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A THEORETICAL AND EXPERIMENTAL ANALYSIS OF THE OUTSIDE WORLD PERCEPTION PROCESS

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SUMMARY

The outside scene is often an important source of information for manual control tasks. Important examples of these are car driving and aircraft control. This paper deals with modelling this visual scene perception process on the basis of linear perspective geometry and the relative motion cues.

Model predictions utilizing psychophysical threshold data from base-line experiments and literature of a variety of visual approach tasks are compared with experimental data. Both the performance and workload results illustrate that the model provides a meaningful description of the outside world perception process, with a useful predictive capability.

INTRODUCTION

Many manual control tasks depend on the visual perception of the outside scene. In the context of aircraft control, the most important example is the visual approach scene. So, in order to investigate a great many flight situations in the approach and landing, it is mandatory to take into account this visual scene perception process which has often a major impact on mission performance.

Based on a concise inventory of the most important characteristics (cues) of the visual scene the visual scene perception process is described (modelled) on the basis of the linear perspective geometry and the relative motion cues. This involves mathematical relationships between these visual cues and the aircraft state variables. After linearization this model can be integrated in the existing framework describing piloted aircraft behavior (the optimal control model). This is the subject of the next chapter.

The visual scene perception model involves assumptions concerning perceptual thresholds of the various cues, noise levels associated with observing these cues and interference among them. Values for these parameters are derived from baseline experimental data supplemented by the psychophysical literature. Based on these values a theoretical analysis is performed dealing with a variety of visual approach conditions.

Furthermore, the results of an experimental program are compared with the model predictions. In addition, model predictions of pilot workload are compared with subjective ratings.

VISUAL SCENE PERCEPTION MODEL

One of the earliest studies of visual scene perception directly related to flight control problems has been performed by Gibson (Refs. 1 and 2). According to Gibson, the most important visual cues which can be derived from the visual field are related to

- the linear perspective geometry
- relative motion or motion parallax
- the apparent size of objects whose real size is known
- a far object covered by a near one
- the distribution of flight and shade over an object
- aerial perspective and the loss of detail with distance.

Of these, the linear perspective geometry provides a variety of cues. This is illustrated by the schematic version of the visual scene in figure 1a which can be thought of to consist of lines and points (textural elements). This involves not only the linear and angular position of the observer with respect to the outside world but also (dynamically) the relative motion. The point of the visual field toward which the observer is moving appears to be stationary ("focus of expansion"). All other textural points move with respect to the observer which can be indicated by velocity vectors ("streamers"). This is shown in figure 1b for the case of rectilinear motion. Various other references mention visual cues which can be conceived as examples of the afore-mentioned basic elements. Most of them are related to the landing approach scene (Refs. 3-5).

From the foregoing it can be derived that a reasonable approach is to model the visual scene perception process on the basis of the linear perspective geometry and the relative motion cues. Following reference 6 this involves a description of the cues which can be derived from the visual scene and their functional relationships with linear and angular positions and velocities of the observer. When, in addition, the relationships between the moving observer and the visual scene can be linearized about a nominal condition, the perception process can be described in standard estimation theoretical terms and included in the optimal control model structure in the following manner.

Let the observer (aircraft*) moving with respect to the outside world be described by the system state x(t). This involves the common linear and

*) Although the following applies to a variety of man-machine situations, this analysis is directed at the aircraft control problem.

angular positions of the aircraft as well as additional parameters to describe relevant characteristics of the moving visual scene (with respect to the aircraft). After linearization about a nominal path the result will be a set of linear, (in general) time-varying equations given by

$$\dot{x}(t) = A(t)\, x(t) + E(t)\, w(t) \tag{1}$$

where A(t) describes the process of the aircraft moving with respect to the outside world, and w(t) represents system disturbances (e.g. turbulence). Furthermore, the visual cues will be described by the display vector y(t). The relationships between these displayed variables and the system state is given by

$$y(t) = C(t)\, x(t) \tag{2}$$

The perception of these variables is accompanied with an equivalent time delay, perceptual thresholds and observation noises. Also the interference between the various visual cues, a.o. arizing from the necessity to scan the visual field and to divide the attention among the various cues, has to be considered (Refs. 7 and 8). Now, these observations of the visual scene are dealt with in the same fashion as observations from other sources (e.g. displays, motion cues, etc.). The system state is estimated optimally (by means of a Kalman-Bucy filter) on the basis of the known (learned) dynamics involved and the observations. This state estimation process can be considered as an internal representation of the task environment.

Relationships between visual scene characteristics and the system state

A schematic version of the visual scene (Fig. 1) can be assumed to comprise textural elements and known objects. Both provide linear perspective geometrical cues (basically, the inclination of lines) and impressions of relative position and velocity.

The inclination Ω, of a line element of the visual scene is given by

$$\Omega = \tan^{-1} Y/H \tag{3}$$

where Y is the distance betwe n the observer and the pertinent line element perpendicular to the looking direction and H is the vertical position of the observer. Assuming small perturbations (y, h and ω) around the trim condition (Y_o, H_o and Ω_o) results after some manipulation (to a first order) in the linear expression

$$\omega = C_h\, h + C_y\, y \tag{4a}$$

where

$$C_h = -\sin 2\Omega_o / 2H_o \tag{4b}$$

Differentiating eq (4a) yields the expression for the inclination rate

$$\dot{\omega} = C_h \dot{h} + C_y \dot{y} \qquad (4c)$$

The small perturbations of the relative position and velocity of an element of the visual scene is simply given by

$$\alpha_h = h/R \; ; \; \alpha_y = y/R$$

and

$$\dot{\alpha}_h = \dot{h}/R \; ; \; \dot{\alpha}_y = \dot{y}/R \qquad (5)$$

where α is the visual angle and R is the distance between the object and the observer.

