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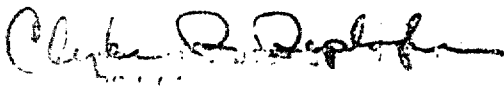
The experiments reported here were conducted according to the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

The voluntary informed consent of the subjects used in this research was obtained as required by Air Force Regulation 80-33.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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This report summarizes the results of a motion sensation literature review conducted to identify current motion cue models which might be used to model pilot behavior in a motion environment. Models for the vestibular end organs are critically reviewed, as are models for subjective sensation of self-velocity and orientation. Modelling deficiencies are identified in terms of body-axis orientation, dynamic response, and threshold behavior. The model implications for workload and cue predictability in a closed-loop piloted task are also discussed.

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SUMMARY

This survey provides a critical assessment of motion sensor models, with the particular viewpoint of applying these models to the problem of understanding how the human operator makes use of motion cues in a moving-base tracking task. Current motion sensor models qualitatively support the changes in tracking behavior seen with motion, but quantitative modelling efforts require well-specified and definitive sensor models. It is the objective here to review the available models, and evaluate their applicability to the functional modelling of human operator performance.

Most of the motion sensation research has been concerned with rotation, and, in particular, yaw-axis rotation about earth-vertical; however, most of the rotational motion encountered by a pilot is in pitch and roll. Although some of the sensation model results can be carried over to these two axes, there is a need for a better definition of pitch and roll time constants and thresholds, for both semicircular canal organ models and for input-output models of subjective sensation. In addition, most of the threshold studies have concentrated on specifying minimum detectable <u>acceleration</u> levels, whereas <u>velocity</u> levels are more appropriate threshold descriptors for human operator applications, because of detection latency considerations. Thus, further velocity threshold research is needed, and with a particular emphasis on determining "operational" thresholds, since the task of active tracking might be expected to raise effective thresholds and cue predictability of pilot induced motions might be expected to lower them.

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Sensation models for tilt and translational cues are less
well-developed than their rotational counterparts, because
otolith organ models fail to explain the dynamics of subjective
sensation, and because the sensation itself is not well-defined.
The resolution of both these issues appears to be a necessary
prerequisite to the successful modelling of response to a general
class of motion cues, although predictions can currently be made
for simple stimulus patterns. However, there has been a general
neglect of left-right acceleration response, necessary for the
development of a roll tilt model to predict pilot response to
the most common aircraft attidtudinal motion. Thus, additional
body-axis studies are needed to define both dynamics and
threshold, with the threshold research emphasizing velocity
rather than acceleration levels, and emphasizing "operational"
levels in the face of the task-loading and cue predictability
which characterize active moving-base tracking.

Even in simplified experimental investigations of moving-
base tracking performance, motion cues rarely consist of a pure
rotation or pure translation; usually, both occur simultaneously,
as in a roll-axis task. Thus, there is a need for an integrated
model of motion cue processing, based on the individual outputs
of rotational and translational motion sensor models, to provide
an estimate of body orientation and velocity. Some of the
studies cited here make it clear that subjective sensation need
not be a direct reflection of sensory organ output, and that
considerable processing and transformation of the output signal
may occur before a "sensation" is generated. If it s presumed
that the human operator is likewise restricted in his access to
primary sensory information, then an integrative perceptual
submodel becomes a necessary component of the human operator
model, for moving-base applications.

Since the development of such a model is one of the goals of current motion sensation research, those working in the field of human operator modellling have few options to choose from. One possibility may be to use the multi-axis model described later in this review, although it is not felt that it has been sufficiently verified, and may require substantial modification to ensure accurate predictions in the motion cue environment typifying human operator research. An alternative involves the independent development of a perceptual "estimator" model, based on the linear estimator structure currently used in the optimal control model (OCM) of the human operator, and guided by the results of past and current vestibular research; such a modelling effort could take advantage of the insights afforded by both motion sensation research and human operator modelling.

The basic closed-loop tracking/regulation task provides a unique opportunity for development of motion perception models, and is an approach which complements the conventional open-loop testing characterizing motion sensation research. Although input-output measurements of pilot tracking cannot, in theory, provide a definitive separation of "estimator" from "controller," the success of the OCM in predicting static tracking performance has shown that such a separation can be made, in practice. If a motion estimator submodel structure were to be assumed, in conjunction with appropriate motion sensor models, it might then v rv well be possible to estimate motion model parameter values, based on the results of closed-loop moving-base tracking experiments. In light of the state of development of the various motion sensation models, and their anticipated shortcomings when applied directly to the pilot modelling problem, this approach may prove to be the most appropriate means of modelling motion cue effects on pilot behavior.

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PREFACE

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Modelling the effects of motion cues on manual tracking behavior has followed a general trend in sophistication, starting with fairly qualitative assessments of motion effects, and progressing to the current development of human operator models which incorporate motion cue perceptual sub-models. Early work in moving-base simulator design recognized that motion cues added realism to the piloted flight task, but attempts to quantify the effects, in terms of performance, handling qualities, or training effectiveness, generally resulted in often contradictory statements regarding the importance of motion cues. Although these questions are still open today, workers in the mid-sixties began to realize that a better controlled experimental situation was called for, one which avoided the complexities of simulated multi-axis aircraft control, and the motion system compromises necessary in practical simulator design.

This led to a more quantitative experimental approach during the mid-sixties, centered around single-axis control of simplified vehicle models (46, 67, 69). By concentrating almost exclusively on compensatory tracking tasks, workers built upon the reasonably well-developed crossover describing function model applicable to static visual tracking situations (45). It was generally recognized that, in a disturbance compensation task, a pilot incorporated motion cues so as to effectively extend his bandwidth (46, 67). This was formalized by an adjustment rule (69) to be applied to the crossover model when motion was present: reduce the pilot's time delay by approximately 0.15s and increase his gain crossover frequency by approximately 1 rad/s.

During this time period, a parallel effort in modelling motion sensation dynamics was also being conducted, based on psychophysical and physiological response measures. Generally, the results complemented the inferences to be made from the moving-base manual tracking results. It was argued that the increase in crossover frequency and delay time reduction could be ascribed to the lead and/or alerting properties of the vestibular organs (46, 67, 69, 79), although it should be clear that the effect of proprioception cannot be discounted (1). Lead information provided by the human's motion sensing system was also consistent with an operator's enhanced ability to control highly unstable vehicles when seated in them (46) and his reduced response time to detect vehicle step disturbances (75). Basically, the notion was established that the vestibular path provides a means of obtaining higher derivative information than that obtainable from visual displays of vehicle attitude.

This correspondence between sensory lead and changes in tracking behavior with motion was satisfying from a mechanistic point of view, but there clearly was a gap between perceptual models and measured tracking response. Thus, no attempts were made to extrapolate from fixed-base to moving-base performance, given the known fixed-base response and the perceptual models of motion sensation. This gap is made most evident in an early paper by Ringland and Stapleford (61) which discusses the effects of motion on a roll tracking task. Simplified vestibular models are initially presented, complete with time constants and thresholds, but used only as qualitative justification for the crossover model motion adjustment rule. No attempt was made to incorporate the sensor models in the overall human operator model. Of course, it might be argued that the descriptive input-output nature of the crossover model is not

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conducive to a functional incorporation of a sensory sub-model; the problem may be more fundamental than that, however.

One means of modelling the human operator's integration of motion cues while tracking is afforded by the state variable structure of the optimal control model developed for pilot modelling (OCM; 2,37). Here, the operator's display vector of vehicle state can be simply augmented to include higher derivatives, to provide for a fairly straightforward accounting for the acceleration (and possibly jerk) sensing properties of the vestibular/proprioceptive sensors (14,40). Although both Dillow (14) and Levison (40) treat sensory thresholds differently, they both ignore dynamic modelling of motion sensation in the model formulation, and still manage to fit response data in both static and motion tracking tasks. This simplified display vector augmentation approach received further support in a study comparing target tracking with disturbance regulation, with and without motion cues (41). Here, it was shown that the task-independent structure of the OCM could be used to model pilot behavior in all four test cases, with the simple expedience of display vector augmentation to account for the motion cases.

The OCM structure also allows for the incorporation of vestibular sensor dynamics in a fairly direct manner. By treating the motion transducer models as extensions of the vehicle to be controlled, the estimator portion of the OCM can be expanded to account for the new dynamics associated with the augmented display vector. In one study (12,13) the vestibular organs were modelle according to the dynamics proposed by Ormsby (56), and the resulting OCM model was then fit to the data obtained from several compensatory tracking tasks investigated by other workers (52,62,67), with varying degrees of success in matching model response to measured data in the diverse experimental situations.

This study, however, did not address the question of whether or not the sensor dynamics needed to be included in the model-matching effort. Levison and Junker (41) considered this aspect of the problem by fitting their roll-axis disturbance compensation data with three versions of the OCM model: a purely "informational" model which simply augmented the display vector and ignored possible sensor dynamics, and two models which included the effects of two different sets of sensor dynamics. The latter two modelling approaches showed no improvement in data matching accuracy over that obtained with the simple informational approach; in fact, the use of one sensor model set (based on the semicircular canal model of Ref. 59 and the otolith model of Ref. 80 resulted in a substantially poorer fit. This suggests that careful consideration be given to the basic question of whether or not motion sensor models need be explicitly included in an analysis of operator behavior in moving-base compensatory nulling tasks.

The bulk of the moving-base studies have been concerned with compensatory target tracking or disturbance nulling of zero-mean signals having a power spectrum generally within the pass-band of the vestibular organs. The argument is thus made (41) that dynamic effects can be ignored, and the acceleration sensing properties of the vestibular orgnas can be approximately modelled by display vector augmentation, at least for the class of steady-state tracking tasks under consideration. Where very low frequency response is concerned, however, such as in a transient step maneuver to a new steady-state attitude, this may not be the case, and there may exist a requirement for modelling the high-pass characteristics of the vestibular (and proprioceptive) organs in order to accommodate measured transient response data. If this should be the case, then careful consi-deration must then be given any selection of a motion sensor

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model from the existing literature; otherwise a considerable operator model mismatch may result, simply because of the choice of inappropriate motion sensor dynamics (41).

The literature search reported on here is a direct response to this consideration. Although initially conceived with the objective of choosing the most appropriate motion-sensor model to be incorporated in a human operator model (and thus paralleling and extending the effort documented by Peters (59)), it was decided that a more critical assessment of motion sensor models must be made, with the particular viewpoint of utility to the problem of human operator modelling in a closed-loop task. Thus, rather than attempting to choose a "best" motion sensor model, the objective here will be to consider whether or not any of the current models are particularly appropriate to the problem at hand.

To do this, of course, requires that a survey be made of the current literature on motion perception, and the results of this survey are presented here. Emphasis is on the functional characteristics of sensor models (e.g., time constants, thresholds, etc.), but an attempt will be made to give equal consideration to the experimental methods used for response measurement and model parameter estimation. It is felt that by considering a motion sensor model within the context of its development one can better appreciate its limitations and applicability to the problem of human operator modelling.

This review is organized into five sections. Section 2 describes perception of rotational mot: cues, and identifies the similarities between measured sensation dynamics and the semi-circular canal transducer characteristics. Section 3 discusses the perception of tilt and linear motion cues, and identifies the basic characteristics of the otolith transducers which are believed responsible for the observed subjective response. Both of these sections review several single-channel functional models which have been proposed in the literature, and an argument for an integrated viewpoint is presented in Section 4. Finally, Section 5 summarizes the major findings of this survey, and relates the current status of the motion sensation modelling effort to the needs of human operator research, and suggests future directions for motion research.

SECTION 2
SEMI-CIRCULAR CANAL MODELS AND ROTATIONAL SENSATION

In attempting to develop a functional model of rotational motion sensation, researchers have drawn upon the results of many studies using quite different response measures, with subjective sensation being only one of several. In fact, the perceptual modelling effort rests on a knowledge of the mechanical properties of the semi-circular canals, the hair cell transduction properties, primary afferent firing rates, secondary unit response in the vestibular nuclei, unit responses in the oculomotor nuclei, nystagmoid eye movements, and vestibularly induced visual illusions. What generally emerges from this broad base of vestibular research is that subjective sensation is heavily influenced by the canal transduction dynamics, although clearly, many factors contribute to the end product of perceived rotation.

For those working in the field of human operator dynamics, it has been convenient to equate canal transduction properties with subjective sensation. This is of course appealing to the controls engineer, since this provides for a simple input-output functional description of how actual rotational motion is converted into a sensation of that motion, and then presumably acted upon in some quasi-optimal manner to perform the controls task at hand. Whether or not such an open-loop (i.e., transducer-type) perceptual model is appropriate, is of course, a basic question which motivates some of the discussion to follow.

Torsion Pendulum Model

Perhaps the most influential model of end-organ dynamics was proposed by Steinhausen (71), who developed a linear second-order model of canal cupula dynamics to explain the

observed characteristics of vestibularly induced eye movements
in the pike. By choosing, appropriate coefficients for his
differential equation model, Steinhausen was able to show how
cupular deflection was characterized by a rapid rise and then
a gradual decay back to its rest position, following a step
input of angular velocity to the canal.

Neurophysiological support for this second-order "wash-
out" model was subsequently provided by the work of Lowenstein
and Sand (42,43), who, by means of ampullar nerve and single
unit recordings, showed that primary afferent response to
mechanical inputs followed a similar time course. The simplest
interpretation of these observations assumed the hair cells to
be approximately linear transducers of cupula motion, so that
the basic characteristics of the afferent response can be con-
sidered to be dictated by the dynamics of cupula deflection,
and not the dynamics of neural transduction. Lowenstein and
Sand also made clear the bidirectional response capabilities
of the canals, and suggested the possibility of a push-pull
interaction between contralateral canals. This has been the
basis for associating corresponding left and right canals, and
treating them functionally as a single bidirectionally
responding canal.

The canal model became more formalized with the introduction
of the "torsion pendulum" model of Van Egmond et al. (74), which
relates cupula deflection δ to head angular velocity ω as
follows:

$$\frac{\delta}{\omega} = \frac{Ks}{(\tau_1 s+1)(\tau_2 s+1)} \tag{1}$$

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This model presumes that angular velocity sensation $\hat{\omega}$ is proportional to cupula deflextion δ, so that psychophysical testing of velocity sensation can be used to infer the model parameters. By monitoring detection latency to an acceleration step, apparent displacement in response to a velocity step, and subjective velocity phase lag as a function of stimulus frequency, they were able to show that one of the time constants in the above model was approximately 10s, and the other approximately 0.1s. Further arguments supported a gain which was equal to the long time constant. The first quantitative model of angular velocity sensation thus took the following form:

$$\frac{\hat{\omega}}{\omega} = \frac{\tau_L s}{(\tau_L s+1)(\tau_S s+1)} \tag{2a}$$

with $\tau_L \approx 10s$ and $\tau_S \approx 0.1s$. This is a unity gain bandpass filter over the range 0.1 to 10 rad/s, and, for lower frequencies, may be approximated as a simple washout filter:

$$\frac{\hat{\omega}}{\omega} \approx \frac{\tau_L s}{\tau_L s+1} \qquad \text{(washout approximation)} \tag{2b}$$

It should be recognized that this torsion pendulum model was developed to describe sensation in response to earth-vertical yaw rotation.

Model Time Constants

Long Time Constant (τ_L)

With this model as a framework for interpreting sub-
jective response data, several researchers conducted studies
both to verify the parameter values and to expand the model's
scope. In particular, Meiry (46) measured detection latency
as a function of angular acceleration step size, and showed
how his data was consistent with the model above, for earth-
vertical yaw-axis rotation. He also showed that, for roll-axis
rotation about earth-vertical (using subjects who were face
down), a long time constant of 7s was more appropriate. This
type of roll motion is different from roll tilt, since tilt
involves a change in the specific force vector and, most
likely, otolith involvement (see Section 4 for further discussion
of off-vertical rotations).

By use of a short period rotational stimulus consisting
of an acceleration pulse doublet, and a response measure of
apparent displacement, Guedry et al. (27,28) inferred the torsion
pendulum model's long time constants for both yaw and pitch
rotation about an earth-vertical axis. They found values of
16s and 7s in yaw and pitch, respectively, the former contrast-
ing with the earlier 10s yaw values, and the latter comparable
to the roll value just noted. What is not clear in this experi-
ment, however, is the effect of the measurement technique on the
inferred time constant values, a subject which is touched upon
briefly by the authors.

Response to earth-vertical rotation about al three body
axes was investigated by Melville Jones et al. (47), using a
velocity step as the stimulus, and the elapsed time to
sensation disappearance as the measured response. By also
measuring the slow phase velocity (SPV) of vestibularly induced

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compensatory eye movements (46), they were able to provide two separate measures of canal function. By assuming the torsion pendulum model to be driving both velocity sensation and eye velocity, they were able to derive two sets of long time constants, for the three axes. Table 1 summarizes their results, and shows that significant differences exist not only between axes, but between measures. In fact, they note that the only time constants which were not significantly different were those associated with subjective sensation in roll and pitch.

Table 1: Torsion Pendulum Long Time Constants (from Ref.47)

	Yaw	Pitch	Roll
subjective sensation	10.2 ± 1.8	5.3 ± 0.7	6.1 ± 1.2
nystagmus SPV	15.6 ± 1.2	6.6 ± 0.7	4.0 ± 0.4

Short Time Constants (τ_S)

The short time constant of the torsion pendulum model is considerably less well-specified. Van Egmond et al. (74) arrived at their estimate for τ_S by use of a torison swing. Recognizing that the model predicts zero phase lag between subjective velocity and swing velocity at the model's natural frequency ($\omega_n^2 = 1/\tau_S\tau_L$), they calculated a short time constant value of 0.1s, given a measured long time constant value of 10s and a natural frequency of 1 rad/s. However, this estimate has not been verified since, and other workers have argued that the short time constant is considerably smaller.

These arguments are based on theoretical considerations involving the dimensions of the canals and the viscosity of the endolymph within them. It suffices to note here that Melville Jones and Spells (49) estimate the time constant to be 0.005s, as do Fernandez and Goldberg (18) and Ormsby (56). Steer (70) comments on the discrepancy between this theoretical value and the subjectively measured value of 0.1s, and argues that primary canal afferents act to effectively low pass filter the cupula deflection to reduce the (mechanical) time constant by one or two orders of magnitude, so as to coincide with the larger measured value.

For the purpose of modelling subjective sensation to rotational motion cues during manual control, the specification of the short time constant is not critical, since its lag contribution is only effective at relatively high frequencies ($\tau_S = 0.1s$ implies a break frequency of 1.6 Hz). Arguments by other workers have been made to simply ignore it for human operator applications, and this will be discussed later in Section 2.6.

