounting of the perceptual responses except to say that the perception of the vertical for these stimuli is most strongly associated with:

1. The low frequency portion of the "rotation information" from the otoliths

plus 2. that part of the canal information which is consistent with the high frequency portion of the "rotation information" from the otoliths.

Since the rate of movement of the perceived vertical may not be consistent with the estimate of rotation based only upon canal information the question arises whether the perception of rotation reflects the movement of $\underline{\hat{DOWN}}$ or canal information or a combination of the two. If the time histories of $\underline{\hat{DOWN}}$ and $\hat{\underline{\omega}}_{\perp}$ (the component of $\hat{\underline{\omega}}$ perpendicular to $\underline{\hat{DOWN}}$) were to be consistent then in the situation in which the direction of $\underline{\hat{DOWN}}$ is constant (in head axes) it must follow that $\hat{\underline{\omega}}_{\perp} = \underline{0}$. The experimental evidence [1, 2, 12]) does not consistently support this conclusion and thus $\underline{\hat{DOWN}}$ and $\hat{\underline{\omega}}_{\perp}$ may not be in agreement. Although such a contradictory sensation (of rotating but not changing one's position) seems difficult to imagine, it is also found in cases in which otolithic and visual information conflict [7, 29] and during caloric testing. The fact that these sensations are contradictory also complicates interpretation of some of the experimental data. For example, if an experimenter asked a subject if he felt himself rotating the subject could answer either "yes" or "no" (in fact an answer of yes <u>and</u> no would be more appropriate!).

A second problem arises in the case of stimuli which are predictable, usually because the subject is thoroughly familiar with the stimulus from past experience and is able

to recognize the underlying stimulus pattern. The phenomena associated with such a situation are significantly different from those which we are attempting to model here since they involve the complex problems of pattern recognition. Furthermore, it is very likely that the processes involved in recognition are strongly dependent on the simplicity of the stimulus, the subject's past exposure, and many other factors which would make an accurate prediction of dynamic orientation extremely difficult. For these reasons the stimulus class for which we are attempting to model the perceptual responses will be assumed to be unpredictable.

Finally, the information upon which the "down" estimator bases its estimate must be considered. Although the information from two sets of semicircular canals and otoliths is available to the brain it is unnecessary to waste computation time performing a dual set of sensory simulations. For this reason, the model simulates cyclopian sensors located near the center of the skull. The three canals are aligned with and are sensitive to rotation about three head fixed, orthogonal axes (the particular set of axes chosen is arbitrary). The combined dynamic response of each canal and its associated higher processor can be approximated [17] by the following linear relationship:

$$\hat{\omega}(t) = \mathcal{L}^{-1}\left\{\frac{540s^2}{(18s+1)(30s+1)}\omega(s)\right\} \qquad (5)$$

where $\omega(s)$ is the Laplace transformed rotation rate about the canal's sensitive axis (radians/second)

$\hat{\omega}(t)$ is the average subjective perception of rotation (radians/second) about that canal's sensitive axis

and $\mathcal{L}^{-1}$ is the inverse Laplace transform operator

The linear relation given in equation 5 is a simplified version of the transfer function developed in [17] because it neglects the short time constant of the canals $(1/(.005s + 1))$ and the slight rate sensitivity seen in canal afferents $(.01s + 1)$. Neither of these terms would have a significant enough effect on the response of the model to justify their presence. Figure 1 summarizes the information available to the "down" estimator from the semicircular canals. The estimates of rotation rate based upon canal information are transformed from sensor coordinates $(\underline{i}_{xc}, \underline{i}_{yc}, \underline{i}_{zc})$ to head coordinates since the principle head axes ($\underline{i}_x$ roll axis, roll right positive; $\underline{i}_y$ pitch axis, pitch down positive; $\underline{i}_z$ yaw axis, yaw left positive) are the most natural coordinates to which to refer our conscious perceptions of dynamic orientation.

The otoliths are modelled as three linear accelerometers sensitive to the components of specific force along three mutually orthogonal axes. The combined dynamic response of these accelerometers and their associated higher processors (see Reference [17] section 3.2) is given by

$$\hat{SF}(t) = \mathcal{L}^{-1}\left[\frac{.911(s + .988)}{(s + .133)(s + 1.95)} SF(s)\right] \qquad (6)$$

where $SF(s)$ is the Laplace transform of the component of $\underline{SF}(t)$ (g's) along the sensitive axis of the accelerometer

$\hat{SF}(t)$ is the average subjective response (g's)

The illusions which arise in the perception of static orientation [3, 4, 5, 10, 11, 14, 15, 16, 20, 21, 23, 24, 25] indicate that errors exist in the sensing of specific force or in the processing of the sensory information related to specific force and that these errors are related to that component of specific force perpendicular to the "average plane" of the utricular macula [18]. For this reason one accelerometer is aligned with its axis ($\underline{i}_{zo}$) perpendicular to the average utricular plane (≈25-30 degrees pitched back relative to the vertical when the head is the normal upright position) while the sensitive axes of the other two accelerometers ($\underline{i}_{xo}$, $\underline{i}_{yo}$) will be orthogonal and lie in the utricular plane. Figure 2 illustrates the information available to the "down" estimator from the otolith sensors. The alteration of the sensed component of specific force along $\underline{i}_{zo}$ is discussed at length in references [17] and [18]. The accelerometers sensitive to changes in specific force along $\underline{i}_{xo}$ and $\underline{i}_{yo}$ are associated with the utricle and the accelerometer aligned with $\underline{i}_{zo}$ is associated with the saccule since the major component of the functional polarization vectors of the utricle and saccule are in the $\underline{i}_{xo}$, $\underline{i}_{yo}$ plane and along the $\underline{i}_{zo}$ axis respectively [8]. Finally the estimates of specific force are transformed from sensor axes ($\underline{i}_{xo}$, $\underline{i}_{yo}$, $\underline{i}_{zo}$) to the principle head axes ($\underline{i}_x$, $\underline{i}_y$, $\underline{i}_z$) as was done for the estimates of rotation.

DOWN Estimator

After numerous algorithms were developed in an attempt to produce an estimator with the desired qualifications, one was found which fulfills all of the requirements discussed previously and which yields very reasonable quantitative results. The discrete "down" estimator is illustrated in Figures 3 and 4. The information available to the "down" estimator at the beginning of each update is the old estimate of down, $\hat{\underline{DOWN}}(t-\Delta t)$ and the new estimates based upon canal information $(\hat{\underline{\omega}}_{HD}(t))$ and upon otolith information $(\hat{\underline{SF}}_{HD}(t))$. Figure 3 illustrates the calculation of the updated perception of down, $\hat{\underline{DOWN}}(t)$ and Figure 4 illustrates the updated perception of rotation, $\hat{\underline{\omega}}(T)$. Each element of the model is labeled with a letter (from A to L) for easy reference and will be discussed in alphabetical order.

The first element, labeled A and marked with an X, represents the following computational procedure: produce a vector $\underline{\omega}_{\hat{SF}}$ which is in the direction $\hat{\underline{SF}}_{HD}(t-\varepsilon) \times \hat{\underline{SF}}_{HD}(t+\varepsilon)$ and which has a magnitude equal to the angular rate of change of the direction of $\hat{\underline{SF}}_{HD}$ at time t. In the computer simulations described later, $\hat{\underline{\omega}}_{SF}$ was calculated each second $(t = 1, 2, 3, 4, \ldots)$ and $\hat{\underline{SF}}_{HD}$ was calculated on the half second $(t = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots)$ so $\varepsilon = \frac{T}{2} = 0.5$ seconds. $\underline{\omega}_{\hat{SF}}$ would represent the information available from the otoliths concerning the rate of rotation of the head <u>if</u> it were assumed that <u>SF</u> was fixed in space.

The low pass filter, labeled B, performs the function of separating out the low frequency component of $\underline{\omega}_{\hat{SF}}$ which is assumed to arise from the change in the body's orientation with respect to the gravitational vertical. The output signal $\underline{\omega}^{L}_{SF}$ is intended to fill in the low frequency information missing from the canal signal $\underline{\hat{\omega}}_{HD}$ for rotation about a horizontal axis. $\underline{\omega}^{H}_{SF}$ is the high frequency component of $\underline{\omega}_{\hat{SF}}$ and typically arises from both transient linear accelerations and abrupt changes in the head's orientation with respect to the gravitational vertical. The best time constant for the low pass filter was found to be approximately 35 seconds.

The transformation labeled C produces a rotation vector $\underline{R}_{OTO}$ from $\underline{\omega}^{L}_{SF}$ as follows:

$$\underline{R}_{OTO} = \begin{cases} \text{Component of } \underline{\omega}^{L}_{SF} \text{ which is perpendicular to the} \\ \text{plane of } \underline{\hat{SF}}_{HD} \text{ and } \underline{\hat{DOWN}}(t-\Delta t) \end{cases} \qquad (7)$$

It may seem odd at first that this transformation allows rotations which might be themselves move $\underline{\hat{DOWN}}$ away from $\underline{\hat{SF}}$. The reason for this is that such rotations are necessary to cancel the canal signals which arise when prolonged rotations are suddenly stopped. It is this mechanism which helps to predict the stabilization of the perception of orientation when prolonged rotations about a horizontal axis are abruptly terminated as was found experimentally by Benson and Bodin [1,2] and Guedry [12]. In all the

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simulations carried out no case has been encountered in which $\underline{R}_{SCC}$ (which will be discussed next) did not cancel completely any $\underline{R}_{OTO}$ which would move $\underline{\hat{DOWN}}$ away from $\underline{\hat{SF}}$. If such a case occurred it would appear reasonable to decrease the magnitude of $\underline{R}_{OTO}$ until the net effect of $\underline{R}_{TOT} = \underline{R}_{OTO} - \underline{R}_{SCC}$ would be to minimize the misalignment of $\underline{\hat{DOWN}}$ and $\underline{SF}$ after rotation. *The combined effect of elements* A, B *and* C *in figure 3 is to produce a rotation vector* $\underline{R}_{OTO}$ *from the current and past estimates of* SF *which represents the low frequency rotational rate information due to the otoliths. It is this characterization of this pathway which is most useful when the model is used to make a qualitative prediction of the response to a simple stimulus without extensive simulation.*

We now turn our attention to the information from the canals. The rotational information from the semicircular canals must be consistent with the high frequency sensations arising from the otoliths (represented by $\underline{\omega}^{H}_{SF}$) if it is to be used to update the sensation of orientation with respect to the vertical. The portion of $\underline{\hat{\omega}}_{HD}(t)$ which is consistent with $\underline{\omega}^{H}_{SF}$ is denoted by $\underline{\omega}^{C}_{C}$ and is calculated by the following procedure:

1) Calculate the component of $-\underline{\hat{\omega}}_{HD}(t)$ which is parallel to $\underline{\omega}^{H}_{SF}$. Call this component $\underline{C}$.
2) If $\underline{C}$ is in a direction opposite to $\underline{\omega}^{H}_{SF}$ then set $\underline{\omega}^{C}_{C} = \underline{0}$

3) If $\underline{C}$ is in the same direction as $\underline{\omega}^H_{SF}$ then set

$$\underline{\omega}^C_C = -\underline{\omega}^H_{SF} \text{ if } |\underline{C}| > |\underline{\omega}^H_{SF}|$$
$$\underline{\omega}^C_C = -\underline{C} \quad \text{if } |\underline{C}| < |\underline{\omega}^H_{SF}| \tag{8}$$

The portion of $\hat{\underline{\omega}}_{HD}(t)$ which is inconsistent with $\underline{\omega}^H_{SF}$ is denoted by $\underline{\omega}^i_C$ and is given by

$$\underline{\omega}^i_C = \hat{\underline{\omega}}_{HD}(t) - \underline{\omega}^C_C \tag{9}$$

The reason that $-\hat{\underline{\omega}}_{HD}(t)$ (instead of $\hat{\underline{\omega}}_{HD}(t)$) was compared with $\underline{\omega}^H_{SF}$ is that for a positive perception of rotation the corresponding rotation of the g vector would be negative.