Furthermore, when the attitude of the observer (aircraft) is taken into account (with attitude angles φ, Θ and ψ) eqs. (4) and (5) become

$$\begin{aligned} \omega &= C_h h + C_y y + \varphi \\ \alpha_h &= h/R + \Theta \\ \alpha_y &= y/R + \psi \end{aligned} \qquad (6)$$

and the corresponding time-derivatives $\dot{\omega} = \ldots$, etc.

Next, these expressions are utilized to describe the cues which can be derived from the visual approach scene.

Visual approach scene

A schematic version of the visual approach scene is shown in figure 2. The cues which are assumed to be derived from this scene are indicated.
The most important cue for lateral guidance is derived from the inclination of the runway sides and/or centerline. The lateral deviation y, is zero if the inclination of both runway sides is the same ($\omega_r = \omega_l$) and the inclination of the centerline is zero ($\omega_c = 0$).
Vertical guidance has to be based on the (average) inclination of the runway sides when no runway end and no horizon is visible. In that case, the observer has to know the nominal inclination (Ω_o), which is range-varying.
The following model analysis and experimental results will show that a better indication of the vertical position is obtained when the length of the runway α_h (or, almost equivalently, the depression of runway threshold with respect to the horizon) is visible. Also in that case, the observer has to know the nominal depression which is, however, constant during a standard approach (e.g., 3 deg).
Glide slope information requires also the estimation of the distance to touchdown. This can be based on the apparent size of ground objects, of which the most important is often the runway width.
Aircraft attitudes provide "inner-loop" information and can be derived from the relative position and inclination of (e.g.) the horizon and any aircraft reference. The pitch angle Θ, which has to be estimated with respect to its (non-zero) nominal value and the bank angle φ are indicated in figure 2.

MODEL ANALYSIS

The linear visual scene perception model (VSPM) can be implemented in the optimal control model (Refs. 6 and 7). Based on the foregoing discussion, a variety of visual approach conditions are selected to analyze theoretically. In addition, an experimental program has been conducted to provide a critical test for the hypotheses (assumptions) underlying the model results. In order to obtain detailed information concerning the information processing involved in the manual approach task, no range-varying effects are considered in the following analysis. In other words, it is assumed that the aircraft is "frozen" at a fixed point of the approach path corresponding with a nominal altitude of 200 ft for a 3° approach ("hovering"). The consequence is a stationary process involved allowing frequency domain measures such as human describing functions and observation noise spectra. Especially the latter will provide a sensitive check on the exactness of the values used for the model parameters under investigation. The primary model parameters are the perceptual thresholds of the various visual cues (display elements) involved because these represent the most uncertain model parameters. The results of several previous experimental studies suggest reasonable accurate values for the remaining model parameters.
Therefore, base-line experiments have been conducted and relevant psychophysical literature have been searched resulting in reasonable reliable estimates for the perceptual thresholds involved. Finally, the last section contains the model analysis proper and the resulting model predictions.

Visual scene configurations

Referring to the foregoing discussion the configurations given in figure 3 were selected for the following model analysis and formal experiment.

Vertical control on the basis of the inclination of the runway sides can be compared with the condition that the depression of the runway threshold below the runway end (α) or below the horizon is visible (configurations 1 and 2). Furthermore, the effect of an aircraft reference providing explicitly pitch information is of interest (configuration 3).

Lateral control utilizing the inclination of the centerline is represented by configuration 4. In case the runway sides are available, the inclination of both sides has to be estimated and compared with each other (configuration 5). A simple model analysis shows that this process is associated with the same observation noise as in the case of a center line. Only the perceptual thresholds involved are different (next section). This will be tested against the experimental results. Again the effect of explicit roll information provided by the aircraft reference is considered by including configuration 6. Configuration 7 concerns roll tracking based on the aircraft reference. This (presumably) easy task is included to evoke some variation in workload in order to yield additional experimental evidence for the workload model of reference 8 and to test the perceptual threshold assumptions involved.

Configurations 8 and 9 are selected to investigate the interference between vertical and lateral control. It is assumed that the pilot has to divide his attention between the various display variables (visual scene cues) involved. This interference is assumed not only within a control task (e.g. attention has to be divided between pitch angle and altitude) but also between vertical and lateral control when performing both tasks simultaneously. This represents a crucial hypothesis which will be tested in the following as the visual scene is widely assumed to represent integrated information and it is a non-trivial question whether the visual scene can be "broken down" into separate elements. Finally, configuration 10 is included to investigate the effect of additional texture. This has, in principle, its implications for the information contents of the visual scene which turned out to be of no interest but also for the psychological aspects (perspective illusion and realism).

Perceptual thresholds

It was anticipated that perceptual threshold phenomena could be important for the foregoing visual scene cues. Thresholds can be accounted for in the optimal control model by modifying the observation noise covariance associated with a particular visual cue.

Although the psychophysical literature reports a wealth of emperical threshold data, these data are known to be affected by numerous experimental conditions which easily explains the typical scatter in "comparable" data. Therefore, a baseline experiment has been conducted to determine the position thresholds of the display elements involved in the visual scene configurations shown in figure 3. These thresholds are primarily due to the lack of explicit visual references concerning zero or nominal, visual scene conditions.

This involves that learning (experience) and temporal cues (memory functioning) are important in measuring and interpreting thresholds.