Model Time Constant Considerations

This brief discussion on model time constants should make clear two points. The first concerns the measured interaxis differences and, underlying that, the implications for time constant assignment to each of the three canal pairs. Because the normal body cues of yaw, pitch and roll do not coincide with the approximately orthogonal input axes of the three canal pairs, any body axis rotation is likely to excite all six canals to some extent. Melville Jones et al. (47), in their three-axis study of time constants, discuss this point and note that:

> ...it is convenient to invoke the concept of an
> "equivalent" time constant of cupular return
> [i.e., long time constant], corresponding
> to the value which would be ascribed to a single
> canal if it was solely responsible for the
> observed response and was oriented parallel to
> the chosen plane of rotation.

Thus, the suggestion is that we take a functional viewpoint which presumes the existence of three orthogonal "equivalent" canals, each having a sensitive input axis aligned with one particular body axis, and each having a distinct long time constant.

With a linear geometric transformation between body axes and canal axes, and (presumed) linear canal dynamics, one would expect each of the three equivalent "body-axis" canals to have a transfer function which is a linear combination of the transfer functions associated with each of the three physical canal pairs. Because of this linearity, a difference in "body-axis" canal time constants implies a difference in physical canal time constants. Thus, the psychophysical results suggest differences in the transducer dynamics associated with each canal pair.

This does not appear to be corroborated by the physiological data, however. Using afferent firing rates to infer time constants, Ledoux (83) found that when rotation is performed about axes approximately aligned with synergystic canal pairs, no significant differences are found between canal pairs. More recent measurements by Fernandez and Goldberg (18), using sinusoidal rotation to infer primary afferent frequency response, support this notion of canal pair equivalence. Although not explicitly stated, they failed to note a significant difference between afferents

associated with different canals, although individual differences were noted. Using the basic torsion pe   .um model with additional terms to account for variations at both frequency extremes (see next two sections), they provided a frequency response fit to the pooled data obtained from all three canals of one vestibular organ; the inference is that all canal units have basically the same transduction dynamics, independent of canal association. One is thus motivated to suggest a more central origin for the body-axis time constant differences observed at the behavioral level.

The second point to be noted regards the time constant discrepancy when the different response measures of nystagmus and subjective sensation are used (recall Table 1). Several models of the vestibulo-ocular reflex have been proposed (see, for instance, (48,63,68,73), with the underlying theme that the slow phase velocity of vestibularly induced nystagmus is due to the head velocity signal provided by the canals. An exceptionally simplistic view is given in Figure 1.

Figure 1. Simplified Vestibulo-Ocular Path
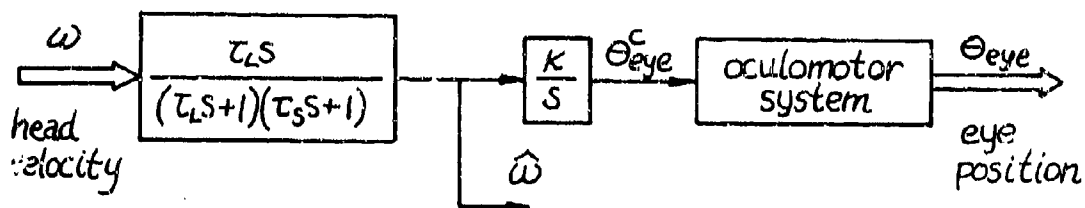
Since the oculomotor system seems to be primarily a position command system, there exists a requirement for some sort of integration of the canal velocity signal, to effect proper eye stabilization in space; hence the integrator in the figure. Assuming that the oculomotor system is relatively wide-band with respect to the canal long time constant, then the decay time for nystagmus slow phase velocity should provide a good measure of the canal long time constant; further, the result should not be significantly different from a value obtained from subjective testing. The differences of Table 1 point to central involvement, and suggest that response measures cannot be so easily ascribed to the physical canal properties. Of course, the same argument just given regarding interaxis differences holds here for the case of nystagmus response measures, so that the problem of canal property inference is further compounded.

The discussion of vestibular nystagmus will be continued in Section 4. For now, it is appropriate to consider the question of adaptation, and one model which has been proposed to help explain differences in nystagmus and subjective velocity measures.

Adaptation

The torsion pendulum model of (2) can obviously be used to predict subjective response for nonphysiologic rotational stimuli. In particular, the model predicts an exponential decay to zero sensation in response to a constant angular velocity step; for a constant angular acceleration step, the model predicts a steady sensation of turning. It was noted by Young and Oman (54,85) that these predictions contradict what is actually measured, since actual velocity step response is typified

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by an overshoot, and acceleration response is typified by an eventual decay towards zero sensation. To resolve this problem, they proposed that an adaptation operator or "washout" be cascaded with the torsion pendulum model. In addition, to resolve the discrepancy between subjective and nystagmus measures, they proposed an abandonment of the simplified model of Figure 1 in favor of a dual-channel model, each channel having its own adaptation operator, and both being driven by the same torsion pendulum transducer model.

Figure 2 shows their proposed model, with the torsion pendulum model of the canal driving both subjective sensation and nystagmus channels, each channel having its own associated washout time constant. The subjective channel washout is shown to be consistent with both velocity step response overshoot and acceleration step response decay. In addition, the modified model still maintains the accuracy of the torsion pendulum model fit to measured frequency response data (32) and to acceleration step detection latencies (46). Perhaps more fundamental, however, is the model's contribution towards resolving the apparent inconsistency between nystagmus and subjective response measures. Young and Oman note that if the model's step response is interpreted in terms of a second order torsion pendulum model, then the apparent time constant for nystagmus decay is 16s, whereas the apparent time constant for sensation decay is 10s, values which are consistent with previously reported values (47), and yet not inconsistent with the single long canal time constant of 16s used in their model. Thus, the time constant disparity between different measures can be resolved, while retaining a fixed parameter (torsion pendulum) transduction model.

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Figure 2.　Adaptation Model for Earth-Vertical Rotation
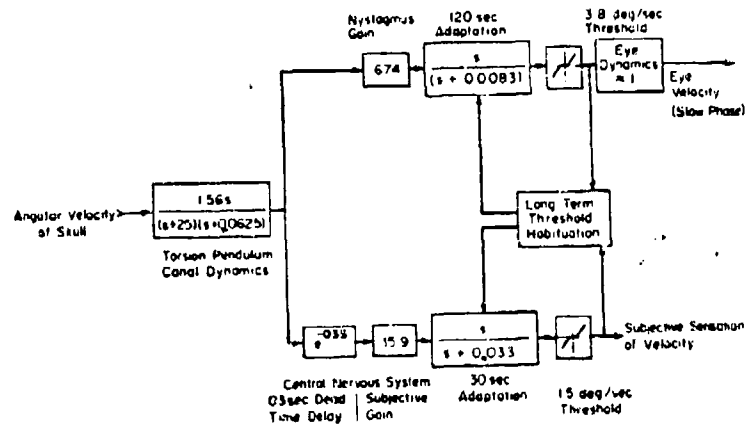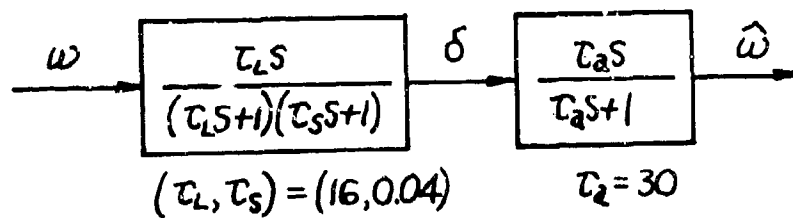　　　　　　　(from Young and Oman (85))

Figure 3.　Linearized Adaptation Model for Subjective Sensation
　　　　　　　(after Young and Oman (85))

This adaptation model was developed for the case of horizontal canal rotation about earth-vertical. Whether or not it can be extended to other axes was not addressed by the proposers, and appears to remain an open issue. If applicable, it may prove to be a means of resolving the apparent time constant differences seen between body axes.

Lead

In addition to the adaptation just discussed, there appears to be evidence of lead sensitivity in vestibular processing of angular velocity information. In studying postural reactions to induced body tilt, Nashner (51) found it necessary to augment the torsion pendulum model with a lead term having a 17 msec time constant, in order to fit reflex latencies to large amplitude disturbances. As noted by Ormsby (56), this type of lead behavior is not inconsistent with the vestibular nystagmus frequency responses reported by Benson (3), in which a high frequency gain rise was noted, consistent with a lead operator having a 60 msec time constant. Finally, in their investigation of primary afferent response of squirrel monkeys to rotational stimuli, Fernandez and Goldberg (18) found that the population average frequency response could be best fit with the inclusion of a lead term having a 50 msec time constant. These findings are summarized in Table 2.

Table 2: Lead Sensitivity to Rotational Stimuli

Lead Term	Measure	Source
(1 + .017s)	posture control	Nashner (51)
(1 + .06s)	nystagmus	Benson/Ormsby (3,56)
(1 + .05s)	primary afferent	Fernandez and Goldberg (18)

The longest time constant is associated with a break frequency
of 2.6 Hz, certainly at the upper end of the test frequency
spectrum used in most moving-base studies of human operator
control. If vibration effects are not an issue, then it would
seem entirely appropriate to ignore the lead term for purposes
of motion sensor modelling.

Threshold

Most of the quantitative measures of vestibular function
have been concerned with threshold determination, perhaps because
it is one of the simplest measurements to make, and does not
require a functional model for data interpretation. Again, most
of the work has been done with yaw-axis rotation about earth-
vertical, and, as in the time constant measurements, several
different response measures have been used to infer vestibular
threshold levels.

Threshold measurements are usually expressed in terms of
the minimum detectable rotational acceleration, determined by
some standard psychophysical criterion (e.g., 75% correct
detection). Thresholds expressed in this manner, that is, in
terms of stimulus intensity, require no functional model for
their interpretation; however, as will be seen shortly, they
fail to adequately describe the temporal dimension of the
detection task. The following section will first describe some
of these acceleration threshold measures, and then consideration
will be given to the problem of how to best model threshold
response. The argument will be centered on acceleration versus
velocity thresholds.

Threshold Measures

In a review of 25 earlier studies which attempted to define an absolute threshold for angular acceleration, Clark (8) notes the wide range in rotational devices, stimuli waveforms, psychophysical methods, and threshold definitions employed by various researchers. One might argue that such diversity should result in a more robust definition of threshold; unfortunately, the threshold values reviewed by Clark show a span of two orders-of-magnitude ($0.035^{\circ}/s^2$ to $\sim 4^{\circ}/s^2$) for yaw-axis earth-vertical rotation. He notes a median of approximately $1^{\circ}/s^2$ and observes that thresholds determined by use of the oculogyral illusion (22) appear to be lower than those obtained by subjective methods; beyond that, however, the particular value to be assigned to an absolute acceleration threshold would appear to be an open issue. Clark (8) concludes:

> ...definitive thresholds for the perception of angular accelerations in man with carefully measured angular accelerations of known durations and an adequate number of observers have yet to be made.

To resolve this issue, Clark and Stewart (11) conducted a study with precisely controlled and accurately measured angular acceleration steps. With 53 men as a data base (to be compared with the two or three typifying earlier experiments), they found a mean threshold, for the perception of yaw-axis rotation about earth-vertical, of $0.41^{\circ}/s^2$, with a fairly skewed distribution as shown in Figure 4. The stimuli were presented for 10s, and no mention is given of detection latency times.

Figure 4. Distribution of Thresholds for the Perception of
Angular Acceleration for 53 Normal Men
(from Clark and Stewart (11))

| N	53
MEAN	0.41
STD. DEV.	0.35
MEDIAN	0.32
RANGE	0.05 - 2.20

α_o (deg/s^2)
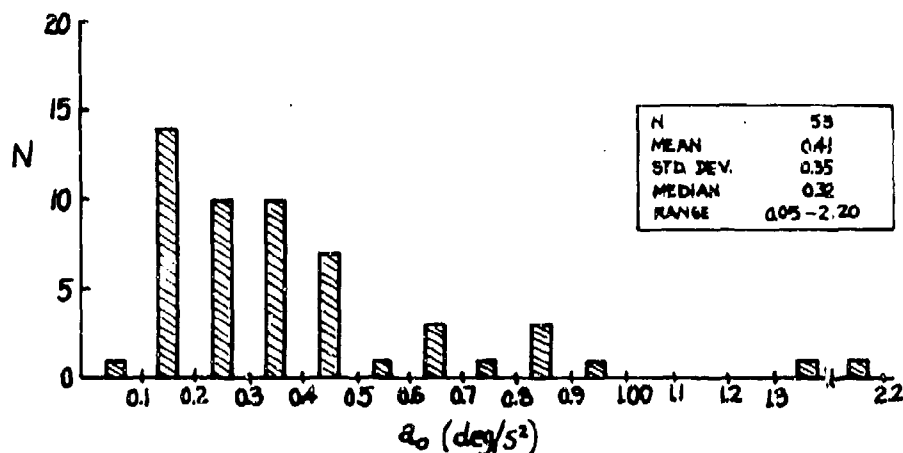
These results confirm the results of an earlier study conducted
by Clark and Stewart (10), in which they found a mean yaw-axis
threshold value of $0.41^\circ/s^2$ over a smaller (N = 18), more
uniform ($\sigma = 0.21^\circ/s^2$) subject population.

In his 10-year-old review article, Clark (8) noted the
paucity of threshold determinations for other axes: of the 25
studies considered, one was concerned with pitch rotation
(64) and one with roll (46). The former reported the highest
threshold values reviewed by Clark, $6.9^\circ/s^2$ for pitch away from
the vertical, while a pilot was operating a Link trainer flight
simulator. The latter reported a threshold value of approximately

$0.5^{\circ}/s^2$, for roll about earth-vertical .th the subject face
down in a yawing vehicle). Since that time, Clark and Stewart
(10) studied thresholds about all three axes, by suitably
positioning the subject so that rotation was always about
earth-vertical. Their results are summarized in Table 3.

Table 3: Subjective Thresholds to Angular Acceleration
Steps About Earth-Vertical (from Clark and Stewart (10))

	roll	pitch	yaw
Body position —	⌐	⊃⊂	⌀
Mean threshold ($N = 18$).....	0.41	0.67	0.41
Median threshold...........	.37	.59	.38
Standard deviation..........	.21	.52	.19
Range.........................	0.17–1.02	0.06–2.24	0.17–0.87
Thresholds compared........	x—y	x—z	y—z
Pearson correlation..........	+0.11	−0.06	+0.26

It is worth noting that although the pitch value is sub-
stantially greater than the roll or yaw values, Clark and Stewart
(10) find the difference to be barely significant ($P \approx 0.05$).
Thus, average threshold values might be considered to be approxi-
mately equal for all three axes. However, this inference from
the population averages does not carry over to individual subjects,
as the authors note that the low correlation coefficients between

axes indicate that no reliable prediction of a subject's threshold
in one axis can be made from a measurement in another. The
implications for multi-axis threshold modelling of subjective
sensation should be clear.

By use of a flight simulator driven by simulated aileron
pulses of constant duration, Gundry (29) investigated roll tilt
motion detection thresholds. By varying pulse magnitude to
provide a variable peak roll rate velocity, a velocity threshold
level of $0.12^{\circ}/s$ was found for the average response of a 10-subject
population. If it is assumed that the velocity profile was a
ramp, then this translates to an acceleration threshold of $0.48^{\circ}/s^2$,
since pulse duration was 0.25s. Note that this value is in good
agreement with Meiry's earlier findings for earth-vertical roll
(46), even though roll tilt detection probably involves otolithic
and proprioceptive cue processing. There is a considerable discrepancy
with earlier findings with the equivalent velocity threshold,
however, and this will be discussed further in the next section.

In another study using a flight simulator, Hosman and Van
der Vaart (33) investigated pitch and roll tilt motion thresholds,
using sinusoidal wave forms. By starting with a very low-
amplitude fixed-frequency sinusoidal acceleration, they were able
to measure the amplitude for detection onset by gradually increasing
the amplitude. After a subject detected the acceleration, amplitude
was decreased until the sensation of motion dropped out, which
provided a lower bound for threshold. Shown in Figure 4 are pitch
and roll acceleration thresholds obtained in this manner, plotted
as a function of stimulus frequency. The authors propose a
method for adjusting this data to arrive at an equivalent accel-
eration step threshold, for direct comparison with the results
of earlier studies; the results are given in Table 4, and it is

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noted in the paper that "these values are remarkably below those found by other researchers," when compared with those of Groen and Jongkees (24), Meiry (46), and Clark and Stewart (10). Although the method of data adjustment is not questioned here, the next section suggests an alternate viewpoint for interpreting the data.

Table 4: Equivalent Step Acceleration Thresholds (from Hosman (33))

Axis	onset ($^{\circ}/s^2$)	dropout ($^{\circ}/s^2$)
roll	0.023-0.035	0.0069-0.015
pitch	0.022-0.053	0.0082-0.026

Figure 5.   Roll Threshold Values   Figure 6.   Pitch Threshold Values
            (from Hosman (33))   (from Hosman (33))

$\dot{p}$ deg/s^2 ω (rad/s)

$\dot{q}$ deg/s^2 ω (rad/s)
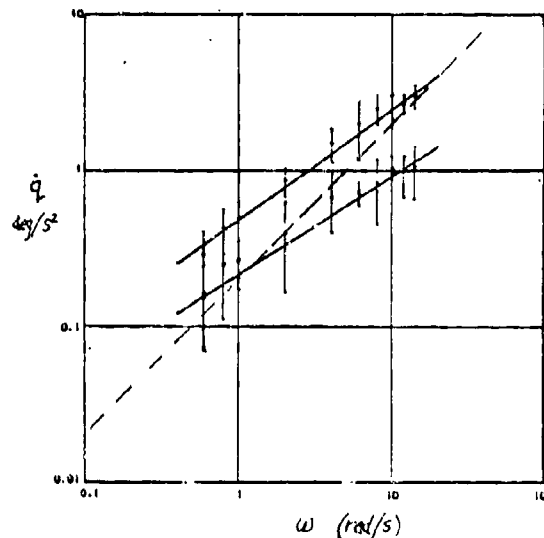
Threshold Modelling

To this point, most of the discussion of thresholds has concentrated on absolute levels of perceivable angular accelerations. However, it was pointed out by Groen and Jongkees (24) that Mulder (in 1908) was the first to recognize that the product of acceleration magnitude α with detection time T is approximately a constant, thus suggesting a velocity threshold mechanism at work. A theoretical justification for this product constancy was given by Van Egmond et al. (74), along the following lines.

