The Estimation of Operator Workload in Complex Systems
by John W. Senders, Brandeis University

INTRODUCTION

It would be of great practical interest to be able to provide even a rough estimate of the workload which will be placed on a human operator by some well-defined system performing some well-defined mission. Estimates of time demands on the operator could be thought of as complementary to estimates of operator error which we have discussed in Chapter Three. The ideas about information, developed in the last chapter, are continued in this chapter. In Chapter Nine, we will look again at operator workload in the context of manual control systems.

The notions which we are emphasizing are those which arise from an examination of eye movements and visual scanning processes. Human monitors of systems do, in fact, sample instruments at different rates and for different durations in a consistent way which appears to be almost completely a function of the nature of the signal presented.*

*Shannon, in his well-known 1948 Bell System Technical Journal monograph, showed that the information in bits per second generated by a continuous time function (subject to certain limitations regarding the shape of the spectrum) was directly proportional to the bandwidth of the signal in cycles per second, and to the logarithm of the ratio of the signal power to the permissible mean-square error power in the readout.

Thus, \( H = \bar{W} \log_2 \frac{A^2}{E^2} \) where \( \bar{W} \) is the signal bandwidth in cycles per second, \( A^2 \) is the signal power, and \( E^2 \) is the error power. \( H \) is in bits per second.

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We derive relationships between the signal bandwidths and required accuracies of reading of the various signals on the one hand, and the frequencies and durations respectively of the fixations on those signals.

We can estimate the percentage workload imposed by the system on the operator as being equal to that percentage of the total time available which is spent on the signals taken as a whole. Since, in fact, the aggregate statistics do not reflect the wide variation in demand which results from the instantaneous conditions of flight, an extended theory based on the notion of a "queue" of instruments waiting for attention provides a means of generating probability distributions of demand and a consequent estimation of the reliability of the operator as a system component (see also Chapter Three).

MEANS OF ESTIMATION

The term "workload" subsumes a number of related concepts. From a strictly operational point of view it means some measure of the performance decrement on a task when the task whose workload is being measured is being performed to a criterion level. Alternatively one would like to be able to measure the "effort" being put forth by a human operator while performing a task, independently of the performance of the task itself. Or, as still another alternative, one can calculate the demand of a task assuming the human operator to be a particular kind of ideal operator defined in some analytical or heuristic way. In a general way we would like to know "how hard a man has to work" in order to perform a particular task. It is an
important thing to know or to be able to estimate, since, as we have already noted in Chapter Three, the probability of success of a man-machine system depends on the reliability of the man as well as on that of the machine, and, to a large extent, the reliability of the man is a function of the load that is placed upon him.

Knowles (1963) summarizes the notion of operator workload as follows:

In the design of equipment and the development of operating and training procedures, it is important to be able to answer questions such as:

- How easy is this equipment to operate?
- How much attention is required?
- How much learning is involved?
- How well will the operator be able to perform additional tasks?

All these questions deal with some aspect of what has come to be called operator workload. Essentially, what is asked is: how busy is the operator?

Two important questions asked by the systems designer are:

1. How does one measure the workload which is imposed on the operator by a system in being?
2. How does one predict the workload which will be imposed on the operator by a system in prospect?

The first question may be answered to some degree by the techniques described by Knowles which involve operator loading tasks. Briefly, an operator loading task is one which is to
be performed at the same time that the operator is engaged in performing, to some established criterion level, the task under investigation. The reduction of performance in the loading task, as compared with the level achieved in the absence of the primary task, is an index of the loading placed on the operator by that primary task. The basic assumptions underlying this methodology are:

1. The operator is a single-channel system.
2. The channel has a fixed capacity.
3. The capacity has a single metric by which any task can be measured.
4. The components of workload are additive linearly no matter what the sources of the load.

For such a system to work, there must also be an assumption that the operator can so schedule his working that the primary tasks are always adequately dealt with, and are mutually non-interfering.