While experimental evidence clearly indicates that the effect of $\underline{\omega}^i_C$ on the perception of orientation is minimal it is not clear that it has no effect in the very short term (<1 sec). For this reason $\underline{\omega}^i_C$ is passed through a high pass filter (E) of the form $\tau s/(\tau s + 1)$ where $\tau < 1$ sec. For the catapult launch simulation described at the end of this paper τ could be no higher than .25 seconds to retain reasonable results. A value of $\tau = 0$ would not be inconsistent with any available experimental evidence.

The rotation vector due to canal information is denoted by $\underline{R}_{SCC}$. $\underline{R}_{SCC}$ is computed by taking the sum of $\underline{\omega}^C_C$ and the result of filtering $\underline{\omega}^i_C$ and then eliminating the component which is parallel to the last estimate of down (since this component is ineffective in changing the direction of $\hat{\underline{\text{DOWN}}}$ relative to the head). *For rapid qualitative predictions,*

this pathway (D and F, ignoring E) can be thought of as isolating that portion of the canal signal which is consistent with $\underline{\omega}^{H}_{\hat{SF}}$ *and is perpendicular to* $\underline{\hat{DOWN}}$.

$\underline{R}_{TOT}$ is then computed by subtracting $\underline{R}_{SCC}$ from $\underline{R}_{OTO}$. $\underline{R}_{TOT}$ represents the estimate of the rotational rate of the outside world around an axis perpendicular to the last estimated direction of down for the purposes of updating that estimate. The transformation labeled G updates $\underline{\hat{DOWN}}(t-\Delta t)$ using $\underline{R}_{TOT}$. The output of G is denoted by $\underline{D}'(t)$ and satisfies

1) $\underline{\hat{DOWN}}(t-\Delta t) \times \underline{D}'(t)$ is in the same direction as $\underline{R}_{TOT}$

and 2) the angle between $\underline{\hat{DOWN}}(t-\Delta t)$ and $\underline{D}'(t)$ is given by $|\underline{R}_{TOT}|\Delta t$

Therefore, if $|\underline{R}_{TOT}| = 30$ degrees/sec and $\Delta t = 0.5$ seconds $\underline{\hat{DOWN}}$ will be rotated about $\underline{R}_{TOT}$ by 15 degrees.

$\underline{D}'(t)$ would normally be considered the new estimate of "down" except that because it is generated through the integration of rate information it is bound to accumulate errors which must be eliminated if permanent discrepancies are to be avoided. This is accomplished through a slow reduction of any discrepancy in direction between $\underline{D}'$ and $\underline{\hat{SF}}$ (elements H and I). The time constant, τ_p, is quite large but was found to be a weak function of the magnitude of the specific force vector (as $|\underline{\hat{SF}}|$ increases, τ_p decreases and $\underline{D}'$ moves toward SF more rapidly). τ_p (in seconds) is given by

$$\tau_p \approx \frac{60}{|\hat{\underline{SF}}|^{1/4}} \qquad (11)$$

The net effect of H and I is that in a steady state condition, the subject adopts the estimated specific force vector, based on otolith information, as the correct direction for $\hat{\underline{DOWN}}$. This insures that the steady state response of the model will exhibit the perceptual errors discussed and modelled in References [17] and [18].

The resulting estimate of $\hat{\underline{DOWN}}(t)$ represents the model's prediction for the subject's perception of the direction of the gravitational force vector with respect to his head. This estimate is then used at time $t + \Delta t$ to generate a new estimate.

The model for predicting the perceived rate of bodily rotation is shown in Figure 4. $\hat{\underline{\omega}}_{||}(t)$ is found simply by taking the component of $\hat{\underline{\omega}}_{HD}(t)$ parallel to $\hat{\underline{DOWN}}(t)$. $\hat{\underline{\omega}}_D$ is defined to be the bodily rate of rotation which would be consistent with the rate of change of the direction of $\hat{\underline{DOWN}}$. The transformation K is similar to that at A in figure 8.3 except for a minus sign. $\hat{\underline{\omega}}_{\perp}(t)$ is formed by:

1) calculating the difference between $\hat{\underline{\omega}}_D$ and the component of $\hat{\underline{\omega}}_{HD}(t)$ which is perpendicular to $\underline{DOWN}$ ($\underline{\omega}_E = \underline{\omega}_{\perp}' - \hat{\underline{\omega}}_D$)
2) passing this difference through a high pass filter (L) and then
3) adding the resulting output to $\hat{\underline{\omega}}_D$.

This arrangement accepts the relatively high frequency changes in rotation rate indicated by the semicircular canal system

while deferring to the rate of rotation consistent with $\hat{\underline{DOWN}}$ for lower frequency changes. Data from Benson and Bodin [1, 2] indicates that a filter of the form $\tau s/(\tau s + 1)$ with $\tau \approx 0$ to 5 seconds should be sufficient (if $\tau = 0$ then $\hat{\underline{\omega}}_{\perp}(t) = \hat{\underline{\omega}}_D$ and $\hat{\underline{\omega}}_{\perp}$ would be completely consistent with $\hat{\underline{DOWN}}$). The total sense of rotation, $\hat{\underline{\omega}}(t)$ is given by the sum of $\hat{\underline{\omega}}_{||}(t)$ and $\hat{\underline{\omega}}_{\perp}(t)$.

This completes the component by component review of the model. Before describing the quantitative results which were produced by computer simulation, some examples of qualitative predictions will be given.

First consider a standard rate aircraft turn which is abruptly stopped by rolling out of the turn rapidly into level flight. Just before the rollout the subject will perceive himself to have zero roll angle with respect to the earth vertical and a slightly pitched back orientation due to the slightly increased g force in the turn (elevator illusion, see Reference [5]). In addition he will have no sense of rotation since the canal response to the rotation of the aircraft has long since decayed to zero and $\hat{\underline{\omega}}_D = 0$. During the roll out the specific force vector will remain aligned with the yaw axis of the body and diminish in intensity to 1 g. $\hat{\underline{SF}}$ will therefore slightly diminish in intensity and will pitch forward about 1 or 2 degrees (to eliminate the slight pitched back sensation). Since the direction of $\hat{\underline{SF}}$ remains practically constant the otolith pathway $\underline{R}_{OTO}$

can be considered inactive. Since $\underline{\omega}^{H}_{SF}$ will also equal zero all of $\hat{\underline{\omega}}_{HD}$ will be considered inconsistent (both that part of $\hat{\underline{\omega}}_{HD}$ generated by the rolling out rotation and that due to the after sensation of stopping the aircraft's turn rate). Consequently all of $\hat{\underline{\omega}}_{HD}$ is passed through the high pass filter and is quickly reduced to zero. Therefore, for rough calculations $\underline{R}_{SCC} = 0$ and except for the elimination of the elevator illusion $\hat{\underline{\text{DOWN}}}$ will remain essentially unchanged and the subject should sense that he is erect.

Since $\hat{\underline{\text{DOWN}}}$ is essentially unchanged, $\underline{\omega}_D$ in Figure 4 is approximately zero. The component of $\hat{\underline{\omega}}_{HD}$ which arose from the roll out motion of the aircraft is $\perp$ to DOWN and will therefore be assigned to $\underline{\omega}_{\perp}$. Since $\underline{\omega}_D = \underline{0}$, $\underline{\omega}_E$ is set equal to $\underline{\omega}_{\perp}$ and is high pass filtered with a time constant less than 5 seconds. $\hat{\underline{\omega}}_{\perp}(t)$ equals the output of this filter (since $\underline{\omega}_D = 0$) which merely implies that the rolling sensation is shorter lived (due to the high pass filter) than it would have been if the otolith information had not contradicted it. The component of $\hat{\underline{\omega}}_{HD}$ which arose from the aircraft stopping its rate of turn will be in the opposite direction to the original turn and will be essentially parallel to the direction of $\hat{\underline{\text{DOWN}}}$. Therefore this component of $\hat{\underline{\omega}}_{HD}$ will become $\hat{\underline{\omega}}_{||}(t)$ and the subject will perceive himself to be turning in a direction opposite to the original turn. The sensations described above are consistent with the illusions known to be associated with aircraft flight. Circumstances which could interfere with

these illusions are the following:

1) A passenger with extensive flying experience who expected the turn or roll out might be capable of interpreting the sensations correctly.

2) The pilot who initiated the roll out would certainly have little inclination towards illusions,

or 3) Any visual information would affect the predicted perception since the model presumes that there are no visual cues.

A second example is that of a step in lateral acceleration of 1 g. Initially the subject correctly perceives himself to be in an erect position in 1 g. Since the subject is never rotated during the experiment the canals are not stimulated and $\hat{\underline{\omega}}_{HD} = \underline{0}$. Referring to Figure 4 we can conclude that:

$$\hat{\underline{\omega}}(t) = \hat{\underline{\omega}}_{\perp}(t) = [1 - \frac{\tau s}{\tau s + 1}]\ \hat{\underline{\omega}}_{D}(t) \qquad (12)$$

The only active pathway in Figure 3 is that for the information from the otoliths. $\hat{\underline{SF}}$ will move very rapidly toward $\underline{SF}$ and then stop which will induce a rapid rise in $\hat{\underline{\omega}}_{SF}$ followed quickly by a rapid decay to zero. $\underline{\omega}^{L}_{SF}$ will rise quickly during the period in which $\hat{\underline{\omega}}_{SF}$ is large and will then slowly decay to zero. Since $\underline{\omega}^{L}_{SF}$ is perpendicular to both $\hat{\underline{DOWN}}(t - \Delta t)$ and $\hat{\underline{SF}}$, it will pass through C and $\underline{R}_{OTO}$ will equal $\underline{\omega}^{L}_{SF}$. Finally $\hat{\underline{DOWN}}$ will move toward $\hat{\underline{SF}}$ at a rate proportional to the magnitude of $\underline{\omega}^{L}_{SF}$ (actually a little faster since the lower pathway in Figure 3 will help somewhat

in moving $\underline{\hat{DOWN}}$ toward $\hat{SF}$). Figure 5 shows a rough sketch of the approximate time course of these signals.