If the torsion pendulum model of (2a) is used to describe sensation in response to an acceleration step of magnitude α, then

$$\hat{\omega}(s) = \frac{\alpha\tau_L/s}{(\tau_L s+1)(\tau_S s+1)} \tag{3a}$$

or, in the time domain,

$$\hat{\omega}(t) \approx \alpha\tau_L [1-e^{-t/\tau_L} + \frac{\tau_S}{\tau_L} e^{-t/\tau_S} \tag{3b}$$

where we have taken advantage of the fact that $\tau_S \ll \tau_L$. Because of this, the last term will always be less than (τ_S/τ_L) times the second term (or less than 1%), so that

$$\hat{\omega}(t) \approx \alpha\tau_L (1-e^{-t/\tau_L}) \tag{3c}$$

which is the acceleration step response of the simplified washout model of (2b). Van Egmond et al. (74) noted that with detection times T small with respect to τ_L,

$$1-e^{-T/\tau_L} \approx T/\tau_L$$

so that (3c) simplifies to the following:

$$\hat{\omega}(T) \approx \alpha T \qquad (4)$$

Thus, if the product αT is found to be a constant from the experimental measures, this strongly supports the existence of a velocity threshold ω_o, operating on the output of the torsion pendulum model, as shown in Figure 7. A value for this velocity threshold ω_o, or "Mulder Product," was estimated by Van Egmond et al. (74) to be approximately $2^\circ/s$, a value consistent with their earlier findings (24).

Figure 7: Velocity Threshold Model (Rotation)
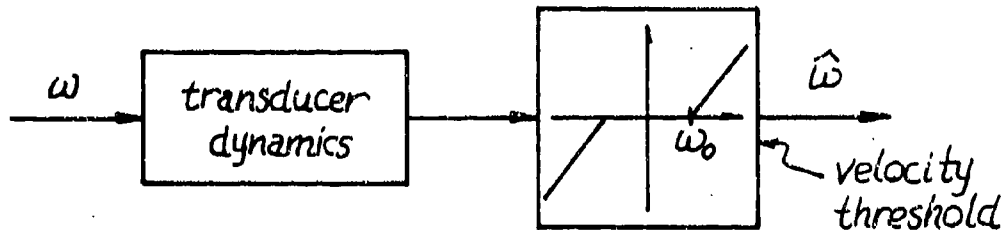
A refinement in predicting detection latency as a function of acceleration magnitude was provided by Meiry (46), who recognized that a simple velocity threshold following the torsion pendulum model could account quite well for both his data and that of Clark and Stewart (9). For yaw rotation about earth-vertical, Meiry (46) finds a velocity threshold of $2.6^\circ/s$; for roll about earth-vertical, a value of approximately $3^\circ/s$ would appear most consistent with his data. Both data sets and the model fit are shown in Figure 8. A similar presentation is
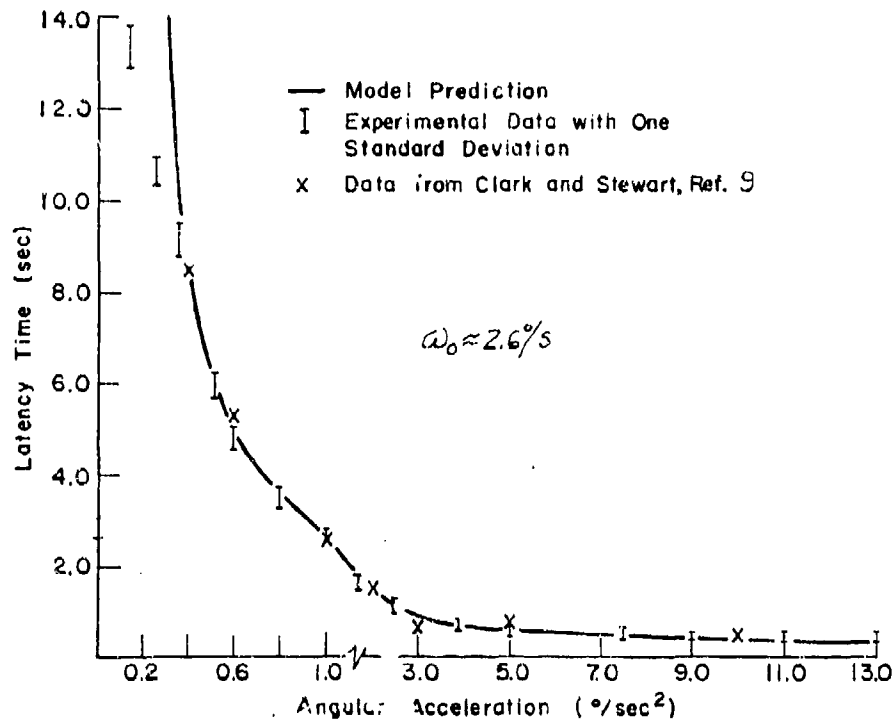
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Fig. 8 : Latency Times for Perception of Angular Acceleration about
The Vertical Axis (Y_h) (from Meiry (46))
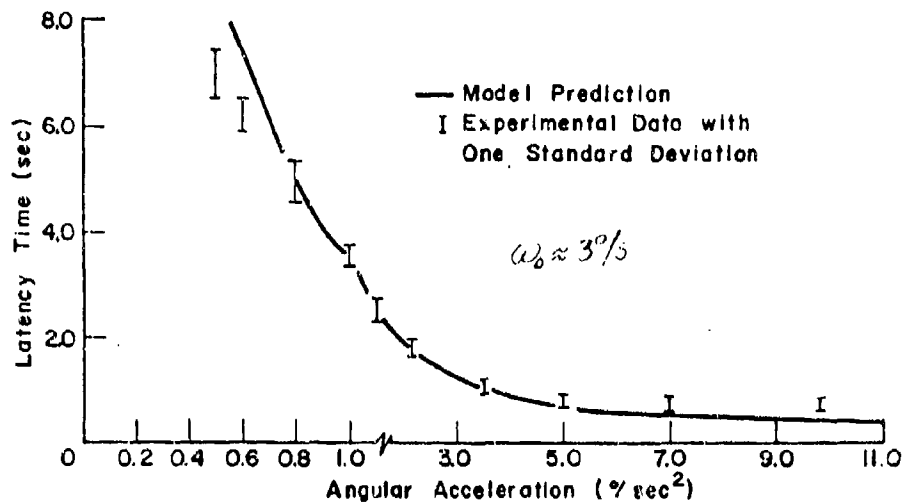Note: Scale Change of Angular Acceleration

Fig. 9 : Latency Times for Perception of Angular Accelerations about
The Roll Axis (X_h) (from Meiry (46))
Note: Scale Change of Angular Acceleration

given by Gundry (29) who provides a plot summarizing the results
of several acceleration/latency studies; he indicates that the
velocity threshold value for earth-vertical rotation is
approximately $4^O/s$.

Whether the yaw threshold is $2.5^O/s$ or $4^O/s$ is secondary
to the basic issue of velocity versus acceleration thresholds.
It is clear that given an infinite time to detect an acceleration
step (i.e., $t \gtrsim 30s$), there does exist an absolute acceleration
threshold; for the manual control problem, however, infinite time
is not available. In fact, if less than a few seconds are
available for a response to a motion input, then, from Figure 6,
it would appear that effective moving-base acceleration thresholds
could be on the order of $1^O/s^2$ to $15^O/s^2$, one to two orders of
magnitude greater than absolute thresholds measured in the
laboratory. What this suggests then, is that absolute acceleration
thresholds be abandoned in favor of velocity thresholds.

It should be recognized that an absolute acceleration
threshold is still implicit in a velocity threshold model,
because of the torsion pendulum model dynamics. From (3c), the
acceleration/latency variables (α, T) will be related to the
threshold velocity ω_o according to:

$$\omega_o = \alpha\tau_L(1-e^{-T/\tau_L}) \tag{5a}$$

so that latency as a function of stimulus magnitude is given by:

$$T = \tau_L \ln[\alpha/(\alpha-\omega_o/\tau_L)] \tag{5b}$$

Infinite detection time corresponds to an acceleration below an absolute threshold level α_o; from the last relation, this implies that

$$\alpha_o = \omega_o/\tau_L \tag{6}$$

Thus, acceleration and velocity thresholds are mathematically interchangeable, via the torsion pendulum model long time constant. This allows for a reinterpretation of some earlier threshold data obtained by Clark and Stewart (10), and presented previously in Table 3. By multiplying their measured acceleration thresholds by the corresponding axis time constants measured by Melville Jones et al. (47), presented previously in Table 2, velocity thresholds for each body axis can be estimated, for earth-vertical rotation. The results are shown in Table 5, and it is worth noting these values seem to be in general agreement with those obtained by Meiry (46) and Van Egmond et al. (74), although these two studies suggest lower values for yaw. The yaw axis value agrees with Gundry's survey (29), although there is more than an order-of-magnitude difference between his estimate (0.12^o/s) and the table value for the roll-axis threshold. Presumably, the roll tilt cue in Gundry's experiment is confounding his rotational velocity threshold estimate.

Table 5: Body Axis Angular Velocity Thresholds (Earth-Vertical Rotation)

Axis Parameter	Yaw	Pitch	Roll	Reference
τ_L (s)	10.2	5.3	6.1	47
α_o (deg/s^2)	0.41	0.67	0.41	10
ω_o (deg/s)	4.2	3.6	2.5	

Threshold Considerations

It is appropriate to discuss briefly three factors which can influence the effective rotational threshold level used in a functional model of subjective sensation: adaptation, stimulus predictability, and task-loading.

The adaptation model of Young and Oman (85), discussed earlier in Section 2, provides for an eventual response decay to an acceleration step. In so doing, their model predicts longer latencies to low acceleration stimuli, when compared to response from the unaugmented torsion pendulum model. To correct for this behavior, the adaptation model utilizes a lower velocity threshold value of $1.5°/s$, as previously illustrated in Figure 2. The fit to the latency data thus remains essentially unchanged from that already seen in Figure 6. The implication, of course, is that the velocity threshold values given in Table 5 may be too large for direct incorporation into an adaptation model of subjective sensation; a recalculation to account for adaptation effects may be in order.

A factor which surely influences the choice of an effective rotational threshold is knowledge of the applied stimulus, either as to its anticipated time of occurrence, or its waveshape. Although this writer is not familiar with any direct studies which investigate motion threshold magnitude dependence on stimulus presentation time, an inference might be made from studies of auditory discrimination. Specifically, it has been shown (15) that a shortening of the time interval within which an auditory stimulus is momentarily presented results in an increase in a subject's detectability index (23), which, for our purposes, may be interpreted as a lowered effective

threshold. A corroborating study (16) shows that as the time interval between a presentation warning light and the auditory stimulus is varied, a subject's detectability index reaches a maximum when the warning and the cue coincide. Thus, as knowledge of stimulus presentation time becomes more precise, the effective threshold decreases.

The inference from these studies in another modality is that similar behavior might be observed in motion detection studies, under similar experimental conditions. The extremely low roll velocity threshold values measured by Gundry (29), on the order of $0.1^{\circ}/s$, support this notion; in his protocol, the motion stimulus always appeared one second after a warning light alerted the subject to a possible cue presentation. Most other researchers use a less predictable cue presentation protocol, and obtain higher velocity threshold values, in the range of $2^{\circ}/s$ to $5^{\circ}/s$.

Knowledge of stimulus waveshape may also affect measured threshold values. In the study of Hosman and Van der Vaart (33) discussed earlier, use of a varying amplitude sinusoidal stimulus showed detection onset thresholds to be higher than sensation drop-out thresholds, suggesting that subjects can follow the stimulus "into the noise," given knowledge of the stimulus waveform. This hysteresis effect is small, however, when compared to the discrepancy between threshold values obtained using sinusoidal stimuli versus those obtained using step stimuli. Figures 5 and 6 of the previous section show unity slope straight line curve fits to the pitch and roll threshold data obtained with sinusoidal stimuli; an acceleration threshold value of $1^{\circ}/s^2$ at a frequency of 5 rad/s implies a velocity threshold of $0.2^{\circ}/s$, an order-of-magnitude lower than that measured with conventional "featureless" acceleration steps

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(compare with Table 5). Whether this difference is due to the predictability of the sinusoidal cue, or is due to the confounding effect of tilt cue processing, is unclear at this time; however, it suggests that some consideration be given to the problem of threshold dependence on the subject's knowledge of stimulus waveform.

Threshold variation with stimulus predictability, either as to time of occurrence or waveshape, should have a direct impact on pilot modelling efforts. A pilot in a closed-loop moving-base target tracking task is subjecting himself to self-generated motion; thus, if he has a perfect internal model of the vehicle he is controlling, and a knowledge of his control commands, he is in a position to predict his self-imposed motion cues. It might then be argued that effective motion thresholds are lower, for this type of active controls task involving target tracking. For a tracking task in which the motion cue is not predictable, such as in gust disturbance regulation, one might expect little change in the pilot's effective motion threshold. Little work has been done in this area, although other workers have pointed out the importance of "expected state" feedback in arriving at an estimate of true body orientation and velocity (see, for example, Ref. 81).

A counterargument can easily be made for higher effective thresholds during active tracking, because of less attention paid to motion cues due to task-loading. This effect has been suggested by several authors (26,29,33,59,72), and, in fact, has been the justification for more "realistic" threshold studies more appropriate to pilot-vehicle analysis, and less tied to the single task of pulse detection in an ideal laboratory environment. Gundry (29) shows roll velocity thresholds to increase by 40% when the subject is loaded with an arithmetic problem; a similar increase in pitch and roll acceleration

thresholds is reported by Hosman and Van der Vaart (33), when their subjects are loaded with an auditory discrimination task in addition to being required to provide active vehicle control.

Demonstration of such task-loading effects is, of course, only the first step in determining effective motion threshold loads for a pilot in a realistic control situation; clearly, much work remains to be done in this area if any of the laboratory threshold measures are to be applied successfully to the active controls problem of modelling motion sensation dynamics.

## Model Applications to Manual Control Analysis

Other workers have been interested in canal/perceptual models from a "user" standpoint, with the objective of incorporating sensory input-output functional models within the larger framework of sensory processing and human operator controls. A brief discussion of some of these approaches is appropriate here.

A fairly extensive survey of vestibular modelling was conducted by Peters (59), who noted the disparity in threshold measures and time constant values obtained by different researchers, and further noted the lack of data for motion other than yaw-axis earth-vertical sensation. Utilizing various arguments to discount some values and accept others, he arrived at the values given in Table 6, associated with the single-axis model given in Figure 10. Note that this is simply the torsion pendulum model coupled with an angular velocity threshold, and that three-axis coverage is provided by three such parallel channels.

Table 6:   Rotation Model Parameters (after Peters (59))

Axis	Short T.C. τ_S(s)	Long T.C. τ_L(s)	Accel Threshold α_o (^{o}/s^2)	Velocity Threshold ω_o (^{o}/s)
yaw	0.1	8.0	0.14	1.1
pitch	0.1	5.3	0.5	2.6
roll	0.1	6.5	0.5	3.2

Figure 10. Rotation Model (from Peters (59))
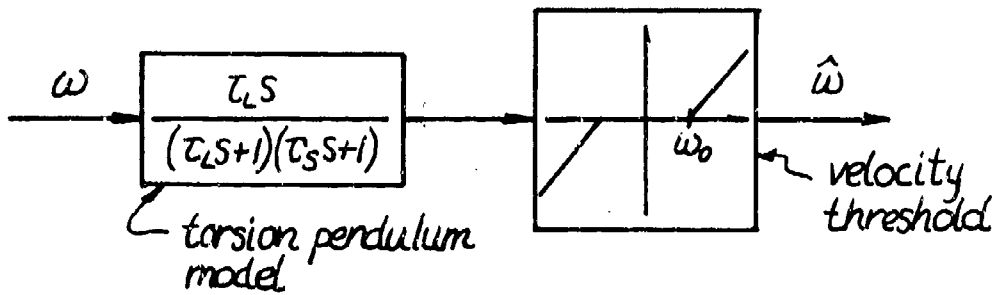
The model's short time constant, assumed the same for all three axes, is based on the estimate of Van Egmond et al. (74). From the discussion given earlier, the 0.1s value would appear to be overly long, with more realistic values an order of magnitude smaller. The long time constants shown are an amalgamation of the results of several studies and are in reasonable agreement with the three axis studies of Melville Jones et al. (47) noted earlier (compare with Table 5). Peters chose acceleration threshold values based on Meiry's results in yaw and roll (46), in turn based on a subject population of three; the pitch value was chosen to equal the roll value. The acceleration values given in Table 6 allow for the calculation of velocity thresholds as done earlier, obtained by multiplying the acceleration threshold by the long time constant τ_L. This, then, is the same model which was discussed by Ringland and Stapleford (61) in their justification for the motion cue adjustment rule for the manual control crossover model.

In his development of a unified model of tilt and rotation sensation, Ormsby (56) took a less simplistic view of canal influence on subjective sensation, and partitioned the problem into one of transduction, filtering, and cross-coupling. Since the cross-coupling portion of the model is only effective when rotation is not about earth-vertical (or, more accurately, when the angular velocity vector is not colinear with the specific force vector), this portion of the model can be ignored for the present discussion. Further, since the filtering algorithm was designed so that it "would not contribute significantly to the overall dynamics of the subjective response," this portion of the model can also be ignored, and concentration be given solely to the transduction model.

Figure 11 illustrates a single c' ~nel transduction model (56), relating head angular velocity to afferent firing rate; the presumption is that perceived angular velocity $\hat{\omega}$ is directly proportional to the change in firing rate, Δf. Note that the torsion pendulum model is coupled with the adaptation operator proposed by Young and Oman (85), and with a lead operator, motivated by considerations similar to those discussed earlier in Section 2.4. Model parameter values are given in Table 7, and apply to all three axes.

Table 7: <u>Rotation Model Parameters (from Ormsby (56))</u>

Short T.C. τ_S (s)	Long T.C. τ_L (s)	Lead T.C. τ_l (s)	Adaptation T.C. τ_a (s)
0.005	18	0.01	30

Figure 11. Rotation Model (after Ormsby (56))
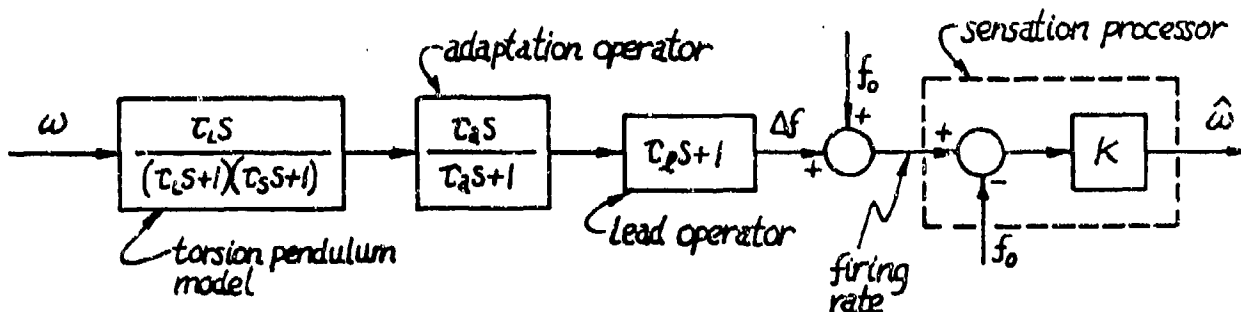
The particular time constant values chosen for the model are based on a diverse set of experimental observations. As noted earlier, the short time constant τ_S is based on the theoretical hydrodynamic properties of the canal, derived by Steer (70), and on the canal radius as measured by Igarashi (35). Ormsby (56) argues that, due to adaptation, the long time constant τ_L should be chosen on the basis of vestibular nystagmus records; the 18s value reported by Schmid et al. (65) is thus used. The adaptation time constant τ_a is taken from Young and Oman (85), based on their model fit to subjective response data. Finally, the lead time constant τ_l is chosen simply as an order of magnitude approximation to the results of previous workers, summarized earlier in Table 2.

