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**FURTHER EXAMINATION OF PILOT INSTRUMENT SCANNING DATA  
AND DEVELOPMENT OF A NEW LINK VALUE ESTIMATOR\***

Lee Gregor Hofmann, Warren F. Clement,  
and Richard E. Blodgett†  
Systems Technology, Inc., Princeton, New Jersey

**ABSTRACT**

Examination of pilot instrument scanning data collected during simulated transport instrument landing approaches has confirmed the existence of two deterministic features of otherwise random pilot instrument scanning behavior. These are: transitions in point of eye fixation which originate and terminate on the same instrument are rare; and transitions in point of eye fixation which originate on one secondary instrument and terminate on another secondary instrument are rare. Link value (the probability that a transition in point of eye fixation is from instrument i to instrument j) estimators are developed using statistics and these two experimental facts. This result has special significance when there is but a single primary instrument, i.e., a flight director. This result can be used to simplify the iterative computational procedure of STI's display theory to a non-iterative procedure for the flight director case.

**INTRODUCTION**

Further examination of the pilot instrument scanning data collected during simulated transport instrument landing approaches (Ref. 1) is motivated by interest in the pilot's crosschecking (i.e., instrument monitoring) behavior. The data in Ref. 1 offer the opportunity to examine this behavior for a single primary integrated flight instrument case, the flight director/attitude indicator, and for a two primary flight instrument case, the attitude indicator and horizontal situation indicator. The result of this improved understanding of pilot crosschecking behavior is a model which can be applied in conjunction with other procedures to predict overall performance of the pilot-control-display-vehicle system as a function of certain display (and other) system parameters.

This paper provides a statistical model of the pilot's primary and cross-check instrument scanning behavior. A companion paper, Ref. 2, shows the

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†Presently graduate student, Columbia University.

technique for applying this model where there is but a single primary instrument, i.e., a flight director. The results are an analytical prediction of pilot-control-display-vehicle system performance and pilot instrument scanning statistics. The computations required are based upon STI's control-display analysis technique (Refs. 3 and 4), but the computations are rendered non-iterative as the result of incorporation of the model of instrument scanning behavior developed herein.

The statistical model of the pilot's primary and crosscheck instrument scanning behavior is based upon several observed experimental facts. These are:

- There is no gross determinism (e.g., a circulatory scanning pattern) in the pilot's scanning behavior (Refs. 5, 6, 7, and more recently, Ref. 1).
- Scanning within the face of a single instrument is rare (Ref. 8).
- Scanning behavior throughout the instrument landing approach appears to be essentially stationary (Ref. 8).
- Transitions in point of eye fixation which originate and terminate on the same instrument are rare.
- Transitions in point of eye fixation which originate on one secondary instrument and terminate on another secondary instrument are rare.

The following section will define the symbols and conventions used throughout the paper. Next, an existing body of eye fixation data is tested for consistency with the latter two assertions above. This is followed by development of the new link value estimators. The new link value estimators are then compared with the old link value estimators and the eye fixation data.

**DEFINITIONS OF SYMBOLS AND CONVENTIONS**

**Definitions of Symbols**

P	Set of primary instruments
S	Set of secondary instruments
i, j, k	Indices designating instruments

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N	Total number of "looks" (i.e., eye fixations) in a data interval
$N_i$	Number of looks at instrument i in a data interval
$N_{ij}$	Number of transitions in point of eye fixation which originate from instrument i and terminate upon instrument j
$v_i$	Look fraction for ith instrument, determined as $v_i = \lim_{N \rightarrow \infty} N_i/N$
$q_{ij}$	Link value (i.e., transition probability) for transitions from instrument i to instrument j, determined by $q_{ij} = \lim_{N \rightarrow \infty} N_{ij}/N$
$T_R$	Length of data interval in sec
$T_i$	Length of time in data interval spent looking at instrument i, in sec
$\bar{F}_s$	Average scanning frequency, determined by $\bar{F}_s = \lim_{N \rightarrow \infty} N/T_R$ , in looks/sec
$\bar{F}_{s1}$	Average scanning frequency for the ith instrument, determined by $\bar{F}_{s1} = \lim_{N \rightarrow \infty} N_i/T_R$ , in looks/sec
$\eta_i$	Dwell fraction; the fraction of time which is spent looking at instrument i, determined by $\eta_i = \lim_{N \rightarrow \infty} T_i/T_R = \bar{T}_{d1} \bar{F}_{s1}$
$i \in B$	Index i ranges over the set B
$A \cup B$	Union of sets A and B
$A \cap B$	Difference of sets A and B where B is a subset of A

**Identities**

$$\sum_{i \in PUS} q_{ij} = v_j$$

$$\sum_{j \in PUS} q_{ij} = v_i$$

$$\sum_{i \in PUS} v_i = \sum_{i,j \in PUS} q_{ij} = 1$$

$$\sum_{i \in PUS} \bar{F}_{s1} = \bar{F}_s$$

\*When values of  $v_i$  are determined from experimental data,  $v_i$  is calculated by  $v_i = N_i/N$ . A similar comment applies for  $q_{ij}$ ,  $\bar{F}_s$ ,  $\bar{F}_{s1}$ , and  $\eta_i$ .