Experimental details are given in reference 9. The resulting measurements are "translated" to values suitable for (as required by) the describing function representation for the assumed dead-zone non-linearity. The results are summarized in table 1.

As discussed in reference 9 thresholds associated with the perception of motion in the visual field can be related to resolution properties. This implies that the motion detection thresholds can be inferred from the foregoing discrimination data. The result is also contained in table 1.

Apart from these (nominal) threshold estimates, in table 1 it is also indicated how reliable these estimates are assumed to be. A sensitivity analysis in the following will serve to relate this incertainty in threshold values to a confidence interval associated with the system performance predictions of the model.

Model predictions

A block diagram of the control task(s) is given in figure 4. System disturbance enters the system parallel to the control input. The resulting output is displayed to the human operator as the pitch and roll angle (for the pertinent configurations) representing K-dynamics. The integral of these outputs are the altitude (or approach angle) and lateral deviation (or center line inclination), respectively (K/s-dynamics). The disturbances are white noise processed by two first order filters with poles at one rad/sec and two rad/sec. The disturbance levels are for the vertical task given by a resulting pitch variance of 0.068 deg^2 and for the lateral task given by a resulting roll variance of 10.5 deg^2 (corresponding with the values used for the experimental program). Details concerning sensitivities and gains involved are contained in reference 9.

Model parameters can be divided in parameters which are constant for all configurations and parameters which are considered as the remaining model variables. Also the experimental results of the next chapter will be related to these (dependent) variables. The key variables are the perceptual thresholds. The nominal values of table 1 are assumed for the model predictions. Furthermore, the effect of the upper- and lower threshold values on the system outputs is also determined and discussed in the following chapter. The overall level of attention (P_o) is also, to same extent, variable, although this value has been shown in previous studies to be relatively constant. A nominal value of -20 dB is assumed and the effect of $\pm$ 2 dB on the system outputs is considered.
The constant model parameters are: a neuro-motor time constant of 0.1 sec, a perceptual time delay of 0.2 sec and a motor noise ratio of -30 dB.

Now, assuming that the human operator divides his attention among the visual cues (position and velocity of all display elements) optimally, i.e., minimizing the given cost functional* (Ref. 8), system performance can be predicted for the various configurations. The results are given in table 2.

Vertical control is superior for the condition that the runway depression angle and the pitch angle can be observed (conf. 3). The contribution of the pitch information amounts to a 20 % reduction of the approach angle variance (σ_α^2 of conf. 2). When the viewing condition is such that no horizon or runway end is visible and control has to be based on the runway sides (ω_l and/or ω_r) and runway threshold variation ($\dot{\alpha}$) the vertical approach performance is degraded substantially. This clearly demonstrates the contribution of the various visual cues involved. Furthermore, in the case of both vertical and lateral control, the vertical approach performance is predicted to deteriorate with 30 % to 50 % (due to the assumed interference between both tasks). The last column of table 1 contains the (optimal) fractions of attention dedicated to the various cues.

The best lateral approach performance is obtained when the runway centerline inclination (ω_c) cue is available (conf. 4). Lateral control utilizing the runway sides is substantially degraded (conf. 5) due to the larger perceptual threshold of this cue. The bank angle provides useful

* According to the instructions given to the subjects in the experiment the system output is assumed to be minimized. In addition the control rate is weighed yielding the neuro-motor time constant of 0.1 sec.

inner loop information (conf. 6). When performing the vertical and lateral task simultaneously, the model predicts a deterioration in lateral performance (confs. 8 and 9) of about 100 %. The model predicts that the effect of the texture (conf. 10) on system performance is negligible.

The effect of the model parameter variations (thresholds and overall attention) on the system scores and additional theoretical results will be discussed in the next chapter where the model predictions will be compared with the experimental results.

EXPERIMENTS

The first objective of the experimental program was to test the foregoing model results with respect to both the fundamental hypotheses involved (optimality in control and attention allocation, interference between cues) and the assumed numerical values of the key model parameters. Secondly, in case significant discrepancy occurs between model and experimental results the appropriate adjustments can (hopefully) be made in the model assumptions underlying the model results.

Experimental procedures

The same 10 configurations as discussed previously are investigated in the experimental program. These configurations were four times presented to the (four) subjects (general aviation pilots) in a random order. Each run lasted 200 sec. Between the runs the subjects were asked to give their impression of the exerted workload (Reference 9 contains the rating scales used and additional experimental details). The subjects were instructed to minimize the mean-squared system output. They were trained on the ten configurations in a random order till a relatively stable performance level was reached. All together, about 250 training trials were performed.

An analog computer was used to simulate the vehicle dynamics and to generate the visual scene characteristics. This visual scene was presented to the subjects on a TV monitor located 2.5 m in front of their point of regard, They manipulated a two-axis isometric hand control. The system parameters were recorded on FM magnetic tape for off-line mean-squared scores and frequency domain computations*.

Comparison of experimental results and model scores

In this section the experimental results in terms of mean-squared performance scores are compared with the model predictions. Based on the results of table 2 firstly the approach angle (α)- and centerline inclination (ω_c) scores are considered (the model predicts attitude- and control scores which are relatively insensitive over the configurations).

* Unfortunately, these frequency domain data were not available in time to include in this paper. These results will be included in reference 9.

Apart from the nominal model predictions (of table 2) the effect of the uncertainty in underlying assumptions (i.e., numerical values of the thresholds and overall attention) on system performance is determined. For the upper- and lower threshold values given in table 1 and, in addition, + 2 dB and -2 dB variation in overall attention the corresponding performance scores are determined. It is hypothesized that the experimental scores lie within the resulting performance interval.