The model of Figure 11 shows no threshold, since Ormsby (56) argues for a "signal-in-noise" model, consisting of white noise summing with the rest firing rate, and a central processor which provides signal detection based on the statistical properties of the signal and noise. However, if the model shown is coupled with a conventional threshold function, it would be difficult to distinguish its input-output characteristics from the previously-discussed adaptive model (see Figure 2) proposed by Young and Oman (85), over frequencies from DC to 10 rad/s, a range which spans typical human operator tracking response.

The single channel model of Figure 11 is based on the result of yaw-axis rotation about earth-vertical, and Ormsby (56) proposes it as a transducer model for all three canal pairs. This may be a valid approximation of transducer characteristics, in light of the work by Ledoux (39) and Fernandez and Goldberg (18), showing no significant response differences between canal pairs, but will result in predictions of subjective sensation

to earth-vertical rotation which are independent of body-axis orientation to the rotation vector. Th clearly conflicts with the earth-vertical rotation studies of Melville Jones et al. (47), and it is unclear at this point how this conflict might be resolved.

This model was modified and incorporated within the optimal control model of the human operator, by Curry et al. (12,13). The short time constant term was dropped (being effective only for frequencies greater than 200 rad/s) and the lead time constant changed to 0.02s to better fit the data. If their resulting canal model is viewed as an estimator of head angular velocity, then its transfer function is given by:

$$\hat{\omega} = K \ s^2 \ \frac{(.02s+1)}{(18s+1)(30s+1)} \ \omega + v \tag{7}$$

where v is additive white noise and K is chosen on the basis of acceleration threshold considerations. As with the simple torsion pendulum model, frequency response is flat in the midband from 0.1 to 50 rad/s, although their gain choice results in a 9 dB underestimation of perceived velocity magnitude, in this frequency regime (with $K = 187.9s^2$, gain at 1(rad/s is - 9.19 dB). Presumably, this is of no serious consequence, since the Kalman estimator used in the model can weight the canal model output accordingly. This model was used to fit moving-base tracking data from three separate previously-reported tasks, two of which involved roll tracking, and the third longitudinal and lateral control of VTOL hover. None of the tasks involved yaw-axis earth-vertical rotation, the type of motion on which Ormsby's model (56) was based.

The same motion sensation model was used by Levison and Junker (41), again within the OCM structure of the human operator, to fit their own roll-axis tracking data. They noted no significant improvement in fitting the data, when compared with the fit obtainable by a simple "informational" approach, an approach in which the operator display vector is simply augmented by higher derivatives of vehicle motion. This might be expected since the test-signal power was within the motion model passband, so that model dynamic effects should have been negligible.

Summary and Discussion

Summary

Although functional models of rotational motion sensation have drawn upon several different response measures using a variety of test stimuli, all seem to have in common the basic torsion pendulum model of the semi-circular canals. The short time constant of this model is not well-defined (with estimates spanning the range of 5 to 100 msec), but it is felt to be sufficiently small so as to contribute little to the dynamics observed during moving-base active tracking/regulation tasks, because of typical human operator bandwidth limitations. The long time constant of the model is better defined, but is highly dependent on the response measure used for its estimate and on body-axis orientation with respect to the rotation vector; this dependence is summarized in Table 1 given earlier. Although variation in the long time constant estimate with response measure can be accounted for by the addition of an adaptation operator, a variation with body-axis orientation is inconsistent with the known physical properties of the canals. The inference is that considerable post-transduction processing by the CNS may be occurring.

Since its introduction, the torsion pendulum model of the canal end organ has been augmented by cascaded linear adaptation and lead operators, initially motivated by subjective sensation measurements. Subsequent physiological studies of end organ response have substantiated the form of this higher order model, although it is unclear whether end organ response is the primary determinant of the measured subjective response dynamics. That is, adaptation and lead time constants associated with subjective response may be attributable to CNS processing of the afferent signals, as opposed to directly reflecting primary afferent transduction behavior.

Rotational thresholds have been customarily measured in units of angular acceleration, with the objective of determining the minimum acceleration detectable within the time allotted by the particular experimental protocol. The few studies which have looked at concurrent detection latencies show an acceleration-latency product constancy, and thus support the notion of an effective velocity threshold. The discussion given here argues that velocity threshold modelling is a more appropriate means of predicting threshold behavior, because it automatically accounts for detection latency, is generalizable to response predictions for different stimuli waveshapes, and provides a more realistic measure of threshold under conditions which demand short detection times, as occur in vehicle control situations. Estimated velocity thresholds for the different body axes are summarized in Table 5.

Discussion

Most of the modelling efforts have relied on results obtained during earth-vertical yaw-axis rotation, under near-ideal laboratory conditions. As just noted, the few studies which have

reoriented the body-axis, but maintained earth-vertical rotation, have demonstrated significant interaxis differences in both time constant and threshold values. Whether these differences would be seen with similar body-axis rotations about earth-horizontal remains to be demonstrated, and may not be, because of the confounding effects of tilt cues. Thus, there arises the question of whether a body roll-axis model, determined from experiments using earth-vertical rotation of supine subjects, can be successfully applied to predict earth-horizontal roll sensation for subjects seated upright. In other words, it appears to be an open issue as to whether the models can be used to accurately predict a pilot's sensation of motion for the most common of all aircraft motions, roll. Naturally, the same comments apply to pitch-axis motion cue modelling.

Most of the threshold studies have been concerned with determining the minimum detectable stimulus magnitude, and not with determining its dependence on other factors which are typically present outside the laboratory situation. Specifically, the task of vehicle control might be expected to raise a pilot's effective motion threshold, due to task-loading effects on attention, but also might be expected to lower it, due to the predictability of pilot-initiated motions. The effect of task loading on effective threshold has only begun to be studied, and it is only recently that the threshold-lowering effect of stimulus predictability has been demonstrated. Whether these effects will render classical laboratory measurements of little use to the pilot-modelling effort is unclear at this time. However, the optimal control model (OCM) of the pilot may provide a convenient means of effectively modelling this threshold sensitivity, because of its capability in specifying attention allocation and its ability to predict pilot-generated cues, via its internal model structure.

A final point regarding rotational sensation models and their applicability to the human operator modelling problem concerns the possible variation of sensation dynamics with operator involvement in moving-base control. Although not demonstrated experimentally, there exists the possibility that the model time constants might vary with operator activity, particularly those time constants generally associated with central processing of afferent information: the adaptation and lead terms. Thus, for a passive observer indicating when his subjective sensation falls to below threshold, one might expect a relatively long time constant to be inferred from the data. In contrast, sensation decay may occur more rapidly in an active controls task, simply because it may be to the operator's advantage to "wash out" long term sensations, and concentrate on transients. Although speculative, a variation such as this would clearly have implications for the choice of model time constant used in a moving base pilot-vehicle model.

SECTION 3
OTOLITH MODELS AND TILT/TRANSLATIONAL SENSATION

Modelling of subjective sensation to tilt and translational cues has somewhat paralleled rotational cue modelling, in that model development has drawn upon diverse fields, ranging from the specification of the anatomy and physiology of the end organs (the utricle and saccule), to subjective and objective behavioral responses to different tilt and linear motion stimuli. Although there are similarities between rotational and translational motion research, several qualitative differences serve to distinguish the resulting functional models.

Considerably less work has been done in the field of linear motion perception (including tilt perception), when compared to the effort devoted to understanding rotational motion sensation. The result is that the end organ transduction dynamics are less well understood, and functional modelling of subjective sensation is not as fully developed. In fact, it would appear that a basic issue regarding subjective sensation modelling has yet to be resolved: the question of whether the otolith-mediated sensation is one of tilt, acceleration, or velocity, or some combination of the three.

The modelling problem is compounded by the fact that quantitative measures of transducer response fail to corroborate the functional models developed for subjective response. This is to be contrasted to the case of rotational motion, in which the torsion pendulum canal model would appear to dictate the major characteristics of subjective response. Thus, a functional model of otolith transduction proves to be an inadequate framework for the development of a subjective sensation model, and recourse must be made to an assumption of significant signal processing by higher centers.

Static Shear Force Model

Although it was recognized for some time that the otolith organs respond to static tilt away from the vertical, it was not until the definitive study by Fernandez et al. (20) that the details of transduction geometry were uncovered. Motivated by functional polarization maps provided by anatomical study of hair cell arrangement on the sensory surface, Fernandez showed that the firing rate of each responding unit was driven by the applied shear force of gravity, determined by head tilt and the unit's orientation within the otolith organ. Since the utricle and saccule are approximately plane surfaces, this implies that each organ can provide a vector measure of the specific force vector (46), restricted to those components of the specific force vector contained within the organ's "receptor" plane. Thus, if $\underline{f}$ is the specific force vector ($\equiv \underline{a}-\underline{g}$, where $\underline{a}$ is linear head acceleration, $\underline{g}$ is gravitational acceleration), and if $\underline{f}_\perp$ is that portion of it normal to the receptor surface, then otolith output, $\underline{s}$, can be modelled as a vector output:

$$\underline{s} = K(\underline{f}-\underline{f}_\perp) \tag{8}$$

which is applicable to static tilt sensations.

This static sensitivity was confirmed by Schöne (66) in a series of psychophysical experiments which investigated perception of the vertical as a function of specific force magnitude and direction. By maintaining the specific force vector in the sagittal (pitch) plane, the apparent vertical was shown to be a linear function of $f \cdot \sin \alpha$, where f is specific force magnitude and α is defined by the force vector and the normal to the utricular otolith plane, as shown in Figure 9.

For this restricted class of specific force inputs, utricular
otolith shear force thus appears to be the adequate stimulus
for the perceived vertical, and thus, of perceived steady-state
pitch tilt away from the vertical.

Figure 12. Schematic of Utricle, Saggital Plane
(from Schone (66))
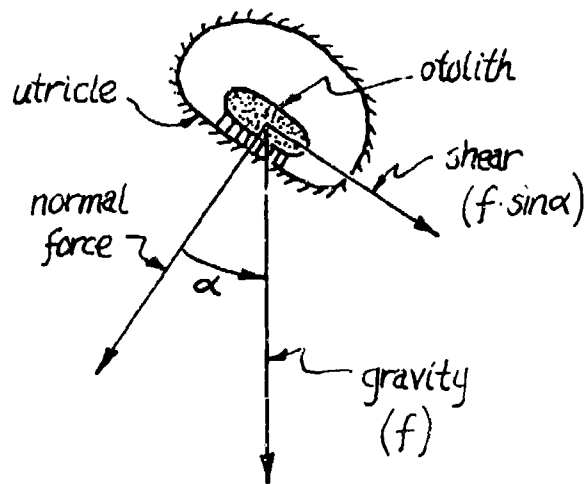
For tilt about the roll axis, Sc¹ . (66) again argues that utricular plane shear force is the adequate stimulus, in this case, for perceived steady-state roll away from the vertical. This relation is only valid to approximately 60°, but Ormsby and Young (57) show how a non-linear modification to specific force vector processing can account for a larger range of stimulus-response behavior. In particular, they propose a functional model which provides for linear transduction of utricular shear force, in combination with non-linear transduction of specific force normal to the ·t⌐' э. Possibly, this latter transduction is effected by the saccule, which is approximately orthogonal to the utricle. The model, which accounts for several steady-state roll and pitch tilt illusions (57), is illustrated in Figure 13 ; the non-linearity characteristics are chosen to approximate the experimental results of several researchers. With this model, it is presumed that the subjective indication of down, $\hat{\underline{d}}$, is given by a simple normalization of the transduced specific force vector, $\hat{\underline{f}}$, according to:

$$\hat{\underline{d}} = \hat{\underline{f}}/|\hat{f}| \tag{9}$$

Note that this model does not address the question of dynamic processing of a changing specific force vector input; presumably, the "accelerometer" blocks contribute to the dynamics of subjective upright sensation.

Figure 13. Model of Subjective Vertical Orientation
(from Ormsby and Young (57))
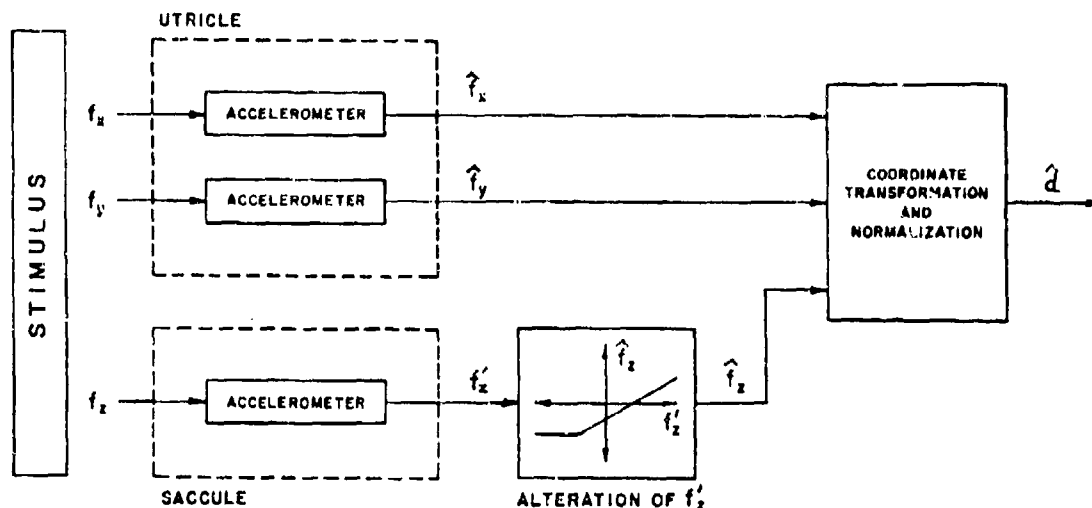
Dynamic Sensation Models

Model Output

To this point, the discussion has been concerned exclusively with response to static tilt away from the vertical, although the nomenclature of specific force has been used to remind the reader of the equivalence between gravitational and actual acceleration, as viewed by an otolith "accelerometer." This equivalence has been taken advantage of in dynamic testing situations, by utilizing linear acceleration cues in place of tilt, thus avoiding the possibility of confusing otolith response with canal-mediated rotation sensation.

Such an approach has its problems, one of which is in interpreting the resulting subjective sensation. If a subject is placed in a tilting chair which he knows cannot undergo translational displacement, then his response to a steady-state tilt cue will be a subjective sensation of tilt away from the

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vertical. If a subject is placed in a linearly translating chair which he knows cannot be rotated, then one might argue that his response to a steady acceleration should be one of constant linear acceleration, while remaining upright. This would not appear to be the case, however, since centrifuge experiments (21) show that subjects identify the steady-state specific force vector with apparent down, and thus interpret the otolith-mediated cue as a tilt cue, rather than one of linear acceleration.

For transient linear accelerations, however, it has been argued that subjects should associate the otolith signals with perceived linear motion, rather than tilt, because of the null signals generated by the canals. Although this will be discussed further in Section 4, the basic idea is that transient otolith signals are associated with linear motion transients, when canal output indicates no rotation has occurred. Such a situation is to be found in the translating chair experiments of various researchers.

Given that this type of motion cue is interpreted as linear motion, the question still remains as to whether it is viewed as an acceleration or a velocity by the subject. One of the arguments, implicit in the literature, is to the effect that if linear acceleration and off-vertical tilt are physically equivalent stimuli, and if subjects perceive tilt in a tilting situation, then they should perceive acceleration in a linear motion situation (in the transient case). This perc ptual equivalence is sketched in Figure 14. However, the act that we recognize the equivalence between the physical cues need not imply that the central nervous system does, and, in fact, it would not be surprising if the CNS were unaware of the

contradiction in equating velocity sensation with tilt sensation, in response to a specific force input. Thus, one might very well argue that otolith-mediated linear motion sensation is interpreted as velocity, rather than acceleration. The question appears to be unresolved in the literature.

Figure 14. Perceptual Equivalence of Tilt and Linear Acceleration
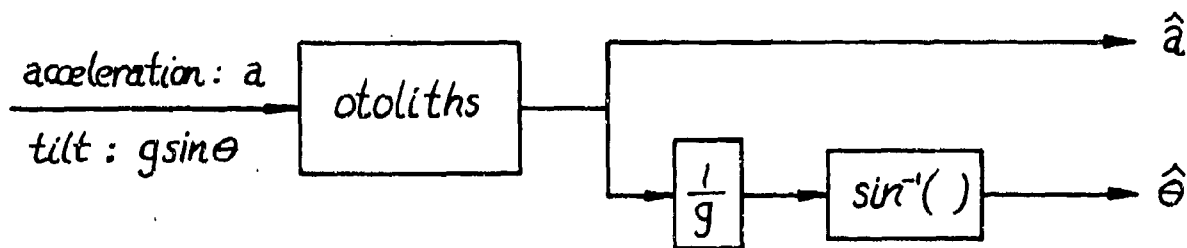
Model Structure

The dynamics of subjective sensation, in response to time-varying specific force cues, were first investigated by Meiry (46), in his linear acceleration studies. Utilizing a cart to provide fore-aft linear sinusoidal motion, and measuring subjective indication of travel direction, he was able to specify phase dependence on stimulus frequency. By assuming that subjects were indicating the sign of the perceived velocity, he constructed a linear transfer function which relates perceived velocity to actual velocity:

$$\frac{\hat{v}}{v} = \frac{K\tau_L s}{(\tau_L s+1)(\tau_S s+1)} \qquad (9)$$

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with the time constants τ_L and τ_S chosen to be 10s and 0.66s, respectively, to fit the phase data over the input test spectrum. Since no amplitude measures were taken, K is unspecified. It should be noted that this model is identical in structure to the torsion pendulum model describing angular velocity perception.

The question of model output was raised by Peters (59), among others, who suggested that the sensation measured in the experiment was not subjective velocity, but rather, subjective acceleration. The argument is given that, in response to an acceleration step, the model predicts a subjective acceleration sensation ($s\hat{v}$) which decays to zero with a 10s time constant. Implicitly assuming the structure of Figure 14, and noting that a step in tilt angle does not result in a decay to zero of perceived tilt angle, he argued that the model output should be perceived acceleration $\hat{a}$, rather than perceived velocity $\hat{v}$.