The last case to be considered before presenting quantitative results is the phenomenon associated with the experiments of Benson and Bodin [1, 2] and Guedry [12]. For a steady state rotation of $\underline{\omega}$ about a horizontal axis:

$$\begin{aligned} \underline{\hat{\omega}}_{HD} &\rightarrow \underline{0} \\ \underline{R}_{SCC} &\rightarrow \underline{0} \\ \underline{\omega}^{L}_{SF} &\rightarrow \underline{\omega}_{\hat{SF}} \simeq \underline{\omega} \\ \underline{R}_{OTO} &= \underline{\omega}^{L}_{SL} \end{aligned} \qquad (13)$$

and $\underline{\hat{DOWN}} \rightarrow \underline{\hat{SF}} \simeq \underline{SF}$

Each of these can easily be understood by reference to Figure 3 except possibly the last relation. It is clear that $\underline{\hat{DOWN}}$ will approach $\underline{SF}$ if it is understood that the rate of rotation of $\underline{\hat{DOWN}}$ ($\underline{\omega}_D$) will eventually match that of $\underline{SF}$ since $\underline{R}_{OTO}$ approaches the true rotation rate and any constant discrepancies (phase lags) will be eliminated by the lower pathway. Consequently the subject's steady state sensation of rotation during the period of rotation should correctly reflect the true rate of rotation ($\underline{\hat{\omega}} \simeq \underline{\omega}$).

Immediately after the rotation stops we can predict that (Figure 3):

$\underline{\hat{\omega}}_{HD}$ will quickly $\rightarrow -\underline{\omega}$ and then decay to zero (this is the typical velocity step response of the canals)

$\underline{\omega}_{\hat{SF}}$ will quickly $\rightarrow \underline{0}$

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$$\begin{aligned}
&\underline{\omega}^{II}_{SF} \text{ will quickly} \rightarrow +\underline{\omega} \text{ and then decay to zero} \\
&\underline{\omega}^{C}_{C} \text{ will quickly} \rightarrow -\underline{\omega} \text{ and then decay to zero} \\
&\underline{R}_{SCC} \text{ will quickly} \rightarrow -\underline{\omega} \text{ and then decay to zero} \\
&\underline{R}_{OTO} \text{ will remain at } -\underline{\omega} \text{ and then decay to zero} \\
&\underline{R}_{TOT} = \underline{R}_{OTO} - \underline{R}_{SCC} \text{ will quickly} \rightarrow \underline{0}
\end{aligned} \tag{14}$$

and furthermore (Figure 4):

$\underline{\omega}^{\wedge}_{D}$ will quickly $\rightarrow 0$

$\underline{\omega}_{\perp}' = \hat{\underline{\omega}}_{HD}$ (since $\hat{\underline{\omega}}_{HD}$ is perpendicular to $\underline{\hat{DOWN}}$) and $\underline{\omega}_{||} = 0$

and

$$\hat{\underline{\omega}}(t) = \hat{\underline{\omega}}_{\perp}(t) = \frac{\tau s}{\tau s + 1}\,\underline{\omega}_{\perp}$$

Therefore the model predicts that while a subject should perceive that his position with respect to the vertical is not changing after the rotation ceases he may have (depending on the value of τ chosen) a brief sensation of rotation opposite to the original rotation. Benson and Bodin [1, 2] had some subjects who reported a brief sensation of rotation and some who didn't. Whether this discrepancy in reporting is due to the conflict between $\underline{\hat{DOWN}}$ and $\underline{\omega}$ or due to different subjects having different values of τ is unclear. That subjects perceive themselves to have a constant orientation relative to the vertical ($\underline{\hat{DOWN}}$ constant) is not in question. Benson and Bodin report "...that they (the subjects) were quite aware that the stretcher had stopped and of its position relative to the gravitational vertical..." Similar stimuli and reports of subjective responses are described in [12].

Quantitative Model Predictions

The model developed in this paper has been programmed so that quantitative predictions can be made for arbitrary stimulus combinations [17]. The programs were written in Fortran IV and they include all functions shown in Figures 1 - 4. Although the model could be implemented with any update interval, $\Delta t = 1$ sec was chosen as a reasonable compromise between computational efficiency and simulation bandwidth. One update interval takes approximately 0.08 seconds of central processor time when utilizing an IBM 370-165 computer.

1. Dynamic Elevator Illusion

In a previous paper [18], the elevator illusion was discussed and a model which correctly predicts its occurrence and magnitude was developed. The transition from head erect in 1 g to the perception of backward tilt with the head erect in 1.75 g was used as a test of the dynamic model presented in this paper. The stimulus input to the model consists of a step in upward acceleration of 0.75 g after the model was stabilized with head erect in 1 g. No rotational stimulus was used. Figure 6 shows the time course of the predicted pitch sensation which resulted. Superimposed on the model's prediction is the data from Cohen [5] in which subjects were given essentially the same stimulus except that the acceleration was produced by a centrifuge. Cohen's subjects

perceived a maximum change in pitch orientation of approximately -19°. The discrepancy in the magnitude of the steady state illusion is discussed in reference 18.

2. Catapult Launch

Cohen et al [6] used a centrifuge to simulate the accelerations encountered in a typical aircraft catapult launching. The average acceleration profile used by Cohen is shown in Figure 7 along with an actual catapult launch acceleration profile. Figure 8 illustrates the manner in which the acceleration was generated on the centrifuge. The following acceleration profile was used in the simulation of the "down" estimator:

$$A_{XHD} = 3.8\sin(\pi t/3.2)g \qquad t < 3.2 \text{ sec}$$
$$= 0 \qquad t > 3.2 \text{ sec} \tag{15}$$

The rotation profile used is given by:

$$\omega_{ZHD} = \frac{2}{3.2}(1 - \cos(2\pi t/3.2) \qquad t < 3.2 \text{ sec}$$
$$= 0 \qquad t > 3.2 \text{ sec} \tag{16}$$

Figure 9 illustrates the movement of $\hat{\underline{DOWN}}$ in response to this stimulus. In addition to the pitch sensation for which Cohen et al tested, the model predicts a possible rolling sensation. If this rolling sensation is truly absent, then the time constant in the high pass filter (element E of Figure 3) should be reduced to zero. If the sensation of rolling is even greater, then τ should be increased above 0.25 sec. Figure 10 compares

the pitch response of the model to the data given by Cohen et al. The above simulation was rerun with $\omega_{ZHD} = 0$ (representative of a real catapult launch) and the predicted perception of pitch was essentially the same.

3. Frequency Response for Small Pitch and Roll Oscillations

The model's use of otolith and canal information can be best understood by comparing the frequency response of the model to each of the sensors. Since the model has nonlinearities for large tilt angles and for conflicting sensory information, it is important to confine the oscillations to small angles (<10°) and to insure that only simple tilting or pitching stimuli are used. The response is essentially the same in both pitch and roll so only the data from the roll stimuli will be illustrated. Eight frequencies from 0.05 to 2.1 rad/sec were tested with stimulus amplitudes of 5 - 10°. Lower frequencies were not tested since extremely long and therefore costly simulations would be necessary. Higher frequencies could not be tested since the update interval for the simulation was 1 second. Figure 11 shows the phase response of the model for these frequencies. The amplitude response of the model is within 5% of unity over the range of frequencies tested. It is clear from Figure 11

that for low frequency stimuli, the model relies on otolith information and for higher frequency stimuli the model relies on information from the semicircular canals. The crossover frequency is approximately 0.5 rad/sec. Nashner [14] found a crossover frequency of approximately 0.1 Hz = 0.628 rad/sec from experiments involving postural control of pitch orientation. Since the phase and amplitude responses are so close to that of a unity gain for frequencies up to about 3 rad/sec the model predicts that our perception for small random tilt oscillations about a head erect position in 1 g should be essentially correct.

Summary

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

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FIGURE LEGENDS

FIGURE 1. Information available to DOWN estimator from the semicircular canals.

FIGURE 2. Information available to the DOWN estimator from the otolith organs.

FIGURE 3. DOWN estimator.

FIGURE 4. Estimator for rotation rate ω.

FIGURE 5. Approximate time course of model parameters and response to a 1 g step in lateral acceleration.

FIGURE 6. Dynamic elevator illusion (1.75 g).

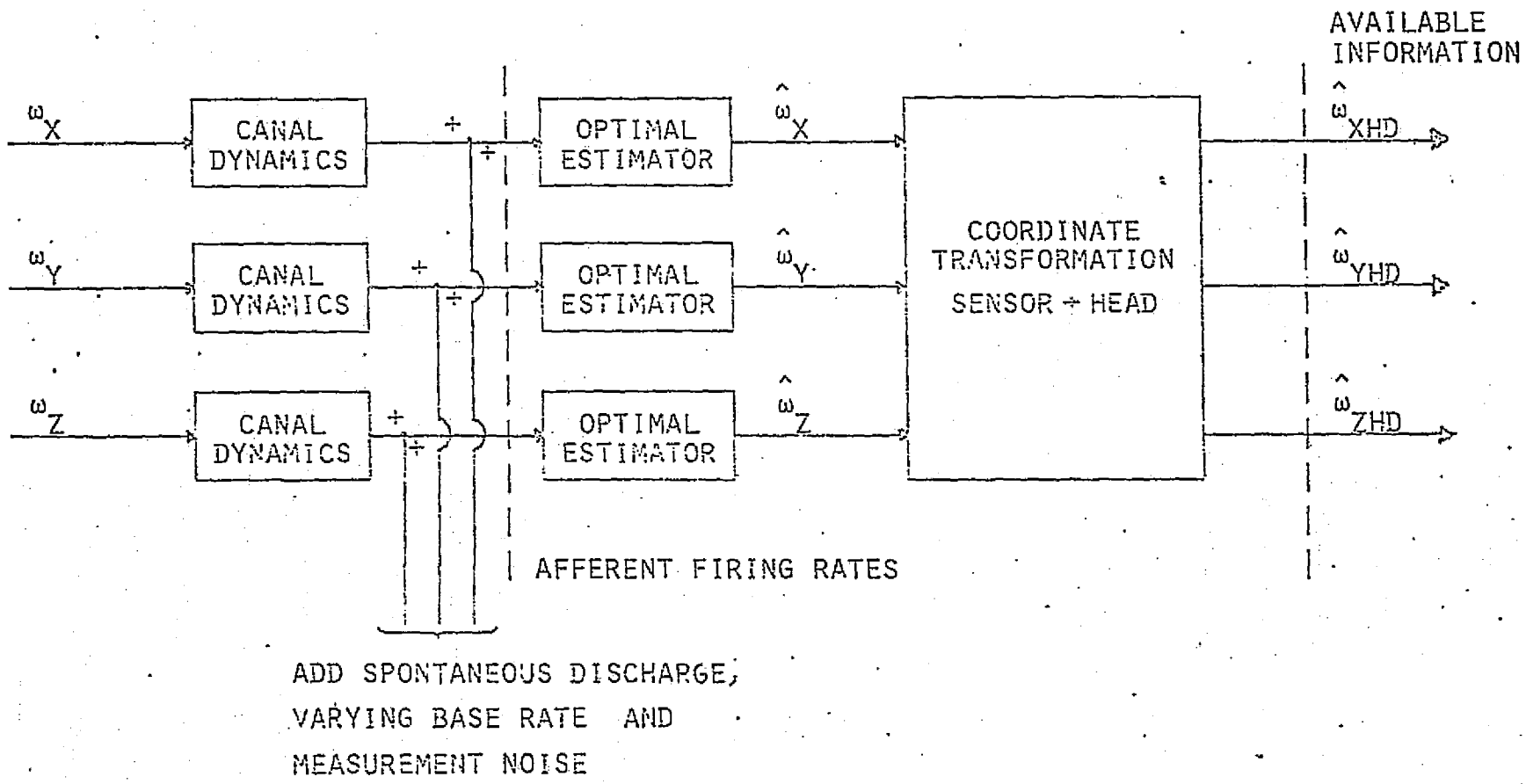
FIGURE 7. Comparison of the G_X accelerations recorded in catapult launch and centrifuge simulation.