In figures 5 and 6 both the experimental means and standard deviations (of 16 runs) and the model predictions are given. For all single-axis tasks the experimental scores lie well within the predicted interval. This indicates not only that the model is "right" but also that the assumed numerical values for the thresholds and overall attention are close to the "real" values.

For the dual-axis tasks the experimental results do clearly not match the model predictions. The experimental data of configuration 9 and 10 have been pooled because both the model predictions and the experimental results for both configurations indicate that the only effect of the texture information is the enhancement of the perspective illusion. This was also apparent during the learning phase. An adjustment of the model parameter values (which has to be appropriate for the single-axis tasks as well) does not result in a good agreement with the experimental scores. Therefore, it is tentatively concluded that the assumed hypothesis of interference between the two tasks has to be rejected. Instead, the following hypothesis is considered: the visual scene stimulates the human operator to perform the dual-axis task just as well as the single-axis task (thus, vertical control is not degraded when the lateral control task is added, and vice versa). So, it is assumed that there is <u>no performance interference</u>. This will be further discussed in the following.

Comparing also the attitude scores (θ and φ) and the control scores (δ_e and δ_a) of the model predictions in table 1 and the measured scores given in table 3 it is apparent that both the measured attitude scores and the measured control scores are much lower than predicted. This indicates that the subjects (being pilots) performed the - to some extent realistic appearing - "approach" tasks in a much smoother fashion than the model predicts on the basis of an assumed neuromotor time constant of 0.1 sec. This is confirmed by pilot commentary indicating that the pilots were reluctant to make rapid control movements and "chase the needles".
Based on this observation the neuromotor time constant was adjusted to a value of 0.25 sec. This value which was kept constant in the following analysis is apparently more representative for outer-loop control behavior. In addition, figure 5 suggests that for the vertical control tasks a better agreement between measured and model results will be obtained when the lower threshold values given in table 2 will be assumed (0.2 $^{\circ}$/sec and 0.4°). This is the only minor adjustment of the model variables.

The resulting model scores are compared with the measured mean-squared values in table 3. In general, the agreement between the measurements and the refined model scores is quite good. Now (with a neuromotor lag of 0.25 sec) the control scores match, on the average, very well. The same can be

said of the system outputs α and, to less extent, ω_c.
A comparison of the pitch attitude scores shows that the pilots were somewhat more conservative in making pitch corrections than the model predicts (apart from configuration 1). These lower pitch scores (and the corresponding somewhat lower control scores) could easily be duplicated by the model, however, by an appropriate weighting of the pitch angle. The mean-squared roll angles match again, rather well*.

The system output scores are summarized in figure 7. For the dual-axis configurations, both the scores corresponding with the assumption that there no performance interference between the two axes and the "full interference" scores are indicated. The results strongly support the hypothesis that there is no interference between the vertical- and lateral axis thanks to the visual scene.

In summary, it can be concluded that for the relatively realistic, outer-loop control tasks under investigation a neuromotor time constant of (say) 0.25 sec is appropriate. Furthermore, only one minor adjustment of the nominal model variables was required to yield, on the average, a good agreement between model results and measurements: a position threshold for α and θ of 0.4° and a velocity threshold for $\dot{\alpha}$ and $\dot{\theta}$ of 0.2°/sec (the same value as found in reference 10). Finally, the experimental results provided convincing support for the hypothesis that the visual scene perception process can be described on the basis of the, mutually interfering, various (separate) visual cues considered. There is no performance degradation (interference) when both the vertical and lateral control task are performed simultaneously.

Workload model results and subjective ratings

Using the foregoing model results human operator workload can be computed. The workload model (a.o. discussed in reference 8) involves not only the level of attention, P_o, dedicated to the task in accordance with the model of reference 11, but also the aspect of arousal ("uncertainty").

The model predictions are compared in figure 8 with subjective ratings on the workload scale given in references 8 and 9. Apart from configuration 1 the linear correlation between subjective ratings and workload model predictions is quite good (r = 0.88). This result provides additional support for the workload model.

The model predicts a much lower workload level for configuration 1 than reflected by the subjective ratings. The explanation for this is that for this configuration the subjects were not sure what the right (nominal) vertical position was. Not only they learned slowly on this configuration (somewhat discouraged by their varying learning-performance) but also they clearly did not like the uncertainty involved in performing the task which can also be related to training. So, the model, not including this learning aspect, predicts that the workload corresponding with this configuration will

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* For the roll-only task (conf.7) an overall level of attention, P_o, of -18 dB had to be assumed in order to match the measured scores.

substantially reduce when the subjects are more trained on (familiar with) this task.

CONCLUSIONS

The visual scene provides a variety of perspective geometrical and relative motion cues. The experimental results have supported that these characteristics can be considered as separate cues among which the human operator has to divide his attention. The commonly accepted idea that pictorial information is better integrated (less interfering) than separate display elements is in the present study specifically demonstrated in that there is no performance interference between the vertical and lateral task. Both the workload model results and the subjective ratings indicate that the workload is increased indeed when performing both tasks.

In the case of guidance control tasks (e.g., the visual approach task) pilots are reluctant to make rapid control movements. This is represented in the optimal control model by a weighting on control rate corresponding with a neuromotor time constant of about 0.25 sec. This outer-loop control behavior is distinguished from attitude (inner-loop) control tasks which can be modelled with a neuromotor time constant of 0.1 sec (Ref. 7).