Such a workload-measurement technique depends on the availability of some kind of hardware or simulation system, and is therefore not applicable to the earliest design stages. Furthermore, it does not attempt to isolate the load placed on the operator by poor interface design from that which would exist in a perfectly human engineered machine. The only way in which use of operator loading tasks could accomplish this purpose would be to apply them in a large number of simulators possessing different interfaces.
An alternative method of estimating operator workload is that used by Siegel and Wolf (1961). This method depends on 'source data' about the task; these data are derived from a prior task analysis (See also Chapter Three). The source data are concerned with such factors as: the average time required for the operator to perform the task; the standard deviation of that time; the average probability of performing the subtask successfully; the necessity of the subtask; the necessary waiting time before which the subtask cannot be begun; and the subtasks which must be performed next in the events of success or failure of the subtask. Use of the technique permits introduction of stress and the effects of stress on performance into the calculations, and results in distributions of trials on which the operator either completes the tasks successfully or runs out of time. Then the distributions for alternative system forms can be compared. Such a technique is useful for the examination of existing systems, but could be used only with difficulty for systems which are hypothetical or conceptual.

Ekstrom (1962) applied both a loading task and an analytical approach to the estimation of the relative workloads associated with two modes of operation of an automatic flight control system. She found that the loading task confirmed the results of the analysis to a marked degree. The technique used in her analysis was essentially that described by Lindquist and Gross (1958). It involves a Second-by-Second-Operational-Analysis (SSOA) which provides instrument use-time
estimates as a basis for laying out panels; and estimates of the
loading, as a function of time, placed on the pilot. It is use-
ful as a means of locating critical periods in the mission. The
means of arriving at many of the numerical estimates is not too
different from that described by Siegel and Wolf.

The analysis of Lindquist and Gross (op cit.) is in large part
based on the application of the theoretical analysis proposed by
Senders (1955), and this in turn has led to the notions expressed
here.

An Approach to System Design

The assessment of the loading to be placed on an operator should
come at the earliest moment in the design of a man-machine system.
Ideally it should come before prototype design and construction and
should be based on an analytic and theoretical foundation. Nor should
its application be limited to human engineering the design of the man-
machine interface, but should rather lead to estimates of the reliabil-
ity of the human component of the total system. The loading-task
approach depends on the existence of a simulator or a prototype of
the actual system hardware; the analysis of Siegel and Wolf depends
on opinion of operators of similar systems. What we propose to do
here is to go from abstract specifications of the system to estimates
of the loading which will be placed on an operator.

The various analyses which will be presented rest on the following
assumptions:

1. Visual distribution of attention is the major indicator of
operator workload.
2. The various signals which must be monitored demand attention in a way which is dependent on the characteristics of the signal and the required precision of readout of the signal by the human operator.

3. The human operator is effectively a single-channel device capable of attending to only one signal at any time.

4. The probability of human failure at any time is equal to the probability that two or more signals will demand simultaneous attention.

Of course, the foregoing assumptions are simplistic in nature, and clearly do not describe real human beings. First, in addition to visual attention, part of the operator workload consists of dealing with auditory input and output, and with the motor activity which is imposed upon him by the control elements of the task and by external perturbations. Second, the restriction of workload to the monitoring situation means that we ignore the visual requirements of control tasks. The more elaborate analysis involving the queueing model deals with this problem. Third, recent work by Levison and Elkind (1967) shows that for properly-designed displays, peripheral visual inputs play a significant role in multi-degree-of-freedom control tasks. This finding, of course, bears on the validity of the fourth assumption above relating to the probability of human failure, in that simultaneous demand by two or more signals is not the inevitable precursor of a failure of attention to all but one of them.

In practice, of course, most devices which have been designed for the display of information are intended to be used by foveal vision alone. It may, in fact, be the case that if attention were
paid during the design process to the requirements of peripheral vision, a different kind of information display would result.