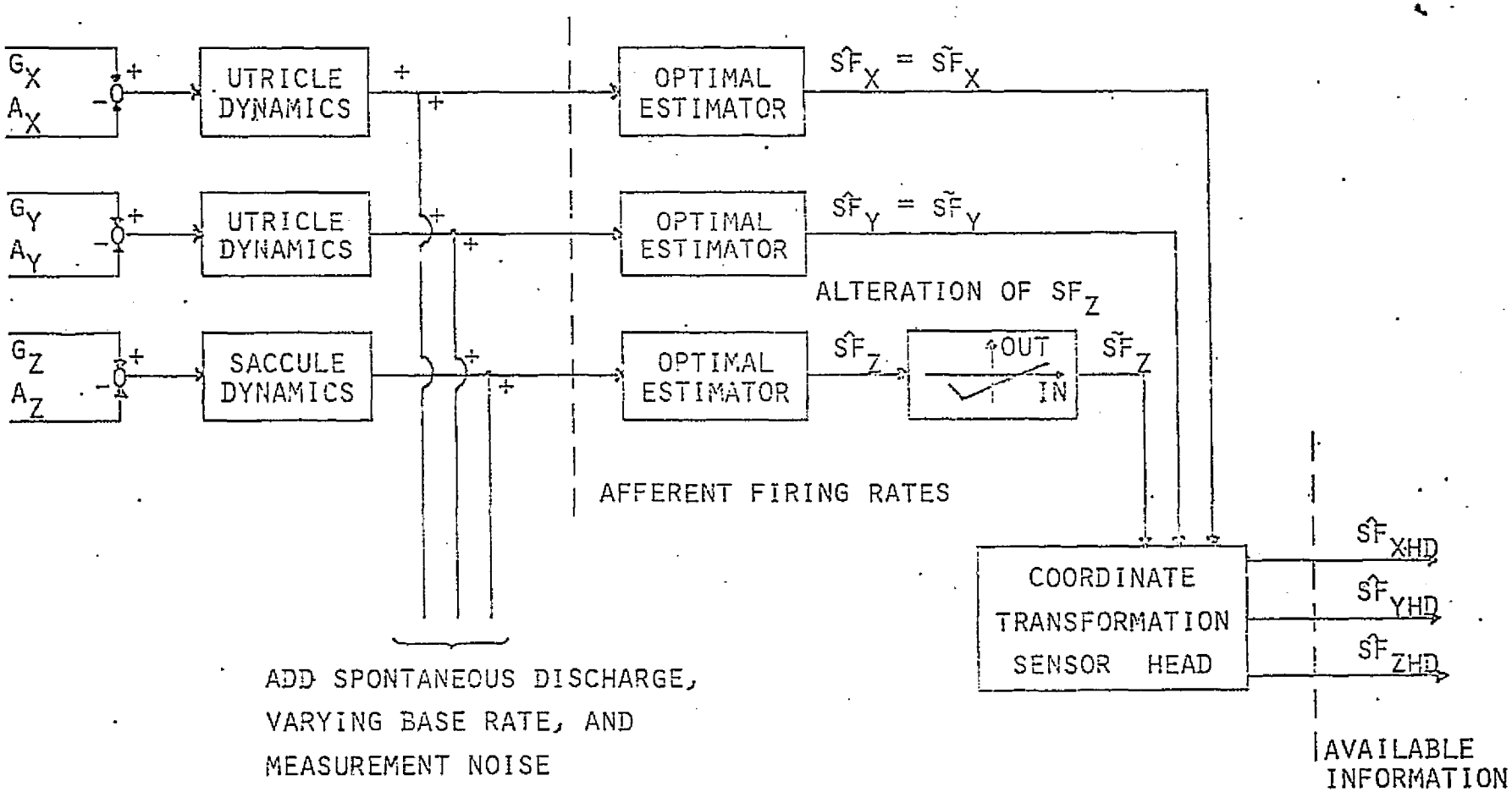
FIGURE 8. Schematic representation of a catapult simulation on the human centrifuge.

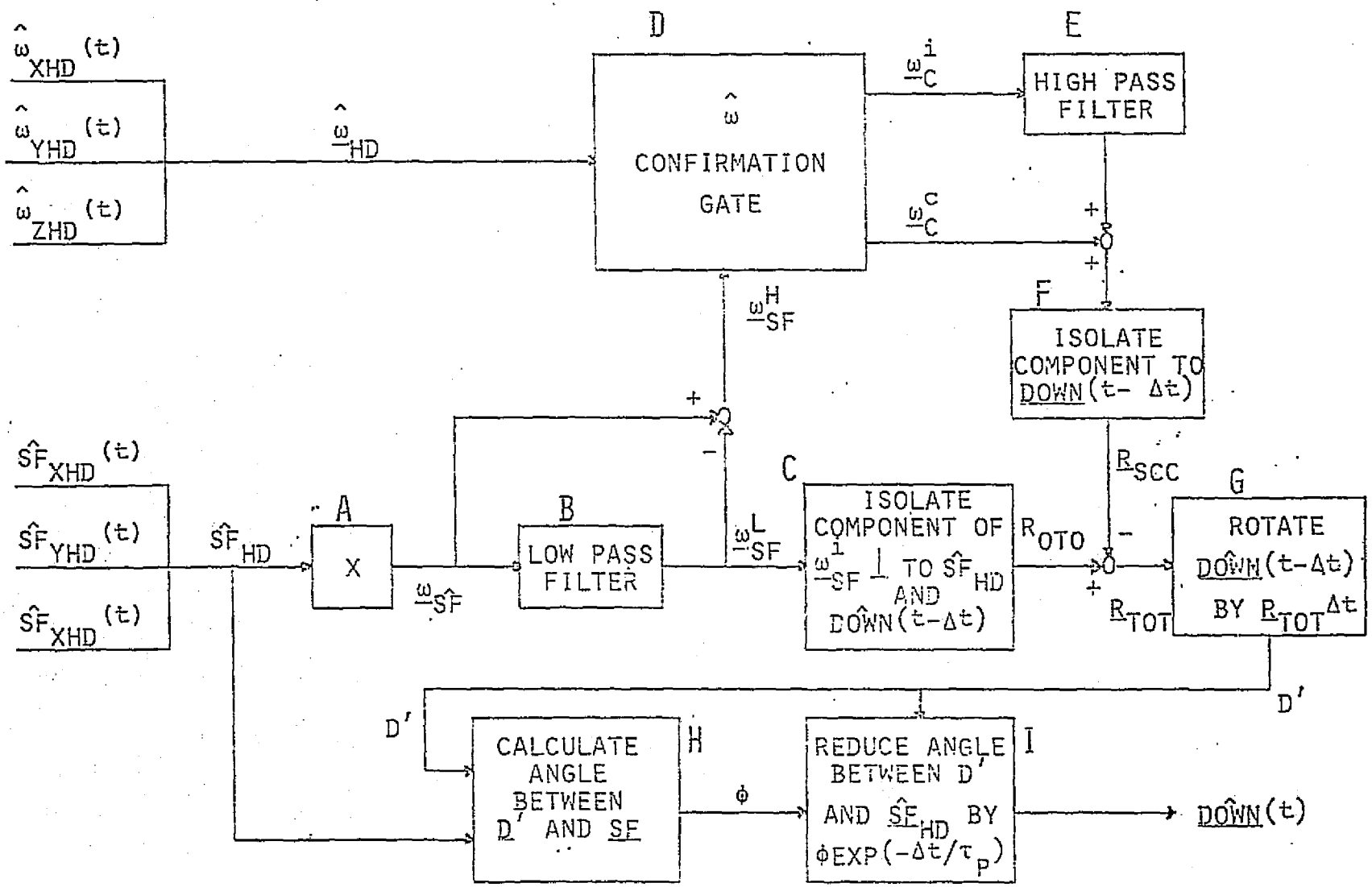
FIGURE 9. Movement of $\widehat{\text{DOWN}}$ for catapult launch simulation.

FIGURE 10. Pitch perception for catapult launch simulation.

FIGURE 11. Phase response of combined model to small tilts (<10°) in pitch and/or roll.


AVAILABLE INFORMATION
ω_X
ω_Y
ω_Z
CANAL DYNAMICS
CANAL DYNAMICS
CANAL DYNAMICS
+
+
+
+
+
+
OPTIMAL ESTIMATOR
OPTIMAL ESTIMATOR
OPTIMAL ESTIMATOR
$\hat{\omega}_X$
$\hat{\omega}_Y$
$\hat{\omega}_Z$
COORDINATE TRANSFORMATION
SENSOR + HEAD
$\hat{\omega}_{XHD}$
$\hat{\omega}_{YHD}$
$\hat{\omega}_{ZHD}$
AFFERENT FIRING RATES
ADD SPONTANEOUS DISCHARGE,
VARYING BASE RATE AND
MEASUREMENT NOISE


G_X
A_X
G_Y
A_Y
G_Z
A_Z
UTRICLE DYNAMICS
UTRICLE DYNAMICS
SACCULE DYNAMICS
OPTIMAL ESTIMATOR
OPTIMAL ESTIMATOR
OPTIMAL ESTIMATOR
$\hat{SF}_X = \tilde{SF}_X$
$\hat{SF}_Y = \tilde{SF}_Y$
ALTERATION OF SF_Z
$\hat{SF}_Z$
OUT
IN
$\tilde{SF}_Z$
AFFERENT FIRING RATES
COORDINATE TRANSFORMATION SENSOR HEAD
$\hat{SF}_{XHD}$
$\hat{SF}_{YHD}$
$\hat{SF}_{ZHD}$
ADD SPONTANEOUS DISCHARGE, VARYING BASE RATE, AND MEASUREMENT NOISE
AVAILABLE INFORMATION