Furthermore, the assumptions concerning the key parameters of this investigation, i.e. the perceptual thresholds, could (indirectly) be checked against the experimental data. Apart from one minor adjustment the a priori assumed threshold values yielded a good agreement between model scores and measurements. The sensitivity analysis visualized in figures 5 and 6 indicates that this result allows a reasonable accurate verification of the underlying model parameters (thresholds and level of attention).

Finally, the workload model predictions have been confirmed convincingly by subjective ratings. Apart from configuration 1 (the performance of which task must have been dominated by a psychologigal effect not included in the model) the linear correlation between model predictions and subjective ratings was 0.9.

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Table 1 Thresholds

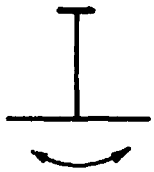
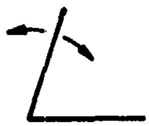
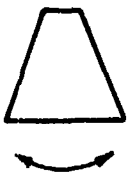
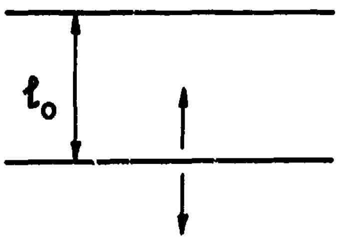
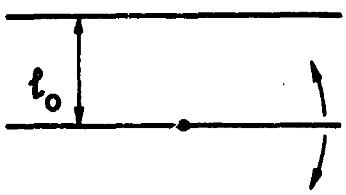
PAR	DISPLAY	THRESHOLD	CONFIDENCE INTERVAL
ω_c $\dot{\omega}_c$		1° $1^{\circ}/s$	- $0.5 - 2^{\circ}/s$
		5° $3^{\circ}/s$	$4 - 5^{\circ}$ $2 - 4^{\circ}/s$
		2° $2^{\circ}/s$	- $1 - 3^{\circ}/s$
θ $\dot{\theta}$		0.5° $0.3^{\circ}/s$	$0.4 - 0.6^{\circ}$ -
α $\dot{\alpha}$		0.5° $0.3^{\circ}/s$	$0.4 - 0.6^{\circ}$ $0.2 - 0.4^{\circ}/s$
φ $\dot{\varphi}$		0.7° $1^{\circ}/s$	- -

Table 2 Model predictions

a) VERTICAL CONTROL

Configuration	$\sigma_\alpha^2 (deg^2)$	$\sigma_\Theta^2 (deg^2)$	$\sigma_{\delta_e}^2 (N^2)$	attention allocation f_i
1	0.211	0.242	57.6	$f_{\omega_1} = 0.55$ $f_{\dot\alpha} = 0.45$
2	0.121	0.239	57.3	$f_\alpha = 0.6$ $f_{\dot\alpha} = 0.4$
3	0.103	0.247	58.8	$f_{\dot\alpha} = 0.6$ $f_\Theta = 0.4$
8	0.156	0.319	70.2	$f_\alpha = 0.42$ $f_{\dot\alpha} = 0.13$
9	0.157	0.331	72.4	$f_\alpha = 0.06$ $f_{\dot\alpha} = 0.27$ $f_\Theta = 0.23$

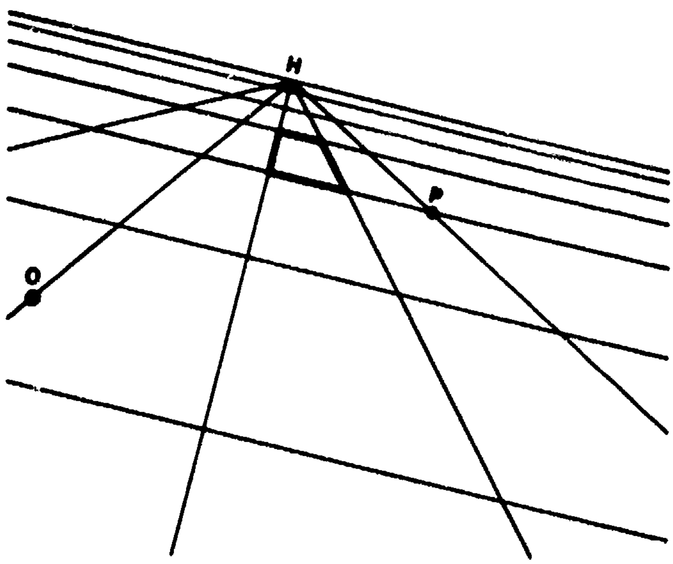
b) LATERAL CONTROL

Configuration	$\sigma_{\omega_c}^2 (deg^2)$	$\sigma_\varphi^2 (deg^2)$	$\sigma_{\delta_a}^2 (N^2)$	attention allocation f_i
4	1.86	9.68	13.1	$f_{\omega_c} = 0.37$ $f_{\dot\omega_c} = 0.63$
5	4.22	14.7	15.7	$f_{\omega_c} = 0.42$ $f_{\dot\omega_c} = 0.58$
6	2.96	9.35	12.9	$f_{\omega_c} = 0.35$ $f_\varphi = 0.65$
8	8.01	24.8	20.9	$f_{\omega_c} = 0.27$ $f_{\dot\omega_c} = 0.18$
9	6.71	19.6	18.2	$f_{\omega_c} = 0.22$ $f_\varphi = 0.22$