Similar points were noted by other workers, and, in response, Young and Meiry (84) proposed a revised model of linear acceleration sensation, which accounts for the noted discrepancies. By shortening the long time constant, and adding a lead term, they were able to model both perceived tilt and linear velocity, in response to a linear acceleration stimulus. The model is shown in Figure 15, and the authors note that it acts as a simple velocity transducer over the frequency range typical of normal head motions, 0.2 rad/s to 1.5 rad/s. Note that this model presumes the equivalence of acceleration sensation with that of tilt.

Figure 15. Revised Dynamic Otolith Model (from Young and Meiry (84))
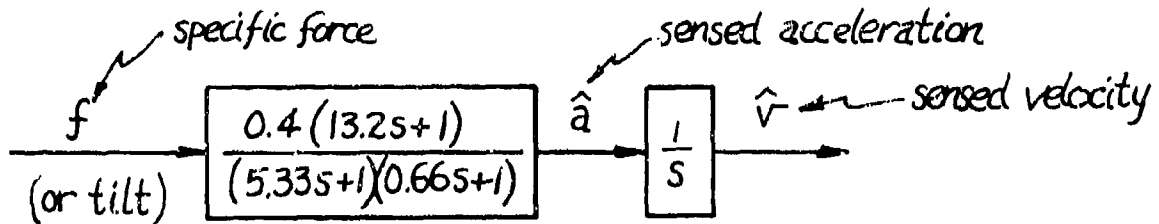
The form of this model's transfer function might be
justified by the known shear force transduction characteristics
of the otolith organs. Specifically, a mass-spring-dashpot
modelling of otoconia motion could be used to justify the two
lag time constants, in much the same manner that the torsion
pendulum model of subjective sensation is based on the
mechanical properties of the canals. The model's lead term
might be similarly ascribed to end organ transduction, perhaps
to high frequency sensitivity of the primary afferents. In
short, one might be motivated to equate the subjective sensation
model of Figure 15 with a transducer model of the otolith.

A detailed look at afferent response to time-varying
stimuli suggests, however, that otolith transduction dynamics
are not consistent with this subjective sensation model.
Recording from otolith primary afferents, Fernandez and
Goldberg (19) confirmed the general structure as shown
(including lead), but showed that the end organ bandwidth is

considerably higher than what might be expected from subjective response studies. In particular, they ___ed that for stimulus frequencies up to 2 Hz,

> "Gain curves are relatively flat. Phase lags
> are seen at higher frequencies and these can
> be simulated by a first order lag element with
> a corner frequency of about 10 Hz". (19)

This implies a long time constant of approximately 16 msec., more than two orders of magnitude smaller than that associated with the model of Figure 15.

This disparity between the dynamics of otolith transduction and tilt/acceleration sensation does not, however, imply that functional modelling of subjective sensation cannot be successful. It does, however, make it more difficult to justify a particular functional form for empirically derived transfer functions based on psychophysical measurements. Perhaps of even greater significance to the modelling effort is that such a disparity implies that a significant amount of tilt cue sensory processing must be conducted by higher centers, centers which may have access to canal information, or, for that matter, information from other modalities. One aspect of this cue mixing possibility is discussed further in Section 4.

Threshold

Relatively few studies have been made of threshold levels for tilt/acceleration cues, and even less effort has been devoted toward functional modelling of threshold effects. The difficulty of making such measurements may be a factor, since tilt threshold measurements can be confounded by the rotational sensitivity of the canals, and low acceleration thresholds, in combination with the type of motion involved, require the use of experimental apparatus of greater sophistication than a simple rotating chair.

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As with the rotational studies, linear motion thresholds
are usually expressed in terms of the minimum detectable accelera-
tion, determined in some standard psychophysical fashion. The
same latency dependence on acceleration magnitude is seen here,
and one is clearly motivated to propose a velocity threshold
model, identical to that already discussed in Section 2.
First, however, it is appropriate to consider some of the
studies which have attempted to define absolute acceleration
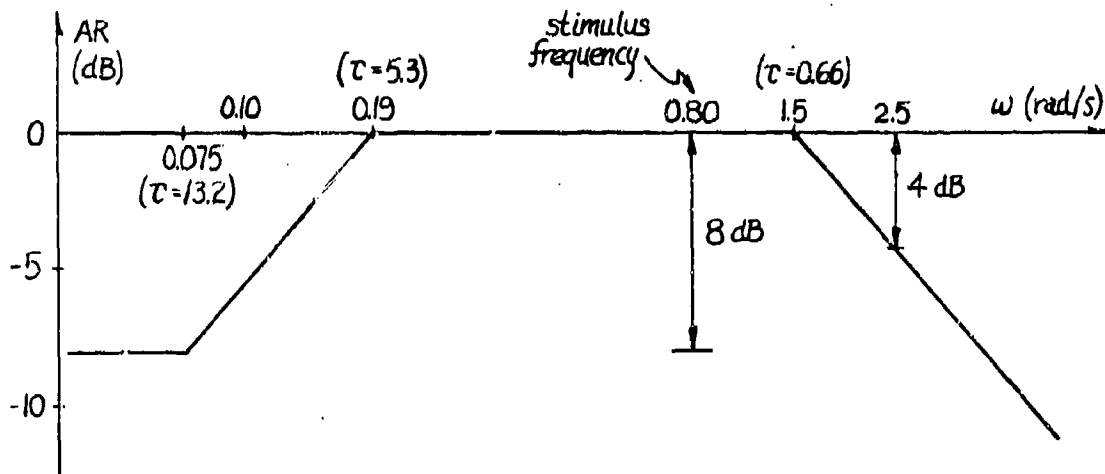thresholds.

Threshold Measures

In a review of 11 earlier studies which attempted to
define an absolute threshold for linear acceleration, Peters (59)
noted an order of magnitude spread in measured threshold
(0.002g to 0.02g), and suggested several possible contribu-
tors to the variation. These include intersubject variability,
type of stimulus used (e.g., sinusoidal versus step), definition
of threshold, and head axis orientation with respect to the
stimulus.

Clearly, these are factors similar to those presumed
responsible for the variations in measured rotational threshold
levels (discussed earlier in Section 2), although in this
instance, the problem is compounded by a smaller number of
studies with a larger variation in measurement techniques.

Only one of the reviewed studies (by Mach, 1875) used a
linear acceleration stimulus in the earth-vertical direction.
Using a balance beam to provide sinusoidal vertical motion, and
with the subject seated upright, Mach calculated an acceleration
threshold of 0.012g, with a stimulus period of 7s (as reported

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by Henn and Young (31)). If we assume approximately the same
dynamic response to both vertical and ! .zontal linear accelera-
tions, then the model of Figure 15 predicts that the stimulus
used is directly in the sensation passband, as illustrated in
Figure 16   Thus, one might expect the measured threshold to be
a low estimate, by approximately 8dB, so that the effective
vertical motion threshold is closer to 0.030g.

Figure 16. Otolith Model Gain (from Figure 12)

Subsequent vertical motion threshold measurements, however, show almost an order-of-magnitude difference with Hosman and van der Vaart (33) reporting an approximate threshold of 0.0085g over the frequency range of 1 to 10 rad/s, and Melville Jones and Young (50) estimating the threshold to be 0.005g. Whether the difference between these more recent estimates and Mach's earlier estimate is due to an improvement in experimental technique, or the use of more sensitive subjects, is not clear. What is clear, however, is the extreme sensitivity of subjects to linear acceleration, especially in view of the fact that these measurements were made in a 1g environment, implying a resolution capability of approximately one part in 200.

Caution should be exercised in interpreting this sensitivity, however, since motion detection sensitivity need not necessarily imply an accurate knowledge of the time course of the motion cue. This is vividly demonstrated by the vertical motion studies conducted by Malcolm and Melville Jones (44), in which subjects were oscillated vertically and asked to indicate their perceived direction of motion. Using frequencies in the range of 0.6 to 3 rad/s, and superthreshold acceleration amplitudes of 0.2g to 0.4g, they found that

> "Without prior knowledge of the movement pattern, subjects
> were aware of movement but registered its form with a
> performance little better than chance." (44)

and

> "...they quickly got out of phase with the time motion
> of the machine, some even reporting that they were
> moving in precisely the opposite direction to that
> of the real helicopter motion!"

The investigators propose that the utricle is basically ineffective as a vertical acceleration sensor because of stimulus orientation with respect to the macula, and that the saccule is similarly

ineffective because few of its hair cell polarization vectors are colinear with the stimulus, even though the saccular macula is approximately coplanar with the stimulus. Thus, Malcolm and Melville Jones (44) suggest that vertical motion tracking, although sensitive, is inaccurate because of the basic geometry of the transducing otolith organs.

Threshold measurements have also been made using linear accelerations in the horizontal plane, with subjects prone or supine. As with the vertical acceleration studies just mentioned, this geometry implies an alignment of the stimulus acceleration vector with the vertical body axis; thus, similar thresholds might be expected, with values in the range of 0.005g to 0.010g. This is confirmed by Lansberg's estimate of 0.009g using a parallel swing and sinusoidal acceleration (as reported by Peters(50)) and by Meiry's estimate of 0.010g using a linear motion cart and acceleration steps (46). However, Walsh (76) found a threshold level of approximately 0.002g in various horizontal body positions, using a sinusoidal stimulus having a 2.5s period. Peters (59) notes that this 2.5 rad/s cue is sufficiently above the 1.5 rad/s dynamic model break frequency (see Figure 16) to cause a dynamic attenuation of approximately 6dB; thus, the suggestion is that the effective threshold value measured by Walsh (76) is closer to 0.001g, an order of magnitude smaller than the upper limit of the 0.005g to 0.010g range typifying the results of other workers. The reason for this discrepancy is not apparent.

The most commonly used test protocol for threshold measurement has been with upright seated subjects responding to fore-aft motion. Meiry notes that with the utricle inclined at approximately 30° up from the horizontal head plane, and

the assumption of saccular non-involvement in motion detection.
then one might expect fore-aft motion thresholds to be lower
than vertical motion thresholds by a factor of (cos $^{\cdot o}$/sin 30°)
or about 1.7. Based on the vertical motion studies. his implies
an expected range of 0.003g to 0.006g, for fore-aft motion
thresholds. In his survey, Peters (59) reports a range of
measured thresholds spanning an order of magnitude, and
containing this predicted range, from 0.002g to 0.020g. Thus,
a comparable level of uncertainty exists with fore-aft thresholds,
as with vertical thresholds.

It should be recognized that fore-aft linear acceleration
thresholds can be used directly to predict steady-state pitch
tilt thresholds, since, for a pitch angel θ, the effective
acceleration is $g\sin\theta$, or, equivalently, $g\theta$. Thus, pitch tilt
thresholds should be in the range of 0.002 to 0.020 radians,
or from 0.1 to 1.0 degree. This writer is unaware of any
tilt threshold measurements confirming this prediction.

Roll tilt thresholds can be similarly predicted, but
require a measurement of acceleration sensitivity to lateral
linear motion, in a direction perpendicular to the sagittal
plane. Walsh (76) appears to be the only worker to have
determined threshold vales for both prone and supine positions,
and he reports values of approximately 0.002g, again using a
sinusoidal stimulus with a 2.5s period. Since the same
argument used above holds here, the effective threshold of
approximately 0.001g translates to an expected roll tilt
threshold of approximately 0.06^o. Whether or not this high
sensitivity has been confirmed by actual roll tilt experiments
is not clear to this writer.

This sensitivity to tilt highlights the problem of attempting to determine angular velocity thresholds associated with the canals, when the rotational stimulus is not constrained to be about earth-vertical. For example, Hosmann and van der Vaart (33) measured an apparent angular acceleration threshold of approximately $1^\circ/s^2$ for a 5 rad/s stimulus acting to roll the subject away from the vertical. As noted earlier in Section 2.5.2, this implies an angular velocity threshold of $0.2^\circ/s$, an order of magnitude smaller than the more commonly measured earth vertical rotational thresholds of $2^\circ/s$ to $5^\circ/s$. However, a roll velocity threshold measurement of $0.2^\circ/s$ at 5 rad/s implies a roll tilt of 0.04°, a value which is very close to the detection limits of the otolith organs. The implication is that tilt sensitivity, due to otolith transduction of specific force, may easily confound "simple" rotational threshold measurements.

Threshold Modelling

The earlier discussion concerning rotational threshold modelling (Section 2). concentrated on the question of acceleration versus velocity threshold functions, because of the integrating angular accelerometer properties of the canals. and the demonstrated latency dependence on stimulus magnitude. The same points can be raised for perception of linear motion, although the argument is less firm because of the uncertainty surrounding the qualities of the otolith-mediated sensation; i.e., the question of sensation being interpreted as tilt, acceleration, or velocity, in response to a specific force input. Although there has been less study of acceleration/tilt threshold modelling, the argument will be made here that the available threshold data can best be modelled at the velocity level.

In his threshold modelling effort described earlier,
Meiry (46) measured detection latencies as a function of linear
acceleration step size. His data is shown in Figure 17, for a
three-subject population responding to linear fore-aft acceleration
steps while seated upright. The model prediction shown fitting the
data is based on the velocity perception model introduced earlier,
given by (9). In response to a velocity ramp of slope a, it
predicts a perceived velocity of

$$\hat{v}(t) = K\tau_L a(1-e^{-t/\tau_L}) \tag{10a}$$

where the effect of the short time constant τ_S has been ignored.
This response is identical in form to that already discussed for
rotational velocity sensation $\hat{\omega}$, and thus the same latency/
acceleration dependence might be expected. Meiry implicitly
assumed a _velocity_ threshold v_o, so that threshold level
accelerations a require T seconds to be detected, the two
variables being related by:

$$v_o = K\tau_L a(1-e^{-T/\tau_L}) \tag{10b}$$

By choosing one experimentally determined response pair (a,T),
Meiry effectively determined $(v_o/K\tau_L)$ from the above relation,
and then used this value in conjunction with (10b) to calculate
the curve shown in Figure 17.

In his model development, Meiry (46) made no argument for
a velocity threshold per se, although his predicted curve
implicitly assumes such. To support this notion, it is
appropriate to replot Meiry's data in a form which can be used
to validate the model prediction of (10b), and infer the value
of the velocity threshold directly. The model predicts an
inverse relationship between the exponential term $(1-e^{-T/\tau_L})$

Figure 17. Latency Times for Perceptic ¬f Horizontal
Linear Acceleration, Upright (from Meiry (46))
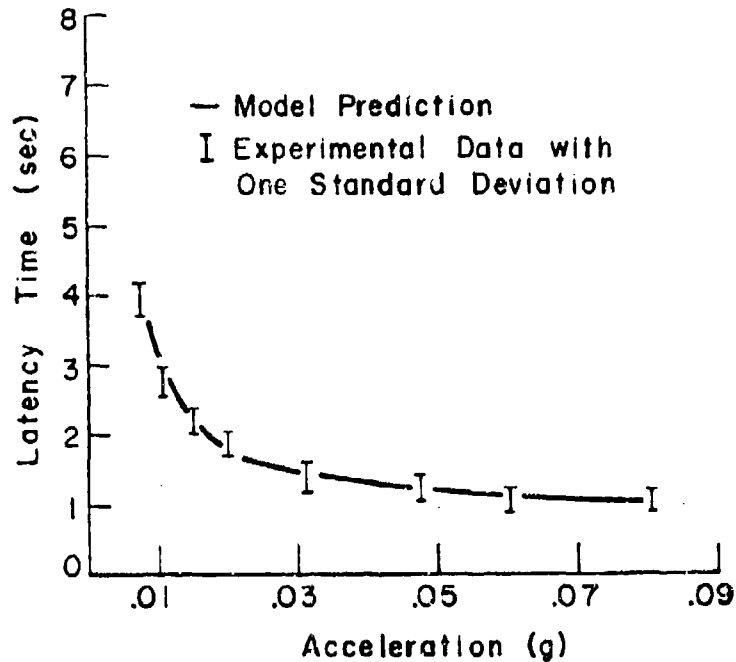
and the acceleration level a; shown in Figure 18 is a cross-plot
of these two terms, with a linear regression to the data. The
close fit (r=0.99) clearly supports the form of the model; the
slope and intercept can be used to infer the model parameters.
Since the model predicts zero latency for an infinitely large
acceleration (a^{-1}=0), the non-zero intercept must be due to a
fixed reaction time associated with the task, T_R. Assuming T_R
small with respect to the model's long time constant (τ_L=10s),
the exponential term is approximated by (T_R/τ_L) at a^{-1}=0, so that

$$T_R/\tau_L = 0.068 \qquad \text{or} \qquad T_R = 0.68s \tag{11a}$$

Figure 18. Latency vs. Inverse Acceleration (linear motion
data from Meiry (46))
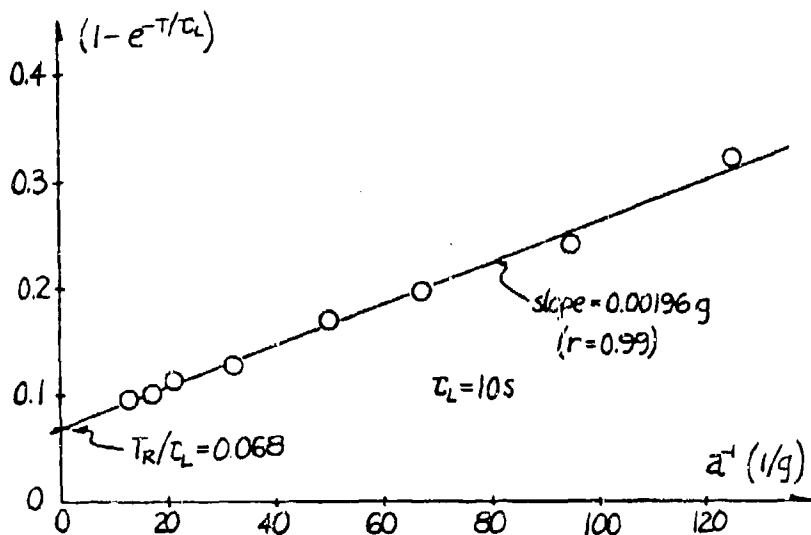
which is a not unreasonable reaction time for this task. Of more
interest, however, is the threshold value to be inferred from
the slope:

$$(v_o/K\tau_L) \approx 0.0020g \qquad \text{or} \qquad v_o/K \approx 0.020g\text{-s} \tag{11b}$$

Thus, the data supports the notion of a linear _velocity_ threshold
of 0.020g-s or 0.3ft/s.

A block diagram of this velocity perception model, with a
velocity threshold output, is shown in Figure 19. This linear
motion model has exactly the same structure as the torsion
pendulum model for rotational sensation (Figure 10), except for
the unspecified gain value K. The model describes fore-aft
linear motion perception while seated upright; a similar modelling
of Meiry's data (46) can be conducted for perception while
supine, and the block diagram shows the appropriate threshold
value for this situation.