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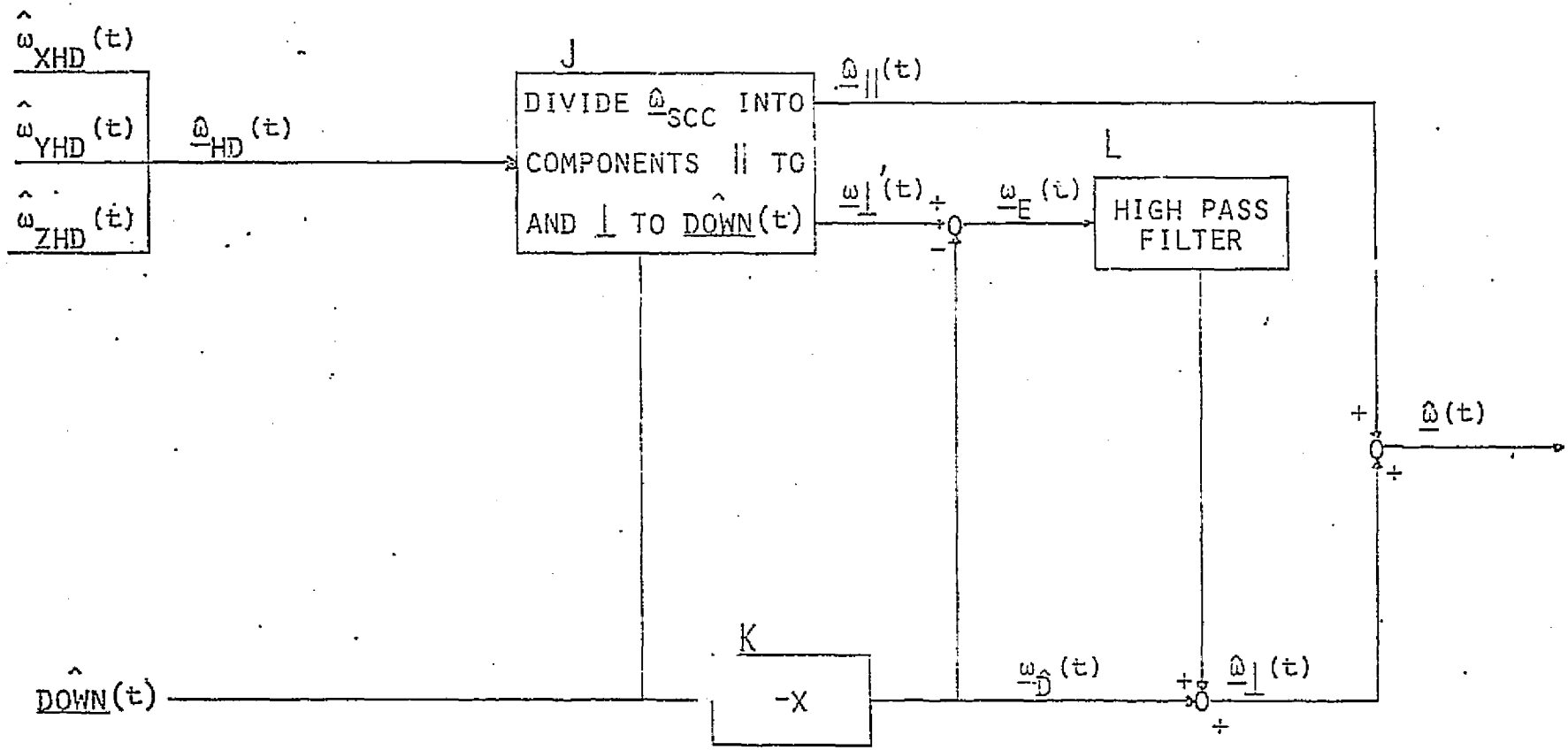
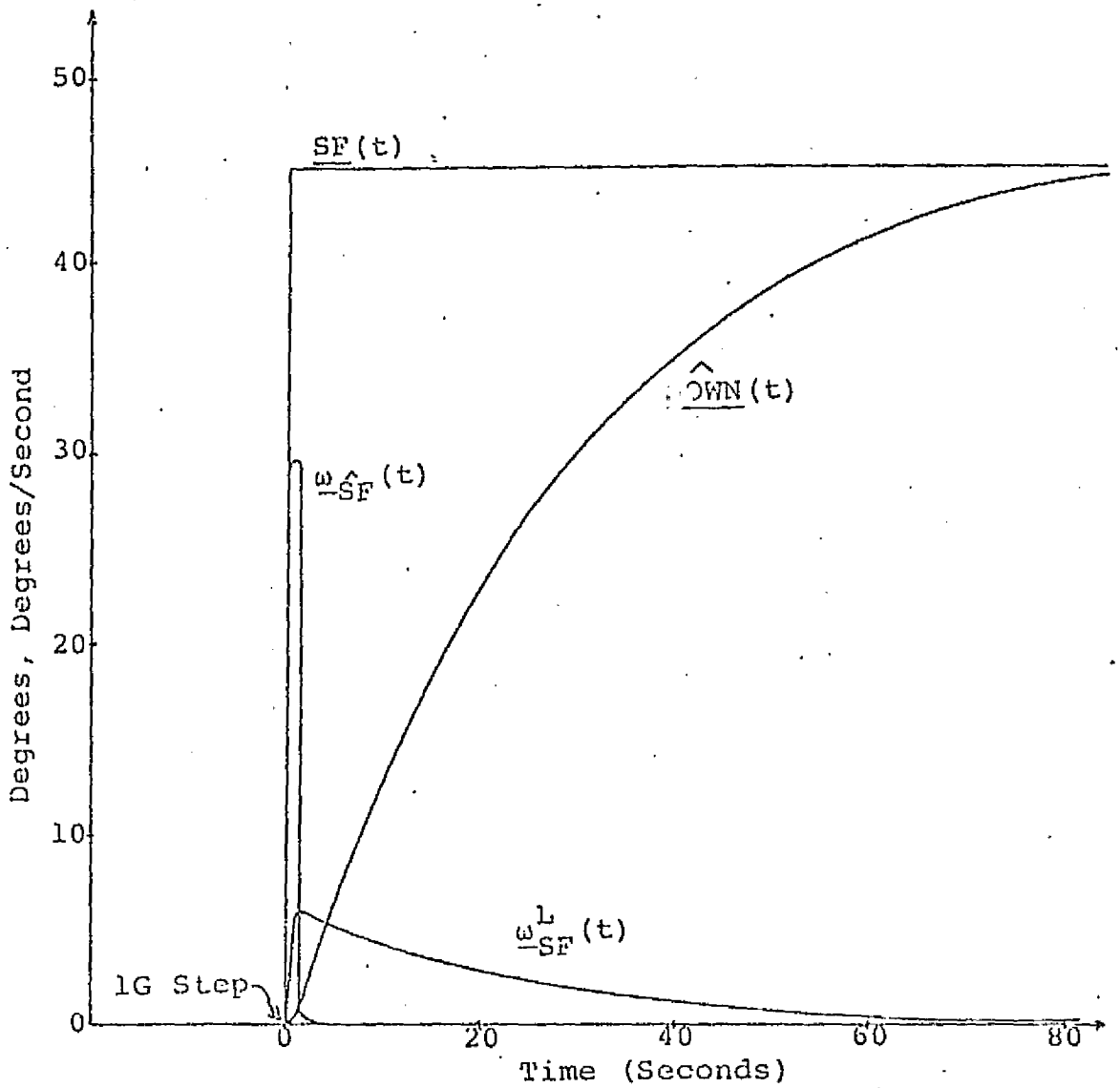
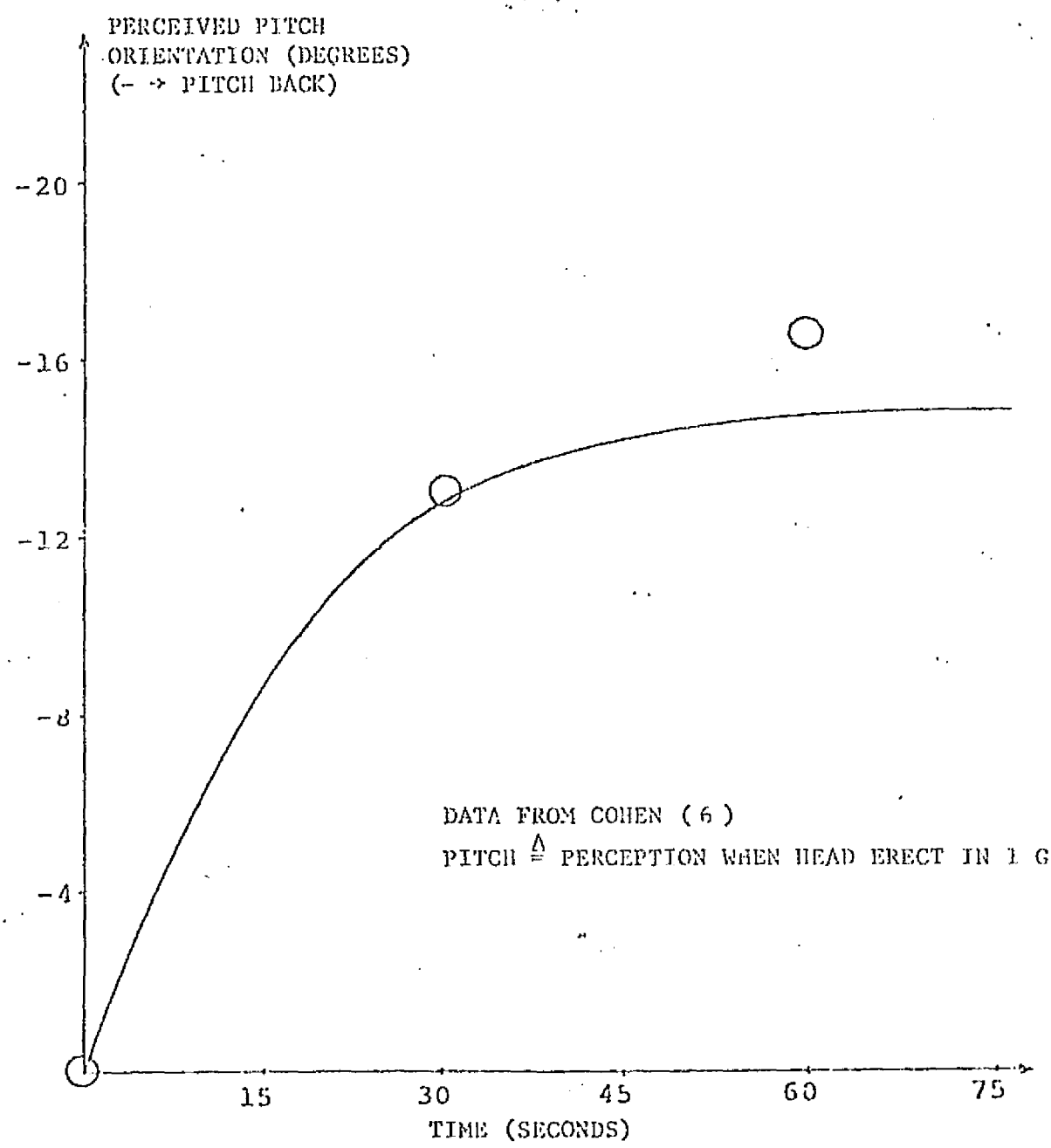
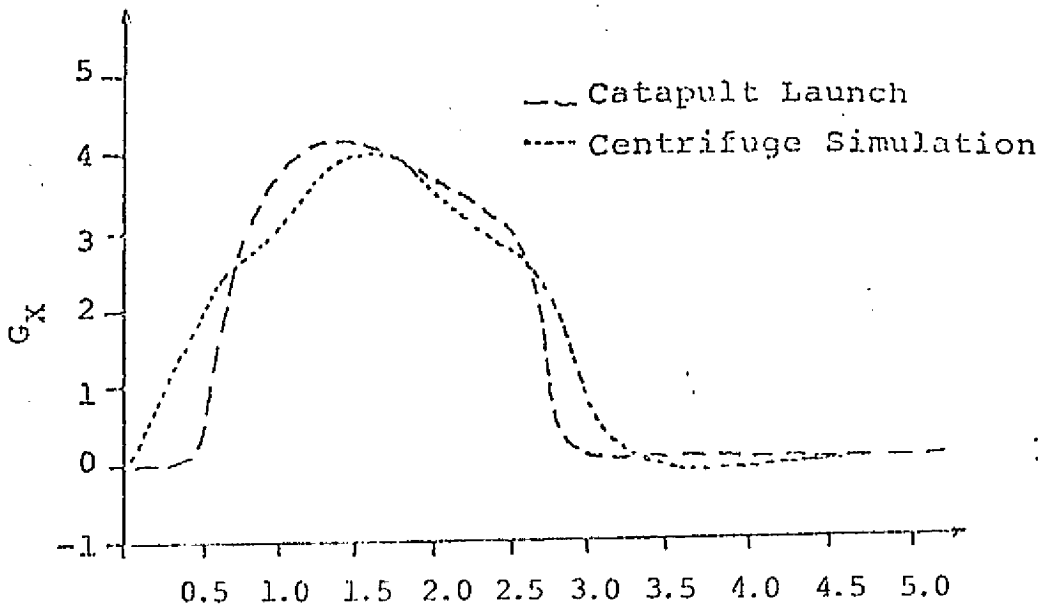