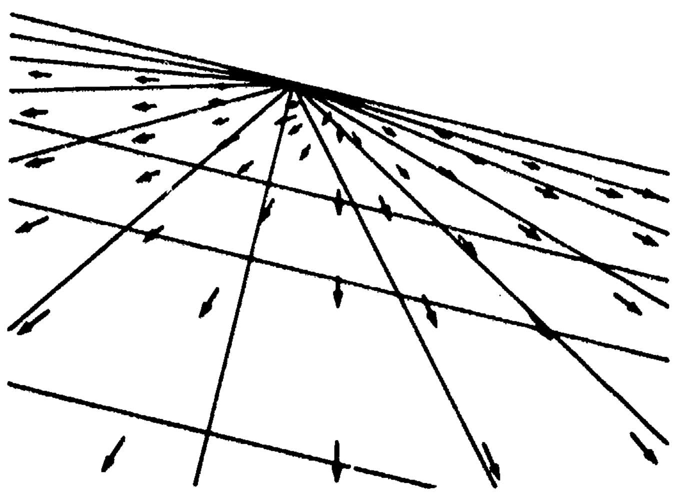
Table 3 Comparison of measured scores and model results

VERTICAL CONFIGURATION		$MS_{\alpha}(deg^2)$	$MS_{\theta}(deg^2)$	MS_{δ_e} (M^2)
1	model	0.189	0.095	26.7
	measured	0.193	0.098	26.4
2	model	0.082	0.096	26.9
	measured	0.077	0.054	23.0
3	model	0.072	0.091	26.4
	measured	0.081	0.047	21.2
8	model	0.085	0.110	28.4
	measured	0.083	0.061	24.6
9, 10	model	0.072	0.095	26.9
	measured	0.065	0.040	20.1

LATERAL CONFIGURATION		MS_{ω_c} (deg^2)	MS_{φ} (deg^2)	MS_{δ_a} (N^2)
4	model	2.78	5.82	9.76
	measured	3.62	7.82	10.9
5	model	5.42	8.40	10.6
	measured	4.72	7.90	10.9
6	model	3.40	5.46	9.62
	measured	3.99	5.40	9.43
7	model	-	2.89	4.54
	measured	-	2.99	4.99
8	model	6.37	10.0	11.2
	measured	6.20	12.1	14.0
9, 10	model	4.14	6.66	10.8
	measured	4.52	6.90	10.8



1a OUTSIDE VIEW



1b RELATIVE MOTION OF THE VISUAL FIELD

Fig. 1: Visual scene

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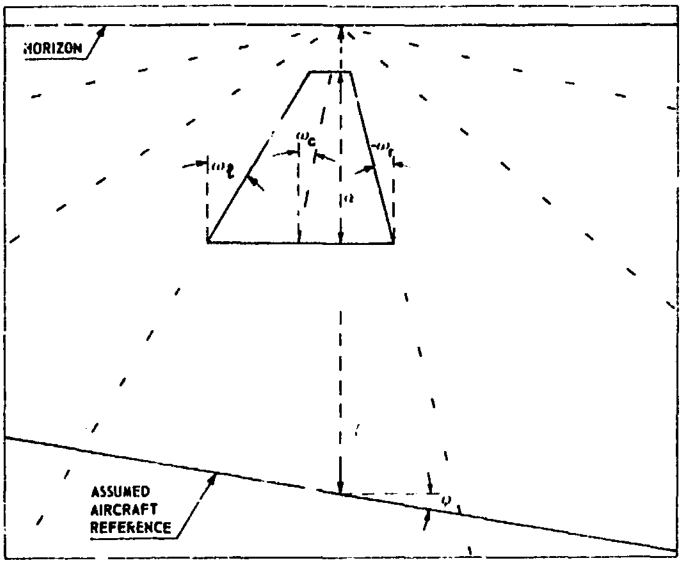
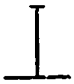
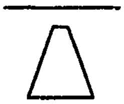