Figure 19.   Velocity Threshold Model (translation)
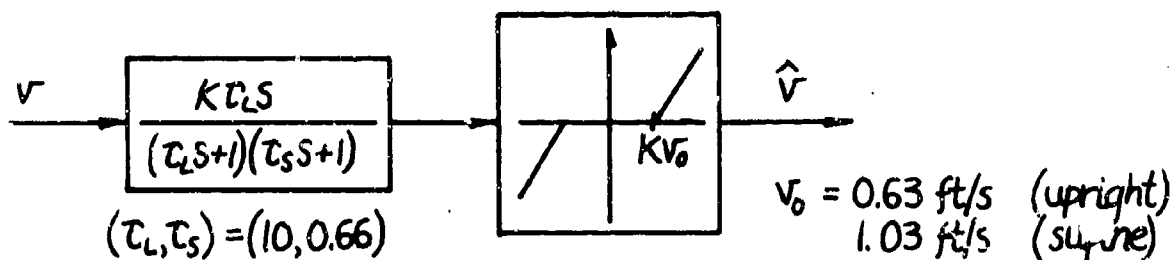
As in the rotational case an absolute acceleration threshold a_0 can be predicted from the model, by recognizing from (10b) that:

$$T = \tau_L \ln[a/(a-v_0/K\tau_L)]$$

(12a)

so that if infinite detection time is associated with an absolute threshold, then

$$a_0 = v_0/K\tau_L$$

(12b)

which, from (11b) is seen to be 0.002g for the upright position; for a supine position, the absolute acceleration threshold is found to be 0.032g. Both of these values differ by a factor of three from those stated by Meiry (46), since he based his acceleration threshold estimate on the 75% correct detection level (0.006g upright, 0.010g supine), and not on the value inferred from the model and subsequently used to fit his latency data.

It is of interest to note that the same conclusion was arrived at by Melville Jones and Young (50), who used a similar analysis of latency/acceleration data provided by their own experiments and by those of Meiry (46). They provide a strong argument for velocity threshold modelling and propose a value of 0.74 ft/s for fore-aft linear motion while upright, based on an analysis of Meiry's data (46). Other threshold values are given in Table 8, for different combinations of head orientation and input acceleration. Melville Jones and Young (50) note that, contrary to Meiry's thesis of utricular sensitivity, the threshold determinant appears to be head orientation with respect to the gravity vector, rather than acceleration vector orientation with respect to the head. To this writer's knowledge, no other velocity threshold estimates appear in the literature.

Table 8: Linear Velocity Thresholds (46,50)

head orientation	motion direction	motion direction w.r.t. head	velocity threshold(ft/s)*	data source
upright	fore-aft	along roll-axis	0.63(0.74)	46
upright	up-down	along long-axis	(0.71)	50
supine	fore-aft	along long-axis	1.03(1.06)	46

*Values shown in parenthesis are estimates obtained by Melville Jones and Young (50).

The discussion to this point has concentrated on velocity threshold modelling, based on response data using linear motion cues. However, tilt thresholds can be directly computed for the situation in which the otolith-mediated sensation is interpreted as a tilt away from earth-vertical, rather than a linear acceleration. As noted in the previous section, tilt thresholds can be obtained from absolute acceleration thresholds simply by dividing by g; since the absolute acceleration threshold a_o is related to the velocity threshold by (12b), then the absolute tilt threshold, according to this model, is given by

$$\theta_o = v_o/K\tau_L g \tag{13}$$

where θ_o represents a roll or pitch tilt angle in radians. As noted earlier, these values are on the order of 0.002 rad, or approximately 0.1 degree. It might be expected that tilt angle detection would show the same latency dependence on magnitude, but clearly, such measures would be confounded by the dynamic response properties of the canals, in detecting angular velocity changes. The subject of off-vertical rotation will be discussed at greater length in Section 4.

A final note on threshold modelling may be made in regard to the revised dynamic model proposed by Young and Meiry (84), discussed earlier and illustrated in Figure 20. They interposed an acceleration threshold between the "mechanical" otolith dynamics and the "neural" lead operator, although f om the discussion just given, a velocity threshold could serve as a useful substitute. The threshold location is conjectural; in fact, the afferent recordings of Fernandez et al. (20) suggest

that neither a mechanical nor neural threshold exists at the end
organ. This observation, taken with the known discrepancy between
transducer response and the time course of subjective sensation,
suggests that this model be interpreted strictly as a functional
characterization of input-output behavior, and not as a detailed
model of individual components along the sensory path.

Figure   20.   Revised Nonlinear Otolith Model (from Young and Meiry
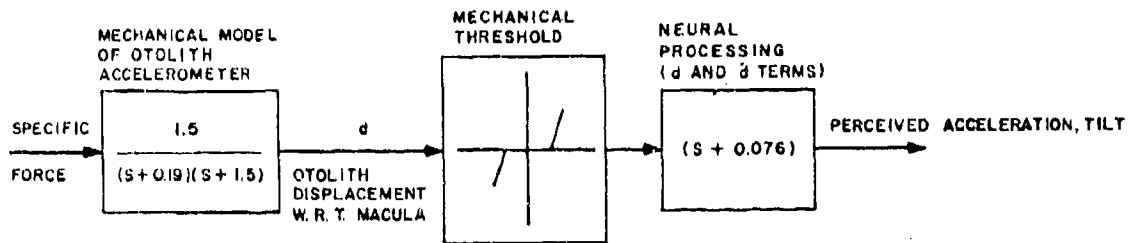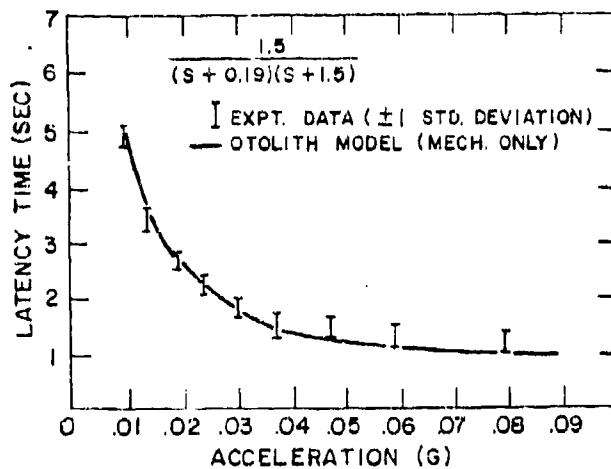   (64))

Figure   21.   Time for Perception of Constant Linear Acceleration:
                Model and Experiment (from Young and Miery (84))

Threshold Considerations

Earlier in Section ?, the question was raised concerning the appropriateness of using reported rotational threshold values in a human operator model of active tracking in a moving-base environment. The question is just as applicable for linear motion/tilt thresholds.

On the one hand, one might expect lower effective thresholds when the subject has some knowledge as to stimulus waveform or time of onset. This is supported by comparing the relatively high threshold of 0.01g reported by Meiry(46) using a non-predictable acceleration step, with the relatively low value of 0.003g reported by Travis and Dodge (1928, as reported by Peters (59)), using a repetitive sinusoidal acceleration. The inference for active tracking task models is that effective thresholds may be lower for self-generated motions.

On the other hand, one might expect higher effective thresholds during active tracking, due to task loading. This notion is supported by the study of Hosmann and van der Vaart (33) who showed a three-fold increase in their measured vertical motion thresholds (from 0.005g to 0.016g), when the subject was concurrently given an auditory discrimination task and the task of controlling vehicle roll attitude, over and above the task of simply acting as a passive vertical motion detector. Thus, the order of magnitude spread in the threshold measurements discussed earlier may be a conservative estimate of effective threshold ranges, when consideration is given to som￼ of the features of an active tracking task.

Model Applications to Manual Control Analysis

As with rotational cue modelling, workers have been interested in otolith/perceptual models from the standpoint of incorporating them in a framework of a human operator model. Some of these models have already been discussed, but it is appropriate to review them here, and mention other "user" models.

It was noted earlier that Peters (59) conducted a fairly extensive survey of the then current vestibular literature, and found that the only modelling of linear motion sensation was that conducted by Meiry (46). His model, relating velocity sensation to acceleration input, has been discussed at some length already, but it is worth restating Peters' proposed modification. He presumed sensation to be one of acceleration (based on the argument given earlier noting the physical equivalence of tilt and acceleration), and assumed Meiry's measured dynamics to still be applicable, thus arriving at the following transfer function relating perceived acceleration to actual acceleration:

$$\frac{\hat{a}}{a} = \frac{1}{(\tau_L s+1)(\tau_S s+1)} \tag{14}$$

with the same time constants noted earlier ($\tau_L = 10s$, $\tau_S = 0.66s$). Note that this model may be useful in relating perceived tilt to actual tilt, but may not be valid for predicting perceived translational velocity.

The revised model proposed by Young and Meiry (84), and discussed in the previous section, serv   is the basis for the simplified perceptual model proposed by Ringland and Stapleford (61). They neglected the low frequency lead and lag terms, on the basis of anticipated vehicle motion frequencies, and neglected the threshold function, presuming it small with respect to typical vehicle motion amplitudes. Their resulting low-pass filter model retains only the lag time constant of the original model:

$$\frac{\hat{a}}{a} = \frac{1}{\tau s+1} \qquad (\tau = 0.67s) \qquad (15)$$

The perceptual model proposed by Ormsby (56), as part of his unified vestibular model, distinguishes between transduction and sensation by partitioning the processing. He presumes a lead-lag otolith transducer model which relates specific force to end organ firing rate (see Figure 27). Neither time constant is directly specified, but the functional form is, by appealing to the wide bandwidth dynamics of the otoliths and the possible lead sensitivity of the primary afferents. As with his canal model (discussed in Section 2), he presumes an additive white noise at the transducer output to model threshold behavior.

To provide an optimal estimate of the specific force in the presence of this sensor noise, Ormsby follows his transducer model with a Wiener-Hopf filter, whose form is shown in Figure 18a. By choosing the filter parameters appropriately (and thus indirectly fixing the transducer parameters since the two parameter sets are directly related) he shows how the overall transducer/estimator model can be made to fit the subjective responses measured by Meiry (46). One might argue that this is a fairly tortuous route to the overall input-output model of subjective sensation given in Figure 23   a model whose form

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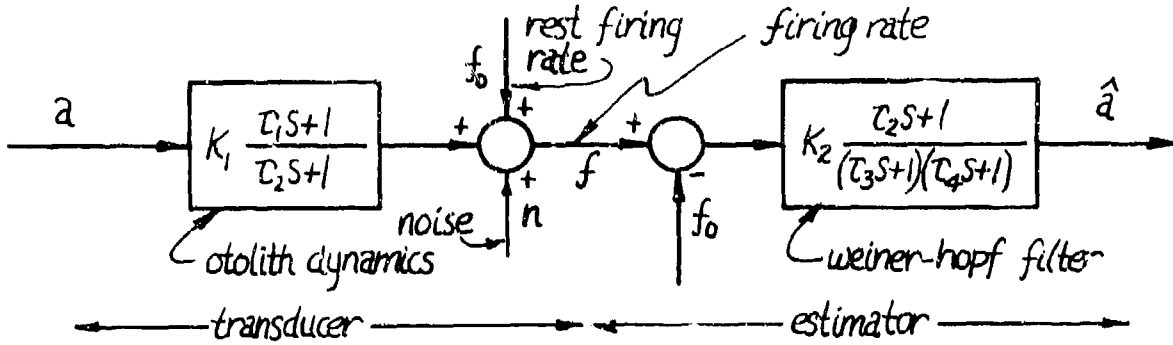Figure 22. Linear Motion Perception Model (after Ormsby (56))

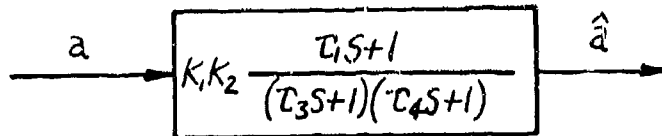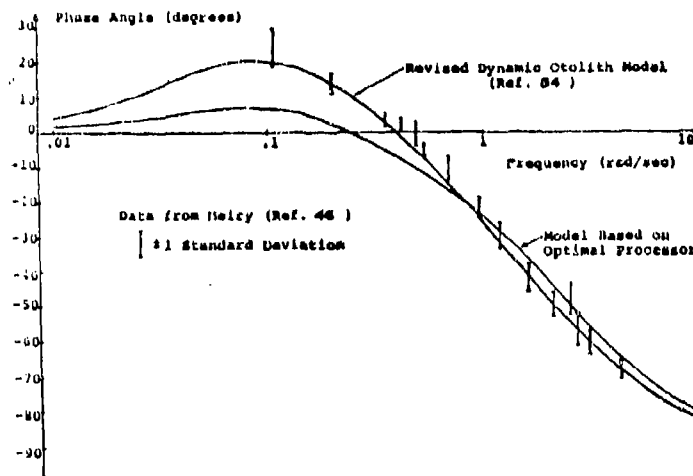Figure 23. Equivalent Input/Output Model

Figure 24. Phase Response of Sensation Models (from Ormsby (56))

was previously proposed by Young and Meiry (84), especially since Ormsby's parameters fail to provi' 1s close a fit to the data as do the parameters of the originally proposed model (see Table 9 and Figure 24). However, this modelling approach does resolve the apparent inconsistency between high bandwidth transducer dynamics and low bandwidth perceptual dynamics. Furthermore, it demonstrates the feasibility of utilizing modern estimation techniques to functionally model sensory processing, an approach which has already been successful in the manual control area. Most importantly, it suggests that transduction and estimation might be best treated as separate processes.

Table 9:   Translation Model Parameter Comparison

Parameter	Ormsby (56)	Young and Meiry (84)
τ_1	10.1	13.2
τ_2	5.0	-
τ_3	7.5	5.3
τ_4	0.51	0.67

By choosing the parameters of the input-output model of Figure 23 to fit the subjective response data, Ormsby (56) indirectly specifies the two time constants of his lead-lag otolith transducer model of Figure 22. The time constants are given in Table 9, and these were used by Curry et al. (13) in their otolith lead-lag submodel of transducer dynamics, for their human operator modelling effort mentioned earlier. This same model was incorporated into the human operator model developed by

Levison and Junker (41), although in contrast to Curry et al. (13), they ignored transducer noise, because of the relatively small thresholds in comparison to the typical motion amplitudes incurred during tracking.

Summary and Discussion

Functional modelling of translation/tilt sensation has attempted to parallel the development of rotational motion sensation models, by ascribing sensation characteristics to end organ properties. This has been successful to some extent, in that the shear force otolith transducer model provides a reasonable accounting of static tilt sensation, when both actual tilt and specific force are varied. The incorporation of a non-linearity in this static model, a non-linearity which might possibly be ascribed to saccular otolith processing, provides for an economic description of response under a wider range of stimulus magnitudes, and helps explain previous measures of subjective tilt estimation errors. However, modelling the dynamic response of sensation to time-varying cues has met with less success, for a number of reasons.

One of the major questions yet to be settled in modelling subjective response to specific force cues concerns the interpretation of the transduced cues. A subject's set will clearly differentiate between linear motion and tilt from the vertical, at least for transient specific force cues. However, when the motion cue is interpreted as linear motion, it is unclear whether the sensation is one of velocity or acceleration. The two dynamic models discussed in Section 3 reflect opposing viewpoints on this issue, although it must be noted that both act as velocity transducers in the mid-band frequency regime; their major differences become evident at very low frequencies.

The other major factor which hinders the understanding
of how specific force cues are processed is the observed disparity
between transducer and sensation dynamics. Both mechanical
considerations and afferent recordings point to a very wide band-
width otolith transduction capability, but input-output measure-
ments of subjective sensation support a relatively low bandwidth
dynamic model. The fact that sensation dynamics cannot be
directly ascribed to transducer characteristics implies that
considerable central processing must be occurring. Thus, a
complete understanding of the end organ response to time-
varying cues may prove to be only marginally helpful in developing
an accurate functional model of sensation. This, of course, is
to be contrasted with the situation in rotational cue processing,
in which an understanding of canal transduction has closely
paralleled the development of rotational sensation models.

Specific force thresholds have been customarily measured
in units of linear acceleration, and, as in the rotational
studies, the measurements have been made with the objective of
determining the minimum acceleration detectable within the time
allotted by the experimental protocol. The discussion presented
here, and in only one of the cited papers, argues for a
functional model incorporating a linear velocity threshold,
since this type of threshold conveniently accounts for the
approximate product constancy observed in acceleration-latency
curves, when detection latencies are measured. Velocity
threshold values are summarized in Table 8, although it should
be recognized that these are based on only two studies, using
only a small number of subjects. A velocity threshold, in
conjunction with the dynamic model of Figure 19 which predicts
velocity sensation as a function of the specific force cue,
proves to be a direct analog of the simplified rotational
sensation model consisting of the torsion pendulum dynamics

followed by an angular velocity threshold. Whether this model correspondence is coincidental or not is open to conjecture.

Discussion

Most of the modelling efforts have relied on results obtained during up-down or fore-aft linear acceleration, in the presence of a one-g gravity field. Although this type of testing can provide a basis for predicting the sensations a pilot might have during vehicle heave, surge, and pitch, a knowledge of subjective response to lateral acceleration is necessary to properly model pilot response to the most common aircraft motion of roll. Only one of the studies cited examined response to left-right accelerations, and, at that, focussed only on threshold determination, and not dynamic response. It might be argued that similar dynamic response might be expected in all three body axes, but this does not seem to be the case, since static g-vector orientation appears to play an important role in determining response to imposed linear accelerations. Subject response, both dynamic and threshold level, needs to be better defined in this lateral direction, if accurate predictions are to be made for pilot response to roll motion cues.

The threshold studies reported on here show a large variation in the estimated acceleration threshold value, with a range of 0.002g to 0.03g. Whether this is due to different body-axis alignments with respect to the vertical and/or with respect to the linear acceleration cue, is unclear, and it is also unclear whether variations in subject sensitivity or test protocol contribute significantly to the order-of-magnitude spread. It may prove that future velocity threshold measurements may serve to reduce this spread, although one might still expect some variance contributions from subject choice, body-axis orientation, and choice of stimulus waveshape.

Threshold dependence on this last factor, stimulus
waveshape, may prove to be significant, with more predictable
cues associated with lower effective thresholds. The earlier
discussion of Section 3   supports this notion, and it was
noted there that the use of an unpredictable acceleration step
resulted in a higher estimated threshold than that obtained
with a predictable sinusoidal stimulus. Thus, in an active
vehicle control situation, a pilot may very well have a lower
effective linear motion (tilt) threshold to motions which he
himself initiates.

The converse might also be justified: higher effective
thresholds during active vehicle control, due to task-loading
and its effect on attention allocation. The one study which
considered task-loading effects showed a three-fold increase
in the estimated vertical motion threshold, but more work
clearly needs to be done in this area. In particular, the
anticipated counterbalancing effects of both task-loading and
cue predictability need a more detailed assessment, if linear
motion (tilt) threshold measurements are to be successfully
applied to the problem of predicting pilot sensation and
behavior in a closed-loop moving-base tracking task.