$\hat{\omega}_{XHD}(t)$
$\hat{\omega}_{YHD}(t)$
$\hat{\omega}_{ZHD}(t)$
$\hat{\underline{\omega}}_{HD}(t)$
J
DIVIDE $\hat{\underline{\omega}}_{SCC}$ INTO COMPONENTS $\parallel$ TO AND $\perp$ TO $\hat{\underline{DOWN}}(t)$
$\hat{\underline{\omega}}_{\parallel}(t)$
$\underline{\omega}_{\perp}'(t)$
$\underline{\omega}_{E}(t)$
L
HIGH PASS FILTER
$\hat{\underline{\omega}}(t)$
K
-X
$\hat{\underline{DOWN}}(t)$
$\underline{\omega}_{\hat{D}}(t)$
$\hat{\underline{\omega}}_{\perp}(t)$

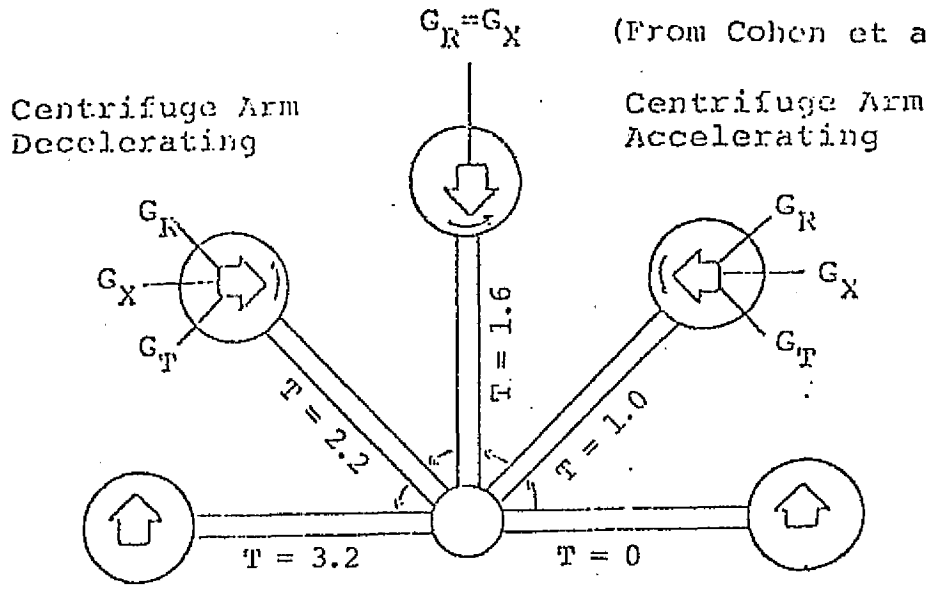

50
40
30
20
10
0
Degrees, Degrees/Second
SF(t)
$\hat{\text{OWN}}$(t)
$\omega_{\hat{SF}}$(t)
ω^{L}_{SF}(t)
1G Step
0
20
40
60
80
Time (Seconds)

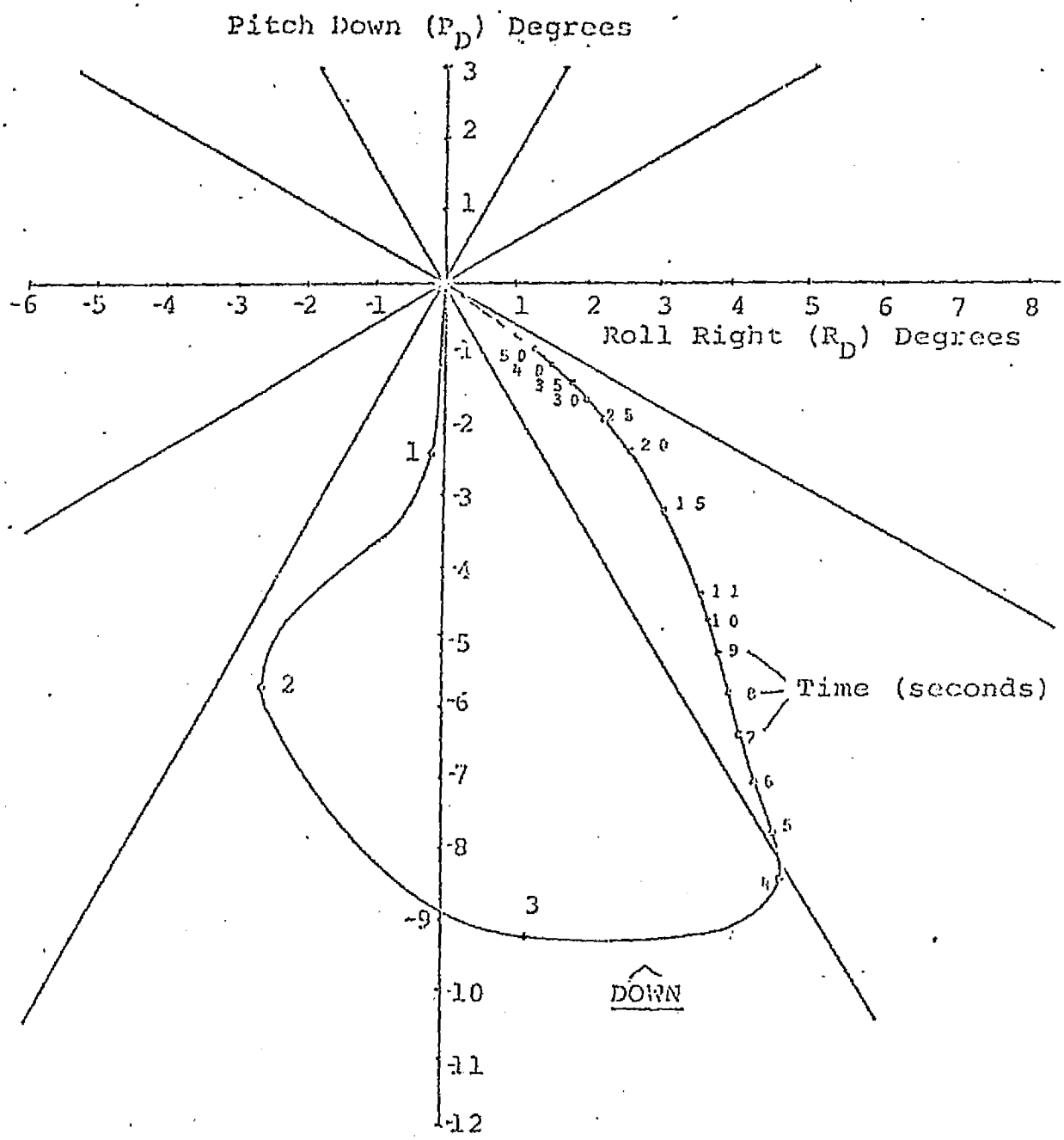

PERCEIVED PITCH
ORIENTATION (DEGREES)
(- → PITCH BACK)
-20
-16
-12
-8
-4
15
30
45
60
75
TIME (SECONDS)
DATA FROM COHEN (6)
PITCH ≙ PERCEPTION WHEN HEAD ERECT IN 1 G

(From Cohen et al, [6])



(From Cohen et al [6])