However, the analyses which are presented here are not concerned with the appearance of information displays, but only with the signals that are presented. The actual means of presentation can do nothing but degrade performance from some ideal operating level. Thus, even though in every case the assumptions may be invalid, the estimates which are obtained, as will be seen, are consistent and sufficiently valid to permit a designer to specify a display arrangement in advance of hardware construction.
MODELS OF VISUAL SAMPLING BEHAVIOR

Periodic Sampling

In a previous report (Senders, 1955) we have considered the question of a human monitor of some large number of informational displays. A theoretical model (Senders, 1964) was suggested, based on the assumption that the task of the monitor was to reconstruct the time functions presented on each of the displays. As a result, it was possible to present equations based on the assumption of periodic sampling, which predicted quite well the average behavior of experimental subjects in the highly constrained laboratory situation. (Senders, 1958) In fact, however, in that laboratory situation the task of the observer was specified to be the detection of a value for each of the signals which exceeded some pre-set value and the subsequent transmission of a signal not that of signal reconstruction.

If we take as the goal of a sampling system this latter task, it is possible to generate a sampling strategy completely different from that of the sampling theory.

When signal reconstruction is the task presented, and there are equal signal powers and equal significant deviations, the periodic sampling model provides adequate estimates of the distribution of attention of the visual sampling behavior of subjects. However, the estimates are only of the means of distributions of intervals between observations. There is nothing in this model which permits an estimate of the distributions themselves or suggests that such distributions will in fact exist.
That there are such distributions is apparent both from data (Senders, 1958), and from purely logical considerations (Senders, date not yet stated). Aperiodicity in the sampling of any one instrument would result from almost any configuration of instruments and bandwidths, except for cases where all the signals had identical bandwidths and identical significant deviations, and in certain other equally unlikely cases.

Data relative to the distributions of durations both of operator observations and of inter-observation intervals, lead us to attempt to account for these distributions in a rational rather than in a descriptive way. The basis of this approach is: (1) the interval between observations is a function of the value previously read; and (2) the duration of an observation is a function of the value then being read by the observer. A discussion of the model based on these findings follows.

Conditional Aperiodic Sampling

Let's consider the problem faced by a monitor (either biological or nonbiological) of limited channel capacity confronted with many signals (that is, more than two) to attend to, but concerned with detection of extreme readings rather than with reconstruction of the signal. Such a monitor may serve not as a channel for the transmission of a complete or continuous time function,* but rather as a channel for the transmission of a dichotomized (or polychotomized) time function. For any function we might assume that there is a threshold value of the function which calls for the transmission of a message, and,

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* Time function are the only functions dealt with in this chapter. The meaning of "function" in subsequent pages should, therefore, be clear.
alternatively, all values of the function below this limit call for no transmission of the message. In other words, a monitor observes the time functions and does nothing so long as they remain with a "safe" interval. When a function exceeds the limits of safe operation, the monitor emits a signal which might be either the present value of the function or some other signal. We may now ask what the appropriate sampling strategy will be for this monitor. It is easy to see that if the permissible error, between the function as presented and the function as read, is equal to the amplitude of the function, no observation is needed.* Similarly, if the permissible error approaches zero, then the information to be absorbed per sample increases and a longer time will be required for the monitor to accept and transmit the information. If the function at the moment of observation has a value of zero (i.e., its mean), then the next sample may be deferred until such time, T as the probability that the function will exceed the limits of safe operation exceeds some arbitrarily set probability.

If the limit of safe operation is some L standard deviations away from the mean, then as time since the last reading increases, the variance of the distribution of signal amplitudes around the expected value also increases. Thus, there will come a time when the probability of a significantly deviant reading will exceed the probability threshold. At that point a sample might be taken.

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*That is, if the error which may be made in reading the signal is as large as the signal itself, we aren't concerned with what the signal really says, since any report would be within the bounds of permissible error. The amplitude of the function is not its instantaneous value, but the total signal amplitude over which the function varies. Thus, if any heading within this total amplitude is acceptable, no observation is required.
If the function when observed is greater than zero, i.e., is some fraction of the way toward the limit, \( L \), then the point at which the probability reaches or exceeds the arbitrarily chosen probability will in general come sooner, and the sample must be taken after a shorter interval. As the observed value of the function approaches \( L \), the inter-sample interval approaches zero.