SECTION 4
OFF-VERTICAL ROTATION SENSATION

To this point, most of the discussion has been concerned
with modelling sensation in response to fairly simple rotational
or translational cues, and most of the studies so far reviewed
have taken care to ensure that only one of these cues is present
in any given experimental situation. With the implicit
assumption that the canals respond only to rotary motion and
that the otoliths respond only to linear translational motion,
a careful control of the motion cue has allowed for inferences
regarding the particular end organ dynamics. Although this
approach has been shown to lead to a discrepancy between a
model of the otolith dynamics and measures of subjective
sensation to specific force cues, the notion of separate rotary
and linear motion transduction remains a basic feature of most
vestibular modelling efforts.

Off-vertical rotation, that is, rotation about an axis
which is not aligned with earth-vertical, allows for a
simultaneous presentation of both a rotary cue and a
dynamically changing specific force cue (as seen in the body-
axis coordinate system). If one were to make the assumption
of separate transduction and processing of these cues, then one
might expect to be able to predict subjective sensation in this
combined cue situation, on the basis of results of the single
cue studies and modelling efforts just discussed. However, if
the prediction fails to agree with the measured response, then
a reexamination of the assumptions is in order. In particular,
one might be forced to question the validity of separate cue
transduction, or the validity of separate processing of these
transduced cues, or both. Simply stated, we might ask:

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a)   Do the canals transduce only ɐngular velocity,
     or are they also affected by specific force?

b)   Do the otoliths transduce only specific force,
     or are they also affected by angular velocity?

c)   Are the transduced signals centrally combined in
     some fashion which provides for other measures of
     body state, other than angular and linear velocity?

This section will describe the results of some studies of
off-vertical rotation, and, in the process, examine the validity
of a simplified cue transduction model, as summarized in the
three questions above. The objective here will not be to
develop or endorse a multi-axis motion cue model for combined
cue processing, but rather, to examine some of the basic issues
of motion cue transduction and processing.

Qualitative Features

As noted earlier, most of the studies of rotational
sensation have been careful to ensure that subject rotation was
conducted about earth-vertical to avoid the possibility of tilt
cue transduction by the otoliths. The few studies already
mentioned which deliberately looked at dynamic tilt cue
sensation (29, 33, 51), were concerned with threshold
behavior, and thus confined off-vertical rotations of pitch
and roll to small deviations away from the vertical. The type
of motion to be discussed here is a large amplitude tilt,
obtained by rotation of a subject about an earth-horizontal
axis.

The most commonly studied rotation of this type is termed
"barbecue-spit" rotation, because the subject is rotated about
his long axis (i.e., body-axis yaw), with the rotation vector
aligned with the horizontal. One of the earliest studies of
response to steady rotation of this type was conducted by
Guedry (25), who looked at both subjective sensation and
nystagmoid eye movements. With a rotation rate of 68°/s
lasting for several minutes, he found both sensation and
nystagmus to persist throughout the stimulus presentation, for
times considerably longer than would be predicted by ascribing
these responses to canal transduction of the rotation vector;
i.e., sensation and compensatory eye movements were maintained
for several minutes, whereas canal response to constant velocity
rotation would be expected to die off in two or three time
constants, perhaps 20 to 30s. Furthermore, an abrubt stop of
the rotation failed to elicit the normal post-rotational responses
seen in earth-vertical rotation: most subjects felt themselves
immediately stopped, and their nystagmus quickly disappeared.
Again, this is to be contrasted with post-rotational reversals
of the response measures predicted by the torsion pendulum
canal model and observed experimentally during earth-vertical
rotation.

Similar findings were reported by Benson and Bodin (5)
who also studied barbecue-spit rotation and nystagmus response.
By correlating slow phase velocity (SPV) of the eye with angular
position of the subject ϕ, they found that the gravity vector
modulated SPV according to:

$$SPV \sim g\sin(\phi+\phi_D) + \omega_o \tag{16}$$

where ϕ_D is a lag dependent on stimulus angular velocity and ω_o
is an angular velocity "bias" term. Since the otoliths are

clearly capable of transducing the shear force gsinϕ, the first
term in the above expression might very well be ascribed to the
otoliths. The source of the second bias term is unclear;
presumably it cannot be ascribed to canal transduction, because
of their known washout properties in the face of a constant
rotation rate.

Studies of post-rotational response by Benson and Bodin
(5, 6) showed that while subjective sensation of rotation
stopped quickly with the stopping of the actual horizontal axis
rotation, nystagmus showed a gradual exponential decay. Using
an impulsive deceleration from a 60°/s constant velocity rotation,
they found a time constant for nystagmus decay of 6.8s, to be
compared with their own determination of an 11.8s time constant
associated with earth-vertical rotation. This decrease of the
effective time constant with off-vertical rotation is presumably
due solely to the tilt cue, since the same canals were stimulated
in both their horizontal and vertical axis studies. Similar time
constant reductions are found in other axes (6).

Response Models

The subjective responses just described would not have
been predicted by the torsion pendulum model of canal dynamics,
and the nystagmus responses show an unexplained velocity bias
not directly attributable to the shear force model of the otoliths.
These apparent inconsistencies motivated a closer look at the
end organ transduction characteristics, and at the problem of
modelling central processing of simultaneous vestibular cues.

End Organ Modelling

If the canals are providing the constant sensation of
turning during barbecue-spit rotation, then one must argue for
a transduction of the rotating g vector (as seen in the body-axis
system), since the torsion pendulum model predicts a response
decay to the concurrently imposed rotation vector. One means
of transduction was proposed by Steer (70), in his "roller-pump"
model of the canals. He suggested that as the g vector rotates in
the head coordinate system, it compresses the flexible canal wall,
and effectively pushes the endolymphatic fluid ahead of it. For
a constant rotation rate of the g vector, the canal cupula will
see a constant fluid pressure. Since this has been argued to
be an adequate stimulus for the canal (55), the canal
might then be expected to provide a constant neural output,
signalling constant velocity rotation throughout the stimulus
presentation. This model provides an elegantly simple
explanation of subjective response to barbecue-spit rotation,
but its adoption clearly puts an end to the simplistic notion of
separate angular and linear motion transduction by the canals
and otoliths, respectively.

Although Steer (70) showed how his model was also
consistent with experiments he conducted with another combination
of specific force and angular velocity, Young (82) reviewed
three studies which argue against adopting the "roller-pump"
model as a specific force transducer. First, canal afferents
show no change in angular velocity response with a changing
specific force vector. Second, a blockage of all six canals
leaves intact the nystagmus SPV bias term associated with
off-vertical rotation (recall (16)). Finally, sectioning of
utricular afferents leads to an elimination of this bias term.
This suggests that the "roller-pump" canal model be dropped,
and a closer look be given to the otoliths.

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In attempting to explain the nystagmus response elicited by barbecue-spit rotation, Benson and Barnes (4) developed a mathematical model of the utricular otoconia which allowed for a torsional mode of motion, in addition to the generally accepted shear mode. Torsion of the otoconia with respect to the macula is shown by the model to be proportional to the square of the rotating g vector, and by postulating an appropriate neural network, it is shown how a steady bias component can arise in the nystagmus SPV. The sinusoidal component seen in the nystagmus traces (recall (16)) is explained in the conventional manner: shear force transduction of the g vector, to give a signal proportional to $g\sin\theta$.

This torsional otolith model is shown to give responses which are qualitatively consistent with measured response under a variety of experimental situations, utilizing different combinations of specific force and rotation (4). However, it has not been verified by afferent recordings in experimental animals, and the authors conclude that

> "...agreement between model predictions and experimental results does not necessarily imply that the physiological mechanism is the same as the theoretical model." (4)

As in the case of the roller-pump canal model, the torsional otolith model needs physiological validation; its adoption would put an end to the accepted notion of separate transduction of angular and linear motion.

Central Processor Modelling

Other researchers have argued that response to off-vertical rotation is a result of additional central processing of the transduced vestibular signals, rather than a result of direct specific force effects on the end organs (17,56,58,81). If it is assumed that the canal output gradually dies out during sustained constant velocity rotation about a horizontal axis, then the maintained sensation of motion must be derived from the otolith signals.* If the otoliths provide a vector output which is proportional to the specific force vector (gravity vector in this case), then the CNS has available to it a constant amplitude vector which is rotating at a constant rate in the body-axis coordinate system. If the CNS presumes this vector to be inertially fixed and parallel to earth-vertical, then the inference must be that the body-axis system is rotating at constant angular velocity; hence the maintained sensation.

Stated in slightly more formal terms, if $\underline{f}$ is the transduced specific force vector rotating at constant angular velocity $\underline{\omega}$ in the body-axis frame, then its derivative is given by

$$\underline{\dot{f}} = \underline{\omega} \times \underline{f} \tag{1.7a}$$

Assuming the CNS can infer derivative information from the otolith output ($\underline{\dot{f}}$), and perform the required vector cross-product, then the body-axis angular velocity estimate $\underline{\hat{\omega}}$ can be obtained from the following relation:

*Almost all of the latyrinthine defective subjects tested by Guedry (25) in his barbecue-spit experiments failed to experience a sensation of horizontal axis rotation, even when they were intellectually aware of the equipment's rotation axis. This argues for a vestibular source of the sensation, either canal or otolith.

$$\hat{\underline{\omega}} = \frac{1}{f^2} \, (\underline{f} \times \dot{\underline{f}}) \tag{17b}$$

where f is the transduced specific force magnitude. This
schema requires no direct transduction of angular velocity,
and will provide a cons' int sensation of rotation about the
off-vertical spin axis. This notion of inferred rotation from
specific force vector orientation is one of the underlying
ideas of Ormsby's integrated vestibular model (56) which will
be discussed shortly.

Before discussing how canal signals might be integrated
with this angular velocity estimate, however, it is worth
reconsidering the previously mentioned nystagmus response
seen during barbecue-spit rotation. It was noted that the
compensatory slow phase velocity consisted of a sinusoidal
term which varied with rotation attitude, and a constant velocity
bias term (recall (16)). Since the sinusoidal term is what
might be expected from a direct otolith to oculomotor cross-
feed, Young (78) introduced the nomenclature "L-nystagmus" to
identify a neural path which provides for compensatory eye
movements oased on linear acceleration of the head. Although
not as readily elicited as rotational nystagmus, L-nystagmus
has been demonstrated to be a contributor to eye stabilization
(5, 38 , 53), and has been shown to have a sensitivity on the
order of 10°/s per g specific force, with an order of magnitude
variation depending on stimulus frequency, as shown in Figure 2_5).

Figure 25.   Composite Frequency Response, L-nystagmus Sensitivity
(from Young (78))
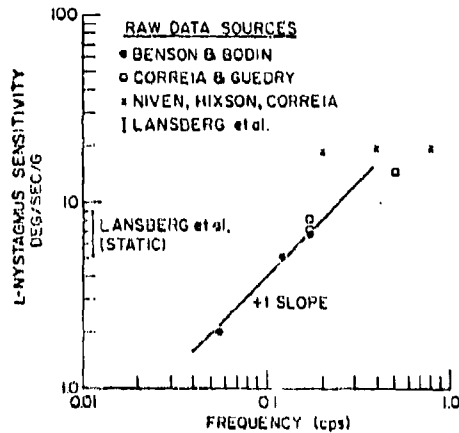
This suggests that the sinusoidal component of nystagmus
SPV is merely a result of direct otolith signal stabilization,
and it is presumed that the neural path is a direct analog of
the canal vestibulo-ocular path, a path which has been verified
at the physiologic level. However, this does not account for the
bias term seen in the SPV histories. One obvious suggestion is
that the bias term arises from the perceived angular velocity $\hat{\omega}$,
a signal which, in theory, can be derived entirely from the
otoliths, given sufficient CNS processing. This writer is
unaware of any suggestions made in the literature to this
effect; the implication is that oculomotor response is not only
due to direct signal paths from the canals and otoliths, but is
also a function of a subject's perceived self-velocity, in turn
dependent on the vestibular organs, among other things.

Returning to the problem of modelling subjective
sensation, it is appropriate to comment on the significance of
extensive CNS processing of vestibular signals. As discussed
in the previous two sections, there is a tendency to associate

end organ output directly with subjective sensation (i.e., canals with rotation, otoliths with tilt/translation). The presumption is that the primary afferents contain the essential perceived state information (e.g., $\hat{\omega}$ and $\hat{v}$), and the subsequent CNS processing serves only to account for threshold behavior and modify the dynamics of subjective response. However, it has just been argued that off-vertical rotation sensation might best be modelled by assuming extensive CNS processing of the afferent signals (recall (17)); it does not seem unreasonable to argue that this may be the normal state of affairs, and not just restricted to off-vertical rotation situations. In brief, subjects may not base their subjective sensations directly on primary afferent information; instead, they may be restricted to only the output of a CNS "state estimator," a neural center which acts as a buffer between the primary afferents and the subjective sensation. This clearly casts a different light on motion sensation modelling, and at this point it is worth briefly discussing two studies which have begun to investigate this aspect of the modelling problem.

In a study of nystagmus response elicited by centrifuge rotational transients Lansberg et al. (38) noted significant differences in SPV patterns with change in body orientation. Since centrifuge start-up involves both a lengthening and rotation of the specific force vector, in combination with a lengthening rotation vector, the cue combination is fairly complicated, and Lansberg et al. (38) provided no functional explanation of their results. However, a subsequent paper by Epstein (17) suggested a possible explanation in terms of a descriptive model which integrates canal and otolith signals. He proposed that perceived body orientation θ, measured about the rotation vector $\underline{\omega}$, is determined by the following relation:

$$\dot{\theta} = a\hat{\omega} + b\gamma \sin\theta \tag{18}$$

where a and b are constants, $\hat{\omega}$ is the canal response to the input angular velocity ω, and γ is the specific force component normal to the angular velocity vector. Although it is not made clear, presumably γ is dependent on otolith output. No attempt to justify the model on physiologic grounds is made, and thus it should be regarded as strictly a descriptive functional model.

By appropriately choosing the constants a and b, Epstein (17) shows how his model can be made to fit the response data of Lansberg et al. (38), although he notes that his solution is strongly initial condition dependent. Mention is also made of the barbecue-spit experiments of Benson and Bodin (6), although no attempt is made to fit their data. Since their experimental protocol always maintained the gravity vector $\underline{g}$ normal to the constant angular velocity vector $\underline{\omega}$, the model given in (18) would assign a value of g to γ, and a value of zero to $\hat{\omega}$ (since the canal output decays to zero). The model would thus predict that

$$\dot{\theta} = bg \sin \theta \qquad\qquad (19)$$

which has a stable equilibrium solution of $\theta = 2\pi n$, with $\dot{\theta}$ equal to zero. The model thus predicts no sensation of rotation (nor nystagmus SPV) during barbecue-spit rotation. Unfortunately, this is entirely at odds with what is observed, as may be recalled from the discussion given earlier. Thus, the model fails to predict sensation in perhaps the simplest case of off-vertical rotation.

An earlier effort at integrating canal and otolith cues
was conducted by Ormsby (56), who provi... a more general
functional framework for combined vestibular cue processing.
He proposed that the two basic outputs of the central
processor be estimates of body angular velocity and body
orientation with respect to gravity, as schematically
illustrated in Figure 20. Note that this model maintains the
classical notion of separate angular velocity and specific
force transduction by the canal and otolith end organs, but
provides a means of "mixing" the transduced signals via the
central processor. The transducer blocks proposed by Ormsby (56)
have already been discussed to some extent in the previous two
sections; what is of interest here are some of the features
of the central estimator.

Figure 26. Central Processor Model Overview (after Ormsby (56))
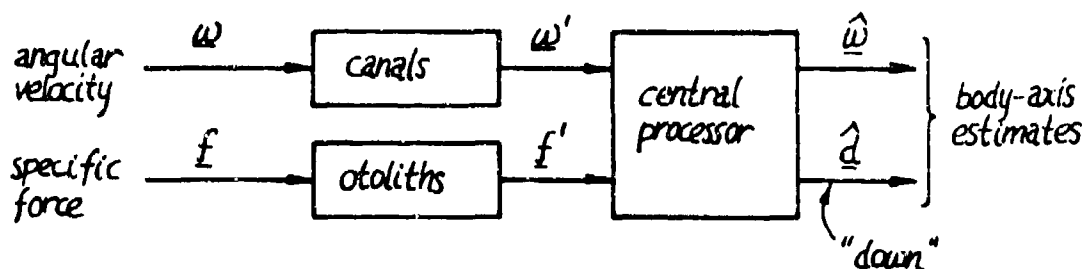
The central processor contains two estimators within it:
a "down" estimator and an angular velocity estimator, both of
which are shown schematically in Figure 27.

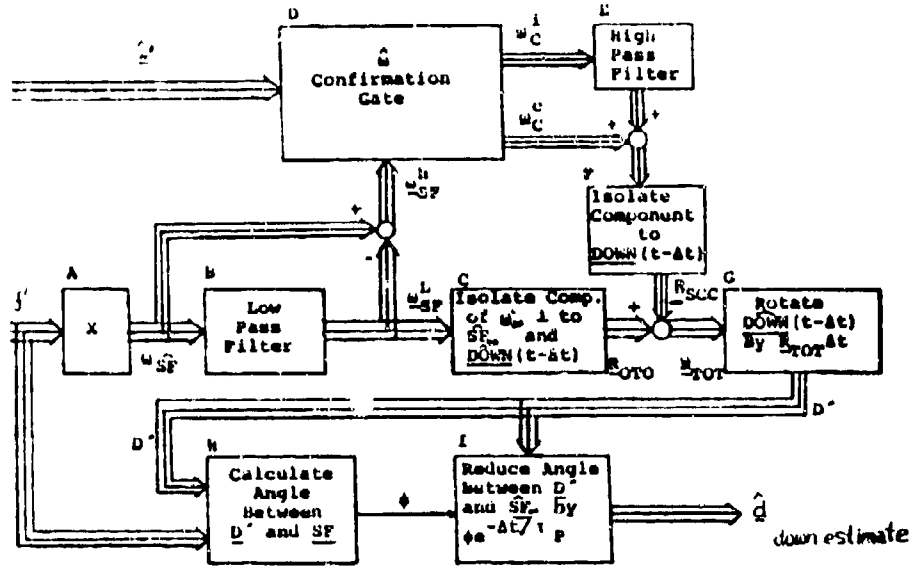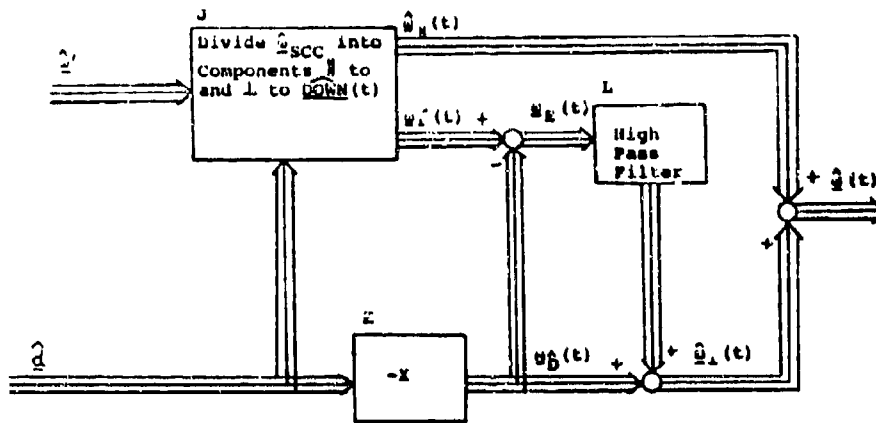Figure 27. Down Estimator (from Ormsby (56))

Figure 28. Angular Velocity Estimator (from Ormsby (56))

In essence, the "down" estimator acts as two cascaded complementary filters, one for the down vector itself, and one for its rate (denoted by R_{TOT} in Figure 27). The rate filter bases its estimate on the otolith and canal signals. Its low-frequency component (shown as R_{OTO}) is based on the inferred rotation rate of the specific force vector (recall (17)), a rate which is subsequently low-pass filtered and geometrically transformed to reflect the current down estimate. The high frequency component of the rate estimate (shown as R_{SCC}) is based primarily on the direct canal output, with provision for correcting for discrepancies between canal rates and rates inferred from the otoliths. Both high- and low-frequency rate estimates (R_{SCC} and R_{OTO}, respectively) are added together to obtain an overall estimate of down vector rotation rate (R_{TOT}), which is then integrated to provide a high-frequency estimate of the down vector itself. The low-frequency estimate for the second complementary filter is provided directly by the otoliths; the two estimates are then combined for an overall estimate of the down vector.