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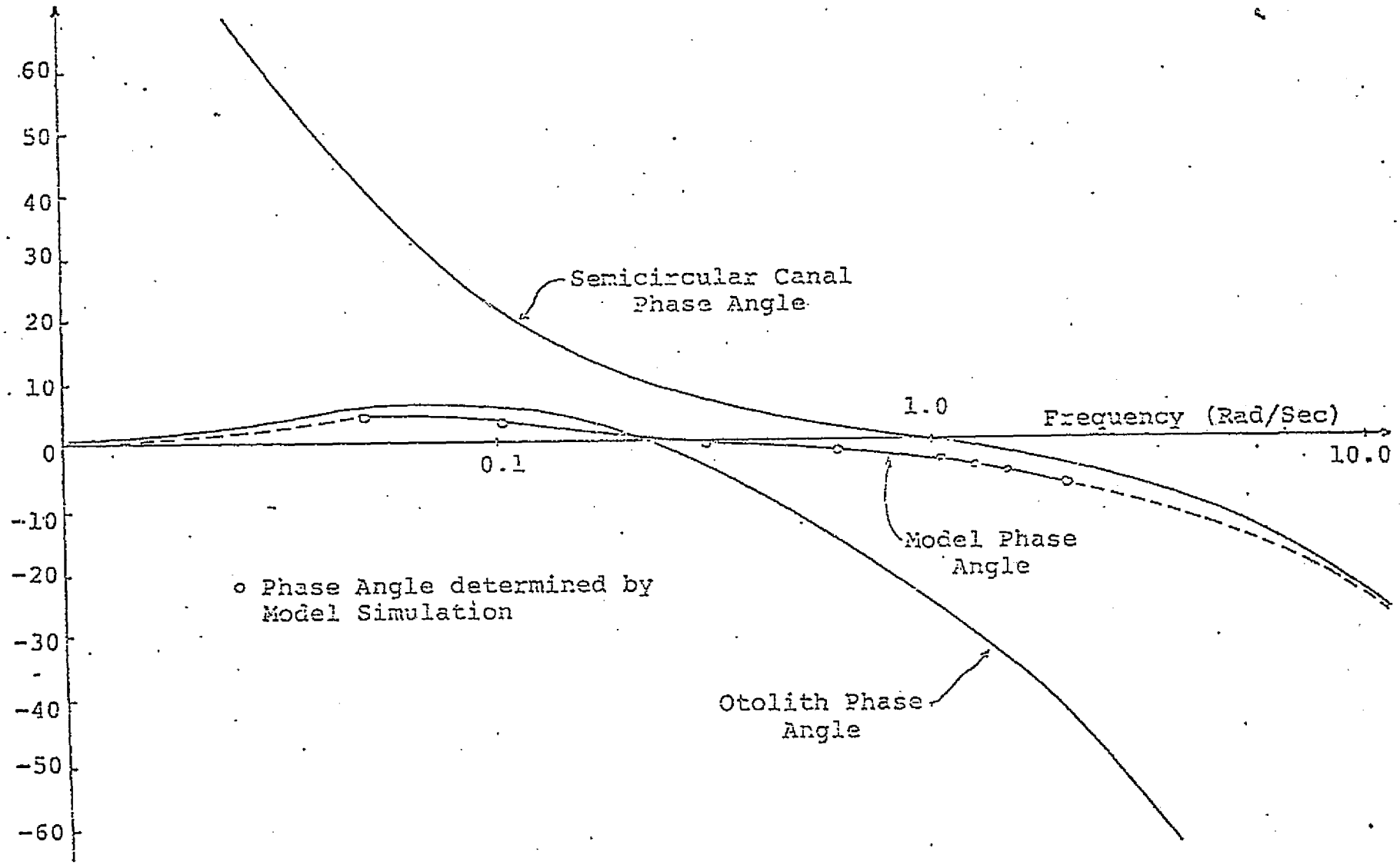
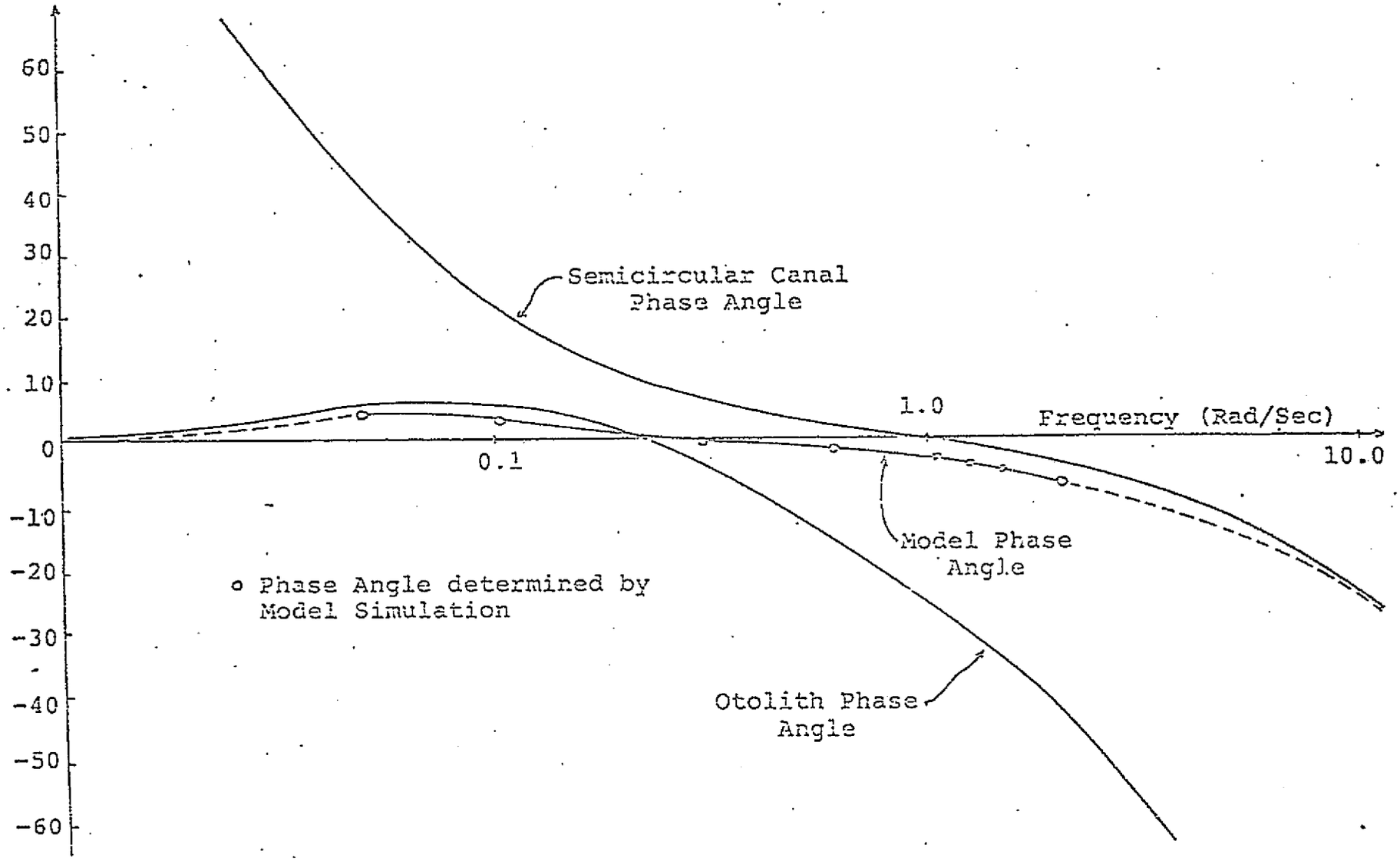

60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0.1
1.0
10.0
Frequency (Rad/Sec)
Semicircular Canal Phase Angle
Model Phase Angle
Otolith Phase Angle
o Phase Angle determined by Model Simulation


60
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20
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0
-10
-20
-30
-40
-50
-60
0.1
1.0
10.0
Frequency (Rad/Sec)
Semicircular Canal
Phase Angle
Model Phase
Angle
o Phase Angle determined by
Model Simulation
Otolith Phase
Angle

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SUBJECTIVE DETECTION OF VERTICAL ACCELERATION: A VELOCITY DEPENDENT RESPONSE?

by

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INTRODUCTION

Subjective orientation estimates have long been known to depend on the orientation of the otolith organs relative to gravity and the imposed linear acceleration (Schöne, 1964; Udo de Haes and Schöne, 1970). Detection of acceleration or tilt is best for horizontal orientation with the head upright, and decreases in accuracy for other orientations, leading to a "blind spot" for detection when the otolithic system is in an "unfavorable position" with the head inverted (Quix, 1925;

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Graybiel and Patterson, 1955). On the other hand, single unit recordings from first order otolith afferents indicate highly sensitive utricular or saccular responses to linear acceleration in all planes (Fernandez et al, 1972). An unresolved problem, therefore, concerns the special difficulty associated with subjective assessment of motion in the vertical direction. Recent experiments with human subjects seated erect in an NAE* computer controlled helicopter and a NASA (Ames Research Center) vertical movement simulator revealed such a peculiar difficulty (Malcolm and Melvill Jones, 1974). During vertical sinusoidal oscillation, in the absence of vision, gross errors frequently occurred in the subjective estimate of phase of the movement. Since these errors bore no systematic relation to stimulus parameters over a wide amplitude-frequency range, they could not be ascribed in a simple way to systematic influence of sensory transduction dynamics of the kind known to occur in the semicircular canals (van Egmond et al, 1949; Melvill Jones and Milsum, 1965; Young, 1969; Melvill Jones, 1972). The present study therefore set out to investigate two other potentially causal factors for these errors:

i. high threshold of sensitivity to vertical linear acceleration with the head erect;

ii. ambiguity in assessing the direction rather than the presence of such movement.

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*Canadian National Aeronautics Establishment

Previous studies in which human subjects were accelerated horizontally along saggital and longitudinal body axes (Walsh, 1962; Meiry, 1965; Young et al, 1966, Young and Meiry, 1968) yielded subjective thresholds which were much lower than the peak acceleration amplitudes of the vertical sinusoidal movements in the experiments of Malcolm and Melvill Jones (1974). Moreover at supra-threshold levels of acceleration there was apparently no difficulty in directional assessment of the horizontal movement. However, the fact that these latter experiments were all conducted in a horizontal plane introduces an additional factor - relative rotation of the gravitoinertial stimulus vector resulting from summation of varying horizontal and static gravitational accelerations. It is well known that this form of vector rotation can provide additional physiological information which might well add sensory clues not available to subjects accelerated parallel to gravity (Correia and Guedry, 1966; Benson and Bodin, 1966; Correia and Money, 1970; Benson et al, 1970, Benson, 1974). In an early investigation, Mach (1873) reported a threshold corresponding to a peak acceleration of 0.012 g's for an upright subject oscillated nearly vertically at the end of a beam, with a period of 7 seconds. Walsh (1962, 1964) examined human subjective response characteristics during sinusoidal accelerations in horizontal and vertical directions. However, Walsh's subjects were supine during vertical accelerations whereas those of Malcolm and Melvill Jones (1974) were seated erect, so that different components of both vestibular and general somatic sensory systems were stimulated in the two sets of experiments.

In order to avoid the complication of changing direction of the acceleration vector, and to conform with the stimulus orientation of the Malcolm and Melvill Jones experiments, we restricted the stimulus to vertically oriented constant linear accelerations while seated erect. Similar methods to those of Meiry (1965) have been used so as to facilitate comparison of results with the findings concerning response latency versus acceleration in the horizontal plane.

METHODS

All experiments were conducted on the NASA Ames Height Control Apparatus as described previously (Malcolm and Melvill Jones, 1974) using the same eight subjects. Subjects were fixed to the seat of the blacked out cabin by a conventional aircraft restraining harness, with an additional headband adjusted to maintain head orientation such that a line joining the infraorbital margin and external auditory meatus was tilted downwards 30° relative to earth horizontal, to bring the major plane of the utricular macula close to the true horizontal. The subject wore blackout goggles behind which he maintained open eyes. The right hand was located on a light-weight, short-throw, three position switch, the mid-position representing zero response and the up and down positions signalling a subjective sensation of the direction of acceleration. Ear muffs containing earphones permitted communication with the remote control cabin and attenuation of external auditory cues. Provision was made to use white noise

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for masking troublesome external sounds, but in practice this proved unnecessary.

The additional head harness was introduced to avoid potential accessory cues from pitching angular movements of the head induced by the vertical linear accelerations with head tilted. The effectiveness of this restraint was verified by means of a small, sensitive, pitch-detecting gyroscope mounted on a dental biteboard. Preliminary runs with three subjects exposed to the whole range of the experiment showed that angular head movements were usually undetectable and never exceeded $\pm 0.5^{\circ}$.

The main experimental series employed 8 adult subjects with no clinical abnormality. One individual held a private pilot's license but was not currently flying. They were each exposed on four occasions to each of eight magnitudes of step change in vertical acceleration. Acceleration magnitudes were all very low, ranging from 0.005 'g' to 0.06 'g' as shown in the top row of Table 1. The distribution of acceleration magnitudes was chosen to concentrate recordings in that part of the data set where the most rapid change of response latency with acceleration was to be expected from the previous horizontal acceleration data of Meiry (1965). An 8 x 8 Latin square design permitted exclusion of learning effects and also a determination of whether practice during the experiment led to significant shortening of response latency.

All subjects were practiced over the range of the experiment and informed of their performance during these runs. They were required to flick the indicator switch as soon as possible after deciding when an acceleration step had occurred, choosing up or down

switch movement according to whether the sensed direction of acceleration was upwards or downwards. Practice was continued until they were satisfied that they knew what to do.

A potentially complicating factor was static friction of the cab in its track, which could produce a detectable jolt on commencing an acceleration from rest. Consequently all test accelerations were begun at randomly chosen times after achieving a steady linear velocity of 2 ft/sec, which in turn was always attained by means of the lowest controllable linear acceleration, namely 0.005 "g". However, since cab movement was inevitably associated with some vibration, this procedure necessitated avoidance of a simple relation between direction of acceleration and any sensed increase or decrease in vibration. This was achieved by balancing the occasions when a given direction of acceleration stimulus would be associated with increasing or decreasing vibration.

Vertical acceleration was recorded from two linear accelerometers, one on the cab and a two dimensional linear accelerometer fixed firmly to the scalp. The head mounting was arranged so that one degree of freedom paralleled the earth horizontal in a fore-aft direction when the head was tilted 30° downwards and forwards. The orthogonal axis was aligned with the true vertical. The system allowed remote checking of the correctness of head position before each run, as well as readjustment of head position in the head-harness when this proved necessary after rests between runs. Simultaneous recording of cab and vertical head accelerometers showed that, apart from some filtering of high frequencies between the cab and the head, there were no significant differences between

the two accelerometer outputs. Also recorded in parallel with these outputs was the subject's switch position and relevant system parameters such as the servo command voltage, safety limiting control outputs and actual cab position derived from a track potentiometer.