Fig. 2: Cues derived from the visual scene

VIEWING CONDITION	CONTROL		
	VERTICAL	LATERAL	BOTH
	1		
		4	
	2	5	8
	3	6	9
			10

N.B. CONFIGURATION 7 CONCERNS ROLL TRACKING BASED ON ROLL BAR ONLY

Fig. 3: Viewing conditions and selected configurations

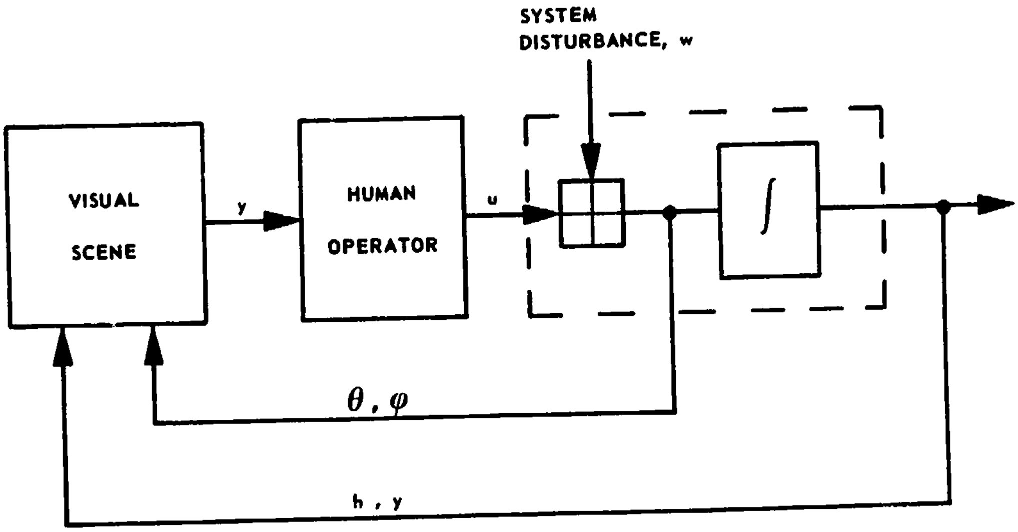


Fig. 4: Control task

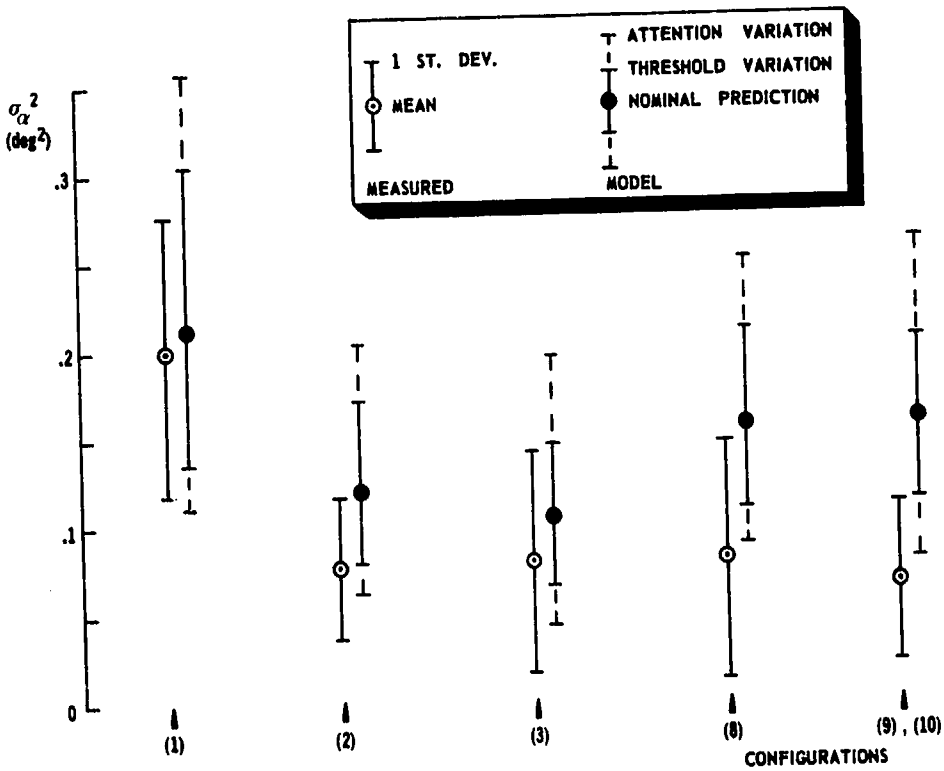


Fig. 5: Comparison of experimental scores and model predictions -- vertical control

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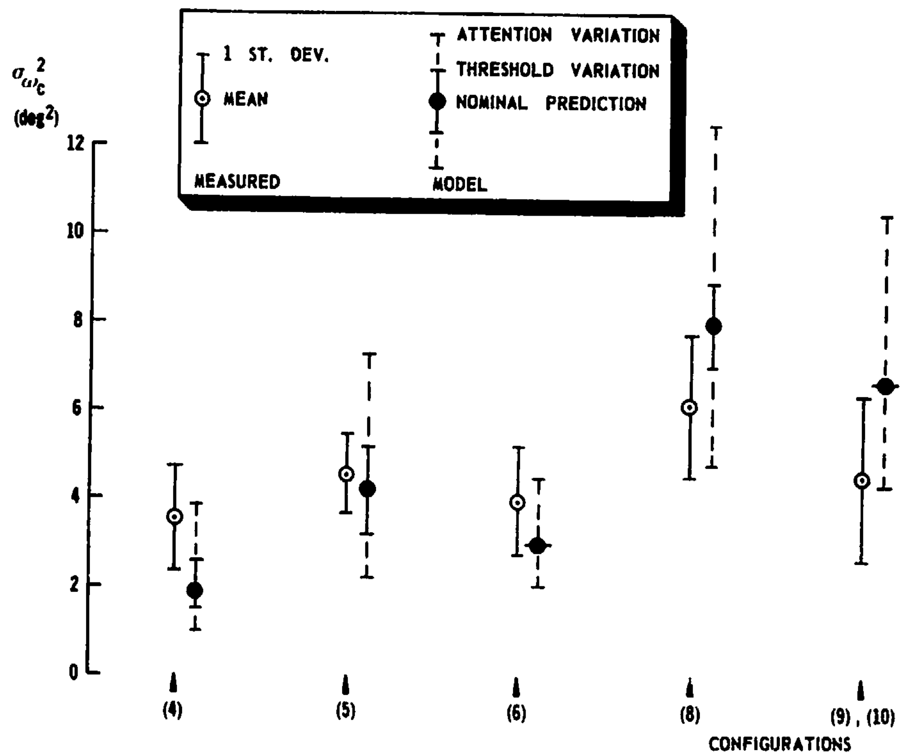

Fig. 6: Comparison of experimental scores and model predictions - lateral control