The rotation rate estimator, shown in Figure 28, requires the down estimate for its operation. Any canal output parallel to the down vector is passed straight to the output, whereas any canal output perpendicular to the down vector is differenced with the down vector rotation rate. This difference signal is then high-pass filtered and added back to the down vector rotation rate, to form the other component of the output. In effect, rotation away from "down" is effected by a complementary filtering of the high-frequency canal cues and the low-frequency down vector rotation rate.

Although this model is considerably more complicated
than the single differential equation proposed by Epstein (17),
it does provide a consistent framework for generalizing combined
cue responses. Ormsby (56) showed the model capable of matching
measured response in a few selected cases (i.e., vertical linear
acceleration, small roll-axis tilting, and centrifuge rotation
and acceleration), and two subsequent model simulations have
shown it to be not inconsistent with the results of other
combined cue experiments (7 , 60). However, the model clearly
needs more extensive verification, both as to scope of
applicability to combined cue response modelling, and as to
accuracy of predicting detailed response characteristics.
Nevertheless, to this author's knowledge, this is the only
quantitative functional model of motion sensation which
attempts to integrate rotational and specific force cues, in
a logically consistent manner, and with the potential of
providing a general "explanation" of sensatic.. uependence on
vestibular cues. It clearly deserves a closer look.

Summary and Discussion

Summary

Modelling of sensation to off-vertical rotational cues
is in a very early stage of development, since the major effort
in this area has been devoted to resolving the end-organ versus
central processing issue. Relying primarily on the results of
barbecue-spit rotation experiments, researchers have proposed
three basic mechanisms for explaining the continued sensation
of constant velocity rotation experienced by subjects during
testing: a mechanical influence of gravity on the canals, a
similar influence on the otoliths, or a central processing of

combined canal and otolith primary afferent signals. However, the canal "roller-pump" model appears to be inconsistent with afferent recording studies, and the "torsional" otolith model has yet to be adequately verified. Acceptance of either of these models would clearly put an end to the intuitively appealing notion of separate cue transduction by the two specialized vestibular end organs, and this has motivated the functional modelling effort which ascribes observed response to CNS processing of the two transduced signals.

The basic assumption of the central processor theory is that the CNS regards the transduced specific force vector to be a reliable indicator of earth-vertical, at least for static and low-frequency cues. Thus, a rotation of the transduced vector seen in the body-axis reference frame can be interpreted as a body-axis rotation in the opposite direction. Of course, any functional model embodying this concept must made provision for incorporating any angular velocity information simultaneously provided by the canals. One model approach was discussed here, and presumes that an estimate of "down" is generated by an effective complementary filtering of the canal and otolith signals; a subsequent mixing of "down" vector rotation rate with the canal information generates the body rotation rate estimate. Although fairly complicated and not adequately verified, this model is currently the only quantitative functional description of integrated vestibular cue processing, and shows promise for predicting subjective response to a general spectrum of combined rotational and specific force cues.

This type of modelling subsumes the results of previous single-axis experiments, and may prove to be a more appropriate framework for interpreting some of the earlier results. Specifically, the linear acceleration experiments described in Section 3, conducted in the presence of a constant gravitational acceleration, might be best viewed in terms of response to a specific force vector which is not only changing in magnitude but also rotating within the body-axis reference frame. Since no actual rotation is taking place, the canals are most likely providing a null output, and any central processing of afferent information must be based entirely on otolith information. If a complementary filter structure is presumed for the central processor, then the otolith output will be effectively low-pass filtered. Without the corroborating high-frequency canal cues which normally accompany specific force vector rotation, subjective sensation might well be expected to show a considerable lag when only linear motion cues are presented, even when transduction is effected by a wide bandwidth otolith end-organ. This speculative resolution of the observed transducer/sensation response disparity obviously needs verification, and this can be accomplished by an application of a central processor model to fit some of the earlier response data.

Discussion

Most of the off-vertical rotation studies have examined response to barbecue-spit rotation, an extreme experimental geometry chosen for its ability to elicit large measurable responses, and not for its similarity to the motion cues which characterize typical vehicle control tasks. What would be more pertinent to the human operator modelling effort would be an

examination of response to body-axis pitch and roll rotations about earth-horizontal. Although response to this type of "tumbling" and "cartwheel" rotation has been examined qualitatively in the past, a more quantitative modelling of sensation is called for, especially if pitch and roll rotation models are to be successfully applied to the pilot-vehicle modelling problem.

The transducer versus central processor argument outlined in this section has direct implications for the incorporation of motion sensor submodels within the larger structure of a human operator model. As discussed in the introductory section, previous efforts at incorporating motion cue models have taken a "transducer" approach: the canal and otolith transducer dynamics are modelled and their outputs are directly incorporated by the vehicle state estimator of the human operator model. This approach avoids the problem of specifying a separate motion sensation model, and only requires a reasonable estimate of the transducer dynamics. However, it assumes that primary afferent information is both directly accessible and properly interpreted by the operator's internal state estimator, assumptions which may not be valid in light of the subjective sensation studies cited in this survey.

A more accurate view may be one in which the operator's state estimator only has access to the output of a subsidiary "vestibular" state estimator, the central processor referred to above as the CNS integrator of canal and otolith information. This hierarchical model with restricted access to primary afferent information is obviously speculative, but may prove to be a more general framework for understanding both motion sensation and moving-base operator performance. The realization

of such an operator model requires the development of a
validated motion sensation estimator capable of off-vertical
motion cue processing, and the beginnings have been made in
this direction.

Summary

An understanding of the human operator's use of motion cues
has progressed from an initial qualitative assessment of motion
cue effects to the current quantitative behavioral models
incorporating motion transducer sub-models. An early effort
in this area centered on the specification of a set of motion
adjustment rules for the "crossover" model, a human operator
model based on static tracking experiments. In general, these
rules provided for a reduction in operator delay and an increase
in crossover frequency, and were shown to be consistent with the
results of separate vestibular modelling efforts, which ascribed
operator lead generation to the rate sensitivity of the peripheral
vestibular organs. More recent efforts with the optimal control
model (OCM) of the human operator have taken advantage of the
OCM structure and simply appended higher derivative vehicle
state information to the operator's display vector, thus
approximating the lead provided by motion cues. Most recently,
motion cue transducer models have been appended to the OCM,
in an effort to account for end-organ dynamic effects, although
the results have been equivocal. That is, inclusion of
transducer sub-models appears to yield little improvement in
fitting operator behavior, when compared with the simpler
"informational" approach of display vector augmentation using
higher derivative information.

Three reasons may account for this finding. First, the
closed-loop tasks which have been used to assess operator
behavior have used target/disturbance signals having most of
their power concentrated within the relatively flat bandpass

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portions of the motion cue transducer models, and thus the
vestibular sensors could be effectively modelled with simple
gains; this permits a simple "informational" approach which
neglects end-organ dynamics. A second reason may be that
the particular transducer models chosen may not have been
appropriate to the particular vehicle control situation
studied: most of the vestibular modelling efforts have
concentrated on yaw-axis rotation about the vertical, whereas
most pilot-vehicle analysis is concerned with roll-axis
motion about the horizontal. Finally, the basic approach to
motion cue modelling may not be appropriate, since the human
operator may not have direct access to motion transducer
outputs, and instead be restricted to the output of a central
integrator of motion information. This question of "transducer"
versus "central" modelling of motion information will be
considered again below.

Rotational Cues

Functional models of rotation sensation have in common
the torsion pendulum model of the canal dynamics, a model which
relates perceived angular velocity to actual angular velocity.
More detailed quantitative measurements have led to the
proposal of cascaded linear adaptation and lead operators in
combination with a nonlinear threshold function to account for
detection capability. Although it is still an open issue as to
whether the inferred dynamics are due to end-organ characteristics
or due to CNS processing of the primary afferent information,
measurements have been made to estimate the various time constants
of the subjective sensation model.

Neither the short time constant of the torsion pendulum model nor the time constant of the lead operator is well-defined, although it would appear that both are so small as to make little difference to the human operator modelling effort, because of the typically low bandwidths characterizing moving-base tracking tasks. The long time constant of the torsion pendulum model appears to be body-axis dependent, and at present, it is not understood why this is so, since there does not appear to be any physiological basis for an interaxis difference. It has been suggested here that these disparities could be accounted for centrally, by the presumption of different adaptation time constants for each axis; this has yet to be confirmed, since adaptation operator modelling has been restricted entirely to yaw-axis body rotations.

Most of the rotational threshold measurements have been concerned with specifying a minimum detectable angular acceleration, but it has been argued here and elsewhere that velocity thresholds provide a more reliable indication of detection performance. This type of threshold modelling allows for a prediction of detection latency as a function of stimulus magnitude, and, when used in conjunction with the appropriate dynamic model, allows for a prediction of effective threshold for an unrestricted class of stimulus waveforms. An estimate of the velocity threshold for each body-axis was made here, but since these were based on the results of two separate studies, further experimental confirmation is clearly called for.

Tilt/Translational Cues

Modelling of subjective sensation to tilt and translational cues has built upon the basic shear force transduction characteristics of the otoliths, and, in the process, has been able to provide

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a reasonable accounting of static tilt sensation to both actual tilt and linear acceleration stimuli. One functional model incorporating a gain nonlinearity was discussed here, and helps fit response curves under a wider range of stimulus magnitudes. There are, however, two basic issues in specific force cue modelling which are yet to be resolved. The first concerns the interpretation of the transduced cue in a linear motion situation: whether it is interpreted by the CNS as a velocity or as an acceleration. The second concerns the observed disparity between the wide bandwidth dynamics of the otolith end-organ and the low bandwidth dynamics associated with the perception of linear acceleration.

A resolution of both of these issues would appear to be a necessary prerequisite to successfully modelling subjective response to a general class of specific force stimuli. In particular, the identification of linear motion sensation as one of either velocity or acceleration will strongly influence the choice of a dynamic model for subjective sensation, and has been illustrated here in the review of two candidate models for describing response to sinusoidal linear acceleration cues. In addition, an understanding of the source of the disparity between transducer characteristics and subjective sensation will be necessary before a model will be able to confidently apportion overall dynamic response between the periphery and the CNS. The resolution of this problem may require a broader view of vestibular processing, one in which CNS processing of both canal and otolith afferents plays a prominent part in determining sensation.

Specific force thresholds have been customarily measured in units of linear acceleration, and the goal of most threshold research has been to determine minimum detectable stimulus values. As in the corresponding rotational studies, there exists a strong inverse dependency of detection latency on stimulus magnitude, a relation which points to an effective velocity threshold mechanism. Little work has been done in this area, perhaps because of the uncertainty concerning the CNS interpretation of suprathreshold motion cues; however, an appropriate functional modelling of threshold behavior will be necessary before general predictions can be made of response to near threshold stimuli having waveshapes other than simple steps.

Recommendations

The objective of this survey has been to review the current literature on motion cue models to determine their applicability to the pilot modelling problem. It has been shown that the various models are in different states of development, and that some basic issues are still unresolved. In cases where it would appear that a specific model can be used with a good deal of confidence in its prediction accuracy, there still exists a question as to its applicability to the particular motion environment typically found in aircraft. Many limitations and open issues have been pointed out in this survey, with two main objectives: to stimulate new "vestibular" research in areas which are of special interest to those working in the pilot modelling field, and to ensure that those engaged in pilot modelling exercise caution when adopting any particular motion sensation model.

This section will briefly outline areas in motion cue modelling in which it is felt that further research is needed for a better understanding of the pilot-vehicle system.

Rotational Cues

Most of the motion sensation research has been conducted using yaw-axis body rotations; however, most of the rotational motion encountered by a pilot is in pitch and roll. One of the studies cited here investigated response dynamics about all three body axes, using earth-vertical rotation, and estimated the torsion pendulum long time constant for each axis. However, similar studies to define the other time constants for all three axes have not been conducted. Although it may not be necessary for human operator modelling efforts to have accurate estimates of the torsion pendulum short time constant and the lead operator time constant, a multi-axis specification of the adaptation time constant would appear to be a necessary prerequisite to accurate response modelling about the pitch and roll axes. As noted earlier, a specification of different adaptation time constant values for each body-axis may provide a means of resolving the interaxis differences inferred for the canal torsion pendulum model, and thus possibly allow for a three-axis transducer model having identical parameter values in all three axes. At the least, a knowledge of the adaptation time constants for the pitch and roll axes will allow for a more accurate modelling of response in typical moving-base tracking tasks.

Rotational threshold modelling is also an area in which human operator modelling needs impose a requirement for further development. Threshold research should emphasize velocity levels rather than acceleration levels, for the reasons explained earlier, and an effort should be made to determine appropriate values for each of the three body axes, since, again, most of the threshold studies have been conducted for the yaw body axis. From the preliminary resul s reported to date,

there would also seem to be a need for further study of
threshold dependence on the two counteracting factors which are
an inherent part of any moving-base track · task: task-loading,
which should raise effective thresholds, and cue predictability,
due to pilot-induced motion, which should lower effective
thresholds. The argument has been made here and elsewhere
that these factors may determine "operational" threshold
levels which may be significantly different from the levels
inferred from a passive detection experiment, conducted under
near-ideal laboratory conditions.

Tilt/Translational Cues

It was noted earlier that a resolution of the acceleration
versus velocity sensation issue is a necessary fiist step in
specifying an appropriate dynamic model of specific force cue
processing. Even if the human operator modelling effort did
not require an accurate specification of the dynamics, the
interpretation issue is still of direct relevance to operator
modelling, since it determines how the transduced cue is to
be incorporated in the operator's display vector (assuming an
OCM structure). Thus, if the otolith cue is interpreted as
acceleration, a simple vector augmentation will suffice; if
velocity, some additional filtering must be presumed. As a
consequence, the subjective interpretation issue might be
expected to directly affect any modelling effort concerned
with off-vertical moving-base operator performance.

Most of the linear acceleration research has been
conducted with fore-aft and up-down motions, and thus pre-
dictions of pilot sensation are restricted to vehicle surge,
pitch, and heave; however, much of the vehicle motion encountered

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by a pilot is in roll. Thus there is a need for a more
intensive modelling of sensation dependence on lateral
variations in the specific force vector, based on left-right
linear acceleration experiments. It is assumed that such
future experiments will pay particular attention to body-axis
orientation with respect to gravity, since one study cited
here noted that this is the major determinant of the inferred
threshold, and not orientation with respect to the imposed
linear acceleration. Thus, there is a need for lateral
acceleration experiments using subjects seated in the normal
upright position typically assumed by pilots.

Threshold modelling of response to translational and
tilt cues is also an area in which further research is needed,
if sensation models are to be directly utilized in the human
operator modelling effort. Arguments presented earlier support
a velocity, rather than an acceleration, threshold, and
additional studies are needed to confirm this type of threshold
model; as in the case of rotation, knowledge of the velocity
threshold is of particular relevance to the operator modelling
effort because of detection latency considerations. Furthermore,
there exists a need for determining velocity threshold dependence
on both task-loading and cue predictability, for exactly the
same reasons which were noted in the discussion of rotational
cue modelling.

Integrated Cue Processing

Even in simplified experimental investigations of moving-
base tracking performance, motion cues rarely consist of a pure
rotation or pure translation; usually, both otoliths and canals
are stimulated, as in a roll-axis tracking task. Thus, there
may be a need for an integrated model of motion cue processing,

based on the individual outputs of the rotational and translational motion transducers, and providing an estimate of body orientation and velocity. The off- tical rotation studies cited here make it clear that subjective sensation need not be a direct reflection of end-organ output, and that considerable processing and transformation of the primary afferent information may occur before a "sensation" is generated. If it is presumed that the human operator is likewise restricted in his access to the primary afferents, then an integrative perceptual submodel becomes a necessary component of the human operator model.

Since the development of such a model is one of the goals of current vestibular research, those working in the field of human operator modelling have few options to choose from. One possibility may be to use the multi-axis model described in Section 4, although it is felt by this author that it has not been sufficiently verified, and may require substantial modification to ensure accurate predictions in the motion cue environment typifying human operator research. Furthermore, the model's non-linearities negate the advantages of linear systems analysis afforded by the linear OCM structure, although it may be possible to linearize the perceptual model. A possible alternative is to independently develop a perceptual "estimator" model, based on the linear estimator structure currently used in the OCM (a Kalman filter and predictor) and guided by the results of past and current vestibular research; such a modelling effort could take advantage of the insights afforded by both motion sensation research and human operator modelling.

The basic closed-loop tracking/regulation task provides a unique opportunity for development of motion perception models, and is an approach which complements the conventional open-loop testing characterizing motion perception research. Although input-output measurements of pilot tracking cannot, in theory, provide a definitive separation of "estimator" from "controller," the success of the OCM in predicting static tracking performance has shown that such a separation can be made, in practice. If a motion estimator submodel structure were to be assumed, in conjunction with appropriate transducer models, it might then very well·be possible to estimate motion model parameter values, based on the results of closed-loop moving-base tracking experiments. In light of the state of development of the various motion sensation models, and their anticipated shortcomings when applied directly to the pilot modelling problem, this approach may prove to be the most appropriate means of modelling motion cue effects on pilot behavior.

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