The above description assumes one possible strategy: the probability threshold criterion. Other sampling strategies might involve the sampling of the parameter at the moment when the probability of exceeding the limit is a maximum, or sampling according to a 'variable signal bandwidth' rule. Senders (1966) presents analyses of such strategies, and shows how one might calculate the interval between a present observation of a signal and the next observation, granted that the signal possesses certain well-defined characteristics.

The various strategies are not necessarily mutually exclusive. The actual process of 'conditional sampling' is probably a combination of two or more strategies. The mathematical model which is appropriate depends on the momentary goal of the observer.

For any of these models, the maximum interval between observations will be that time for which the next sample is statistically independent of the former, but in general, the intervals will be shorter than that. Thus, samples will be taken by the observer more often than would be calculated on the basis of the sampling theorem. If the observer, human or inhuman, can also detect velocities, then it has been shown that the maximum permissible interval between samples may be doubled (Fogel (1956)).

*In our discussion here, a strategy is something adopted by the observer as a decision rule. If we allow him that strategy, we can then construct a mathematical model of what the entire process will look like.
Since some low velocities will be below threshold, the curves would not be linear and we would expect that low frequency signals would be sampled more often than would be predicted by any simple theory. This is observed to be the case in our laboratory studies. Transition Probabilities (Link Values)

We have considered various models for sampling strategies which will permit an observer to achieve some specified goal. Either by applying the models to hypothetical or known signals, or by direct measurement of the relative times spent observing the various instruments or display devices in a man-machine system, we can arrive at estimates of the probability of fixation of each of the signal sources or instruments. The utility of such estimates is apparent: the greater the probability that a signal will be fixated, the more centrally in the visual field should it be displayed (Senders, 1964). The original series of 'Pilot Eye-Movement Studies' was aimed at determining by direct measurement the various fixation probabilities and using them to determine the locations of the instruments then used in a variety of aircraft.

In addition to measurement of fixation probabilities, these studies also determined the successive pairs of instruments fixated. The goal was to establish links between instruments which could act as a guide to the placement of instruments relative to one another. Here again the utility of the estimated transition probabilities is apparent: the greater the probability of transition between two signals, the closer together they should be displayed.
One model for the transition process treats the observer as if he draws at random from the set of displayed signals with probabilities equal to the fixation probabilities, each time a transition is to be made. Such an observer would make transitions between instruments without regard for any real or imagined relation between signals displayed. Although it is not contended that pilots in fact behave this way in aircraft, it is nonetheless the case that the predictions of the model are in close enough accord with the actual link values measured in flight to have served as a basis for instrument panel layout decisions. The correspondence between the predictions of the model and the results of laboratory studies (Senders, date not yet indicated) (8) are even closer and suggest that in the laboratory situation the model accounts for nearly all of the observed behaviors. The laboratory data were gathered on a set of random, unrelated signals. Thus, there would be no basis for selection other than the probability of fixation itself. A deviation on one instrument was not indicative of the signal which might be observed on any other. In the aircraft, on the other hand, there would be two processes which would determine the next item to be selected by the observer. If the prior observation found the signal inside the acceptable region, then the selection of a signal for the succeeding observation could be made on an appropriately weighted random basis. If the prior observation were of a significant deviation, then the coupling which existed between the displayed signals would lead to a rational selection of an instrument
which might be presumed to be related to the observed deviation. Our expectation therefore should be that the demands of the simple model will constrain partially the sampling behavior of the pilot and that this will be particularly true for those signals which have the highest probabilities of fixation.

Validation Studies

In addition to the experiments reported by Senders (1964), three more recent studies of visual sampling behavior have been completed (Senders, 1966; Senders et al., 1968; McRuer et al., 1967) (15). The results of this series of experiments and analyses provides strong support for the hypothesis that human observers behave in a way which is lawfully related to the bandwidths and the accuracy requirements of the signals which they are to monitor. The failures of agreement between the simpler models and the data have led us to more sophisticated analyses of the determiners of the distribution of visual attention. Among these are the direct perception of visual rate, the assignment of differential costs to extreme deviations of different signals (Carbonell et al., 1968), the effect of incorrect perception of the signal characteristics by the observer smallwood (date not yet established) and the effects of coupling and correlation between the various displayed signals (Senders et al., 1966). The application of the subjective model reported by Smallwood has resulted in the remarkably close approximation to the actual behavior displayed by the subjects in the laboratory situation. The other notions have
been tested from elaborate studies involving the use of fixed base
flight simulators.