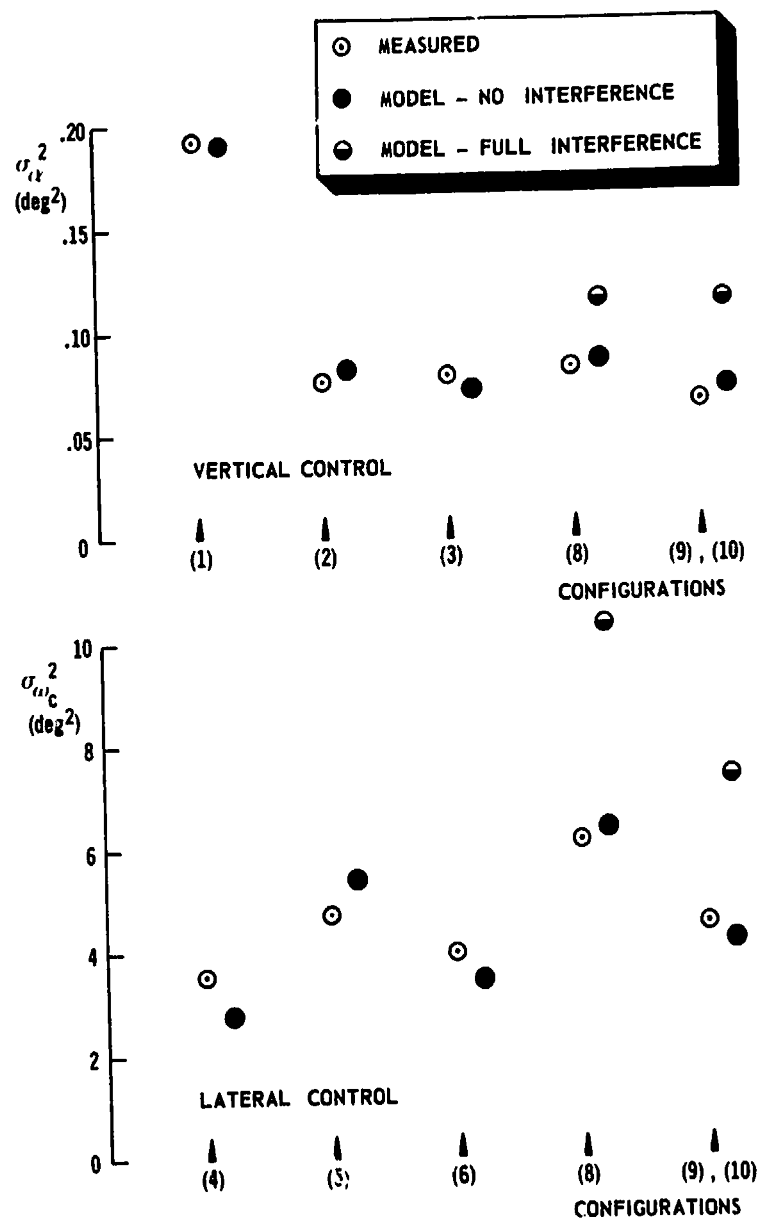

Fig. 7: Refined model scores and experimental results

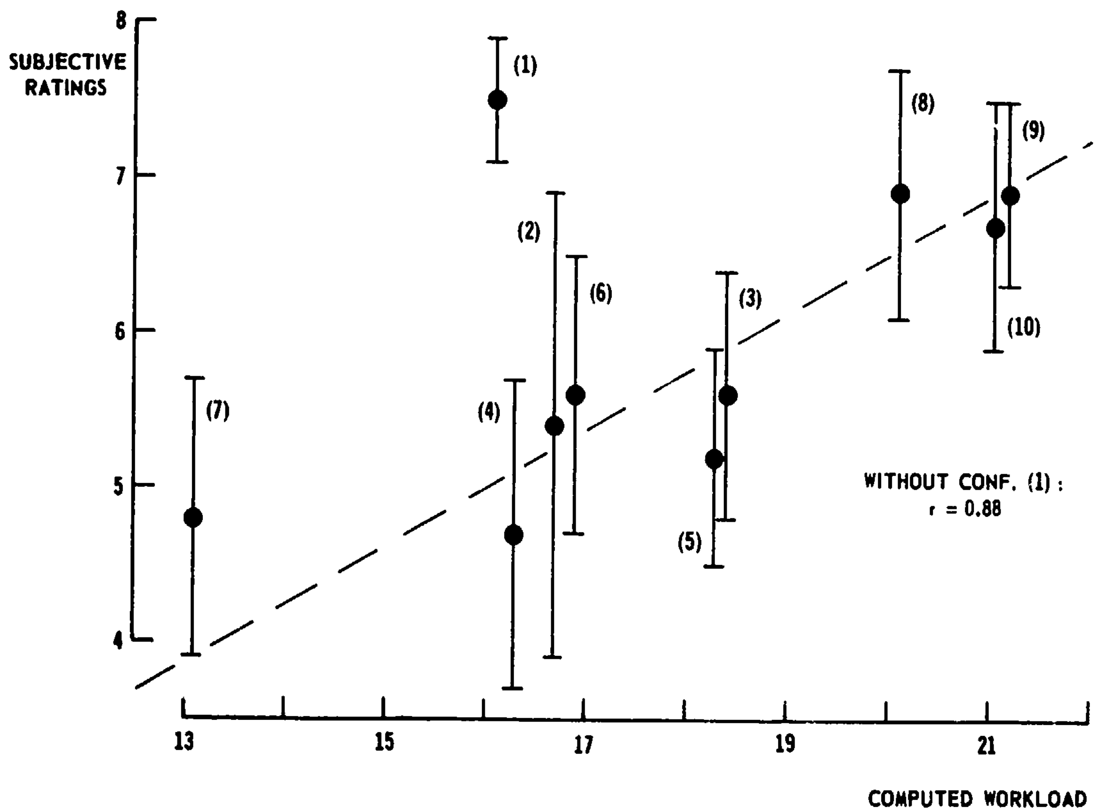

Fig. 8: Subjective workload ratings and computed workload