RESULTS

Figure 1 represents an original record obtained from a single test run. The upper trace is recorded from the vertically-oriented linear accelerometer mounted on the head. Starting from rest, there was an initial period of very low upward acceleration (A) at the standard value of 0.005 'g' (0.16 ft/sec^2) until attainment of a steady, or plateau, upward velocity of 2 ft/sec. Then, after a randomly chosen duration of between 4 and 10 seconds (b) the test acceleration was applied (upwards in this example) and maintained (C) until after the subject had registered his response by flicking the 3-way switch up or down (up in this example). The response latency was assessed as the time between initiation of the recorded test acceleration and the registration of subjective response. In practice all records were tape recorded and these latencies were measured from records played back on a suitably expanded time scale.

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insert Figure 1 about here

Figure 2 shows the mean values of latency (filled circles ± Standard Error) obtained in this way for all subjects and all runs at each of the eight acceleration magnitudes. The values shown in this figure are independent of whether the subject made a correct or incorrect assessment of direction and, of course, only those occasions when responses were indicated contribute to the curve. In practice, and as will be described below, all subjects responded on all possible occasions at acceleration magnitudes above 0.015 'g'. However, as shown in the middle row of Table 1, and as is to be expected, progressively fewer test accelerations were detected as acceleration magnitudes decreased below this value.

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insert Figure 2 about here

The continuous line in Figure 2 shows the calculated least squares regression line fitted to the average latencies according to the hyperbolic relation

$$T = B/A + T_{min} \quad (\text{for } A > 0.005 \text{ g}) \qquad (1)$$

where

T = mean measured response latency (sec)

A = step acceleration magnitude ('g')

T_{min} = reaction time independent of A

B = slope of the regression line when plotting T against 1/A

The close fit of this calculated regression curve implies that the value of B in equation (1) represents a meaningful constant. The important feature of this conclusion is that this constant has the dimensions of linear velocity, as is evident in the alternative form of the equation

$$B = (T - T_{min})A \qquad (2)$$

A reasonable interpretation, therefore, would seem to be that over the whole range of this experiment, the value B represents a consistent threshold linear velocity which had to be attained before generation of a sensation of the changed movement. The calculated value of this velocity (B) for the regression curve of Figure 2 is 0.022 g-sec (21.6 cm/sec = 0.71 ft/sec). Amongst the eight subjects tested, the individual calculated values of B ranged from 14.8 to 27.0 cm/sec (S.D. ± 5.3).

T_{min} in equations (1) and (2) is interpreted as the constant residual reaction time for initiation of mechanical movement of the "up-down" lever after perception of changed velocity. The calculated value of this residual reaction time, T_{min}, was 0.37 sec. This value is shown graphically as the dashed straight line in Figure 2, representing the asymptotic limit of the calculated hyperbolic regression curve.

In order to compare these results wth those of Meiry (1965), obtained in a similar way for fore-aft horizontal accelerations, his data has been re-fitted with a similar least squares hyperbolic regression curve which is drawn as the intermittent curved line in

Figure 2. This curve is defined by equation (1) with B = 0.023 g-sec, (22.6 cm/sec = 0.74 ft/sec), and T_{min} = 0.76 sec. Thus the two sets of data lie remarkably close to one another, despite the fact that they were derived from different experiments using different subjects, equipment and directions of linear acceleration. Both curves can be well fitted by calculated hyperbolic regression lines, with the common feature that the constant "threshold" linear velocity term, B, has essentially the same value for the two curves. (For the related experiment of longitudinal acceleration with the subject supine, Meiry's (1965) data can be matched by equation (1) with B = 0.033 g-sec (32.8 cm/sec = 1.06 ft/sec) and T_{min} = 0.76 sec.)

The values of T_{min} differ somewhat from the Meiry experiments to the present one. But, as already indicated, this term probably corresponds to the time required to move the lever after reaching sensation threshold, and would not therefore represent an integral component of physiological response to the acceleration per se. Presumably the difference in T_{min} between the two sets of data could be accounted for by the different conditions of the experiments.

The similarity in the present results and those of Meiry was unexpected in view of the specific difficulty described by Malcolm and Melvill Jones (1974) in tracking vertical accelerative motion when seated erect. Clearly the above results show that this difficulty cannot be attributed to a specifically low sensitivity to vertical acceleration along the body's long axis.

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insert Table 1 about here

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An alternative explanation is suggested by the results given in Table 1. Here the middle row shows that, as expected, the percentage of failures to detect the presence of an acceleration stimulus decreased rapidly to zero as the magnitude of the acceleration increased. However, in marked contrast to this, the percentage of incorrect assessments of the direction of acceleration (bottom row) remained essentially constant at about 30%, and was therefore independent of acceleration magnitude over the entire range of the experiment. As discussed further below, there was a specific difficulty in detecting the direction of vertical accelerations imposed along the long axis of the body, which was independent of the stimulus magnitude over the range investigated.

The statistical design of the present experiments also permits investigation of effects upon response due to

a. practice during the trials

b. up-going or down-going directions of acceleration, and

c. increasing and decreasing vibration associated with the stimulus.

No statistically significant effects of any of these influences were evident in the results.

DISCUSSION

The original objective of these experiments was to investigate further a previously described difficulty in the subjective tracking of whole body vertical accelerative movement parallel to the long axis of the body. The results in Table 1 show that a similar difficulty was encountered in the present experiments. However, the important additional feature emerged that this difficulty was identified specifically as a consistent uncertainty in the direction of imposed acceleration, rather than low sensitivity to vertical acceleration. Thus Figure 2 reveals a remarkable similarity in the threshold sensitivity curves obtained from these experiments and those of Meiry (1965) conducted with fore-aft accelerations, subjects upright, in the horizontal plane.

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insert Figure 3 about here

This similarity is highlighted by superposition of the two data sets as shown in Figure 3. Here the ordinate gives response times for detection of vertical and horizontal accelerations after subtraction of the respective minimum reaction times (T_{min}). This resulting response time ($T - T_{min}$) is plotted against the inverse of stimulus acceleration magnitude, so that a linear (previously hyperbolic, Figure 2) relation is obtained. Clearly there is no significant distinction between the two data sets displayed in this way ($p < 0.05$), the slopes of the two calculated regression lines

hair cell orientation (Spoendlin, 1968) and neural response (Fernandez et al, 1972) appears to be predominantly vertical and horizontal respectively in these two end-organ components.) The fact that Young and Graybiel (unpublished) found that labyrinthine defective subjects had 8 to 15 timesothe normal threshold for detection of horizontal linear acceleration certainly implicates the vestibular end-organ as the predominant sensor at the low acceleration amplitudes employed here.

Given the validity of this inference, the peculiar difficulty of directional assesment associated with vertical movement suggests that despite similar sensitivities, there are nevertheless significant differences in the neural mechanisms responsible for perception of saccular and utricular sensory inputs. In their model for static orientation sensation, Young and Ormsby (1976) assumed a specific uncertainty in the processing of certain information from the saccules. However, at least in the cat, there appears to be no significant differences in the numbers and sensitivities of central vestibular neurones excited respectively by up and down going vertical accelerations (Melvill Jones and Daunton, 1973). If this is also true in man, then presumably the difficulty in perceptual interpretation of the central message could be associated with a difference in the "need to know" about the direction of acceleration in horizontal and vertical directions, rather than objective limitations in the neuronal information available to the brain.

Of central interest in this connection is the additional finding of these authors that there was also no significant difference in numbers and sensitivities of vestibular neural units

being 21.6 and 22.6 cm/sec for the vertical and horizontal data respectively.

The possibility arises that the subjects' apparent insensitivity to direction could be due to their having responded simply to some form of change of vibration. A number of features, however, suggest this is an unlikely explanation. First, if the subjective response to acceleration carried good directional information, then since the sensory signal would presumably increase with increasing acceleration magnitude, one might expect there would then be a corresponding reduction of the directional uncertainty, which there was not. Moreover, similarity between the present data and that of Meiry (1965) over the whole range of experiment is too close to have been fortuitous as will be discussed below, and yet in marked contrast to the present results, Meiry's subjects were able to detect direction with a high degree of certainty.

As pointed out in the Results, an important conclusion derives from the fact that the constant B in equations (1) and (2) has the dimensions of linear velocity, and hence conceptually describes a fixed velocity increment threshold for the subjective perception of the accelerative movement. The fact that this threshold value proves to be statistically similar for both orientations of movement suggests similar sensitivities in vertically and horizontally responding sensory systems. In so far as these can be identified primarily with the vestibular end organs, the finding implies that similar sensitivities are obtained in the saccular and utricular components of the otolith end-organs. (Direction specificity of

responding to fore-aft horizontal and up-down vertical accelerations of equal magnitude. Furthermore, single central vestibular units were found respondi. g in both orthogonal planes down to acceleration magnitudes at least as low as 0.005 g, which supports the likelihood that similar central neural responses would have been available to our human subjects in these experiments.

The conclusion that threshold conditions are determined by the velocity attained rather than the acceleration amplitude over a certain acceleration range is closely akin to that associated with the well known "Mülder product" (van Egmond et al, 1949) for the semicircular canals. Thus, akin to these experiments, the product of angular acceleration and time-to-detect proves to be constant (1.5 - 2.0°/sec) over a wide range of suprathreshold step changes of angular acceleration. Here again the implication is that threshold sensation is associated with attainment of a fixed change in angular velocity, rather than the magnitude of the imposed acceleration. For the canals, this conclusion is well matched to the integrating characteristics of endolymph hydrodynamics. However, a mechanical analogy in the otolith organs, although suggested by these results, is not currently available.

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FIGURES ARE BEING REDRAWN, AND ARE NOT AVAILABLE AT THIS TIME.

FIGURE LEGENDS

1. Records of stimulus (head acceleration) and response (subjective response) from a single test run. The initial acceleration (A) was always 0.005 'g', either up or down. The plateau velocity (B) was always 2 ft/sec either up or down. In this example an upward acceleration of 0.04 'g' was imposed after 10 seconds of plateau velocity, and correctly identified with a latency of 1.1 seconds.

2. Relations between response latency and stimulus acceleration magnitude. The continuous curve shows the calculated regression hyperbola for the present results (O ± S.E.) obtained during vertical accelerations. The dashed curve gives the corresponding hyperbola calculated from the data of Meiry (1965) obtained during fore-aft, head erect, horizontal accelerations. T = total response latency, A = step acceleration, T_{min} = calculated hyperbolic asymptote for the present results.

3. Comparison of response times to vertical (O) and horizontal (O) accelerations, after subtraction of the calculated minimum reaction times (T_{min} in equations (1) and (2)). Mean response time in seconds (ordinate) are plotted against the <u>inverse</u> of the acceleration stimulus (g^{-1}) in order to illustrate the closeness of fit of these data to the hyperbolic relation in equation (1). Continuous and intermittent lines are calculated regression lines for the "vertical" and "horizontal" data respectively.

TABLF 1

Dependence of detectability of stimulus and directional assessment of acceleration upon stimulus acceleration magnitude

STEP ACCELERATION MAGNITUDE 'g'	0.005	0.007	0.009	0.011	0.015	0.020	0.040	0.060
% OF UNDETECTED STIMULI	28	17	13	13	3	0	0	0
% OF WRONG ASSESS-MENTS OF DIRECTION	30	28	38	26	29	23	34	28