Certain difficulties arise when one attempts to test the models
against the available data. The simple sampling model and the condition-
al sampling model described in the references both depend on the
ability of the designer or the investigator to estimate two para-
meters of the signal: the bandwith and the required accuracy of
reading. In the former case, the two interact over an appreciable
period of time. That is, the ratio of signal power to permissible
error power for any signal will determine the effective bandwidth,
in that as the permissible error goes down, the bandwith of the
information-bearing portion of the signal goes up. The permissible
error in reading a signal must be considered as a variable in the
short term, which is dependent upon the observed value of the signal
on the previous fixation. As a consequence, the simple assumptions
which are required for the application of the earlier "periodic"
sampling model can hardly be met in operational situations involving
real systems.

Let us consider how the models might be applied. Our goal is
the estimation of the frequencies and durations of observations on
each of the instruments in a man-machine system. On the basis of
a physical analysis of the system and a definition of the mission
requirements, the steps would be as follows:

1. The physical system must be described by a set of differential
   equations
2. From the equations of the system, the frequency characteristics of the signals which will flow in the control loops can be calculated.

3. From the mission specifications and the stability requirements of the system, the required accuracy and precision for each of the signals can be determined.

4. From the frequency and accuracy requirements the frequencies and durations of observations can be calculated on the basis of the model chosen.

5. The product of mean frequency and mean duration of observation for each signal gives the percent of the total time available that must be spent observing that signal.

6. The sum of these products then provides an estimate of the mean loading placed by the system on the human operator.

The instrument panel would then be laid out with the most frequently observed instruments in the central areas, and the least-frequently observed in the peripheral areas. The link values calculated on the basis of the simple transition model will provide the data for an analysis of the cost of any particular panel layout in terms of eye movements. If one were to choose arbitrary costs for eye movements as a function of both direction and distance, a signal layout of minimum cost could be computed. However, the models, in their simpler form, apply to monitoring behavior, and it can be seen upon reflection that for manually-controlled loops the power of the signal at any frequency will diminish as a function of the amount of control
which is exercised, that is, as a function of the amount of attention which is paid. Thus, we might find that for a man exercising very tight control, the greater the high-frequency error power, the smaller would be the amount of attention paid to that particular signal.

In order to deal with the problems raised by processes which are under continuous control, it is necessary to construct a somewhat different model of the human operator. The assumptions upon which this model is based are elaborated in detail by Carbonell et al (op cit). The results of applying this model to the actual behavior of pilots controlling a fixed-base flight simulator can be seen in the accompanying tables. The first table shows the observed and simulated (generated by the model) eye fixations in percent of total time for three pilots during turn maneuver.

[Insert Table 7.1 about here]

Table 7.2 shows similar data for a single pilot during three different phases of the flight.

[Insert Table 7.2 about here]


<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>PILOT</th>
<th></th>
<th></th>
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<tr>
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<td>J.F.</td>
<td>D.M.</td>
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<td>Model</td>
<td>Data</td>
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<td>22.7</td>
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<tr>
<td>3</td>
<td></td>
<td></td>
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<td>Air Speed</td>
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<td>8.0</td>
<td>7.0</td>
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<td>4</td>
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<td>14.4</td>
<td>15.8</td>
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<td></td>
<td></td>
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<td>Pitch &amp; Roll</td>
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<td>13</td>
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<tr>
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<td>14.6</td>
<td>14.4</td>
<td>15.4</td>
<td>0.7</td>
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<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
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</table>

OBSERVED AND SIMULATED EYE FIXATIONS IN PERCENT FOR THREE PILOTS DURING PHASE II OF FLIGHT (TURN)
Table 7

OBSERVED AND SIMULATED EYE FIXATIONS IN PERCENT FOR A GIVEN PILOT (P.M.) DURING THREE DIFFERENT PHASES OF THE FLIGHT

<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>PHASE I Beginning of Descent</th>
<th>PHASE II Turn</th>
<th>PHASE III Landing Approach</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Data</td>
<td>Model</td>
<td>Data</td>
</tr>
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<td>13.6</td>
<td>13.3</td>
<td>8.5</td>
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<tr>
<td>4</td>
<td>11.4</td>
<td>13.3</td>
<td>15.9</td>
</tr>
<tr>
<td>5 &amp; 6</td>
<td>41.5</td>
<td>41.3</td>
<td>46.0</td>
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<tr>
<td>13</td>
<td>15.3</td>
<td>15.8</td>
<td>10.0</td>
</tr>
<tr>
<td>14 &amp; 15</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Finally, it is of interest to compare the simple sampling model results applied to the same data with those of the queueing model. Table 7.3 presents the correlations between observed and predicted (model) data for each of the two models for three pilots and three phases of flight. In all cases, the number on the left of each cell is that obtained from the simple sampling model, the number on the right that obtained from the queueing model. The queueing model gives consistently higher correlations. This suggests that the more complex procedures involved in the latter model provide a significant improvement in precision of prediction for complex situations.

[Insert Table 7.3 about here]
Table 3

COMPARISON OF CORRELATION COEFFICIENTS BETWEEN DATA AND MODEL FOR NYQUIST MODEL (LEFT) VERSUS QUEUEING MODEL (RIGHT)

<table>
<thead>
<tr>
<th>PILOT</th>
<th>PHASE</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I Beginning of Descent</td>
<td>II Turn</td>
<td>III Landing Approach</td>
<td></td>
</tr>
<tr>
<td>D.M.</td>
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<td>0.730/0.974</td>
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<td></td>
</tr>
<tr>
<td>P.M.</td>
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<td>0.940/0.983</td>
<td>0.653/0.917</td>
<td></td>
</tr>
<tr>
<td>J.F.</td>
<td></td>
<td>0.903/0.984</td>
<td>-0.263/0.837</td>
<td></td>
</tr>
</tbody>
</table>
Still more recently, as described in Senders et al., (1968), McGraw et al. used the simpler model to predict link values and instrument panel layout for the ILS (instrument landing) phase of a Boeing 707. The predicted fixation probabilities were calculated on the basis of signal bandwidth and the link values or transition probabilities between instruments were calculated on the assumption of a zero-order process, and these link values in turn, were used to lay out a panel. This procedure was performed for two alternative instrumentation schemes. One produced an exact correspondence for ten instruments to the configuration actually adopted by an airline for F.A.A. Category 2 certification. The other alternative produced an almost exact correspondence, with minor deviations, for the configuration actually adopted by another airline for their Category 2 certification.

Since it may be presumed that for well-known and well-understood systems there would be an "evolutionary" convergence on optimum or nearly optimum display configurations, the correspondence between the results of a completely analytical calculation and actual design behavior suggests that the same process will have general utility for systems whose histories are so short as to provide little opportunity for evolutionary design processes to occur. The work has been described in terms derived from aircraft-pilot systems. However, there is no reason to assume that the rationale and procedures are not general for a very wide variety of systems. Such systems might range from novel vehicles to organizational structures involving communication, supervision, and chain-of-command.
SUMMARY

To recapitulate briefly, assume that the operator or observer is a single-channel device and the demands are made upon this device by sources of information in the environment; that the sources, in a sense, arrive at the single channel device and form a queue; and the length of the queue formed by the information sources at any time is a direct measure of the degree of interference which will exist in any situation involving "simultaneous attending to two or more sources of information." The length of the queue is a function of the probability of simultaneous demand. The notion of the queue can serve as a rational basis for attack on the questions of perceptual overload and workload in general. The possibility of calculating analytically the statistics of observing behavior permits the evaluation of instrument designs in operational situations by the comparison of predicted and observed behavior, and thus offers the possibility of a rational and quantitative display design evaluation procedure. Lastly, the transition model offers a rational basis for instrument panel layout.
BIBLIOGRAPHY