**Distinguishing Between Primary and Secondary Instruments**

Secondary instruments include those which must merely be monitored (i.e., crosschecked). Instruments in this category are consistently found to have mean dwell times,  $\bar{T}_{d1}$ , of approximately 0.4 sec. Of this mean dwell time, approximately 0.2 sec is recognized as the mean ocular refractory period. Consequently, secondary instruments are easily identified from experimental data by their characteristic mean dwell time. Secondary instruments may be identified in analytical applications of control-display theory (Refs. 3 and 4) by virtue of their not being required for the purpose of control and, in addition, by  $\eta_i \approx 0.4 \bar{F}_{s1}$  for those instruments when control-display system performance is optimized.

For the purpose of this paper, any instrument for which  $\bar{T}_{d1} \approx 0.4$  sec will be treated as a secondary instrument. For example, the indicated airspeed instrument for an aircraft executing a landing approach on the "front-side" of the power required versus trim airspeed performance curve, is a primary instrument by virtue of its being required for the purpose of control for high performance in the absence of strong speed stability for the augmented aircraft. However, since  $\bar{T}_{dIAS} \approx 0.4$  sec in this situation, we shall here regard the indicated airspeed instrument as effectively being a secondary instrument.

Primary instruments will here be regarded as those for which the mean dwell time consistently exceeds approximately 0.6 sec.

**TESTING FOR DETERMINISM IN EYE SCANNING DATA**

Table 1 lists the one-way link value data,  $q_{ij}$ , in matrix form for the experimental configurations described in Table 2. Additional experimental eye scanning data, averaged for each configuration-subject pair, is given in Table 3.

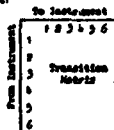
**Self-Transitions**

Examination of Table 1 reveals that no self-transitions exist for any secondary instrument. That is,  $q_{ii} = 0$  for  $i \in S$ . Or, more specifically, for configurations B, C, D,  $q_{ii} = 0$  for  $i = 1, 3, 4, 6$ ; and for configurations E, F,  $q_{ii} = 0$  for  $i = 1, 3, 4, 5, 6$ . Furthermore, the self-transition

TABLE 1. ONE-WAY LINK TRANSITION MATRICES (From Ref. 1)

CONFIGURATION	ONE-WAY LINK MATRICES*															
	PILOT 1						PILOT 2									
	1	2	3	4	5	6	1	2	3	4	5	6				
B	1		0.018	0.004	0.000	0.043	0.004	1								
	2	0.031		0.024		0.078	0.016	2	0.016	0.016	0.000		0.071			
	3	0.004	0.000			0.000	0.000	3							0.000	
	4		0.018			0.038		4								
	5	0.000	0.004	0.000	0.012	0.000	0.012	5		0.011	0.000					0.000
	6			0.004		0.000		6								0.000
C	1		0.017	0.000	0.000	0.019		1		0.030						
	2	0.019	0.000	0.000	0.000	0.000	0.000	2	0.000	0.016	0.010	0.000	0.072	0.000		
	3	0.000	0.019			0.042	0.007	3		0.000				0.000		
	4		0.000			0.000		4		0.000						
	5	0.001	0.000	0.036		0.000	0.014	5		0.014				0.000	0.000	
	6	0.000	0.000	0.000		0.000		6		0.000					0.000	
D	1		0.034	0.000	0.000	0.000	0.000	1		0.004					0.000	
	2	0.000	0.000	0.000	0.000	0.000	0.000	2			0.000				0.000	
	3	0.000	0.000	0.000	0.000	0.000	0.000	3		0.000					0.000	
	4	0.000	0.000	0.000	0.000	0.000	0.000	4								
	5	0.014	0.000	0.000		0.000	0.000	5	0.004	0.000	0.015				0.000	0.100
	6			0.000		0.000		6	0.000	0.000					0.100	
E	1		0.100	0.000	0.000	0.000		1		0.070						
	2	0.100	0.000	0.000	0.000	0.000	0.000	2	0.070	0.000	0.000	0.010	0.011	0.070		
	3	0.000	0.100			0.000		3		0.000				0.000	0.000	
	4	0.000	0.000					4		0.000						
	5	0.000	0.000	0.000		0.000	0.011	5		0.000	0.000				0.000	0.000
	6			0.000		0.000		6		0.000	0.000				0.010	
F	1		0.100			0.010		1		0.001						
	2	0.100	0.000	0.000		0.010	0.000	2	0.001	0.001			0.001	0.010		
	3		0.100			0.000	0.000	3		0.000						
	4							4								
	5	0.000	0.100	0.000		0.010	0.010	5		0.001	0.010					
	6			0.000		0.000		6		0.010						

\*Percent



Note: Transition from i to j indicates an interruption due to a blink.

TABLE 2. EXPERIMENTAL CONFIGURATIONS (From Ref. 1)

CONFIGURATION	DESCRIPTION	PERFORMANCE	REMARKS	REMARKS TO SUBJECTS
A (From Ref. 1) (Fixed range, varying range)	Single axis tracking task with pitch attitude display and forcing function. Other parameters varied. Other axes controlled by autopilot. No flight director.	Is to with single loop tracking task.	Is to with single loop tracking task.	Simulate a portion of the approach task. Control pitch attitude only, and try to keep pitch error equal to zero. There is some turbulence. The lateral autopilot is on.
B (Fixed range, varying range)	Three degree of freedom longitudinal task. Forcing function and torque on m. Control axis under autopilot. No flight director.	Provides longitudinal tracking task, and basis for validating autopilot pitch response model.	Provides longitudinal tracking task, and basis for validating autopilot pitch response model.	Simulate a split-axis manual approach under Category II conditions. Control only the longitudinal motion. As complete as controlling the lateral motion. There is some turbulence. Try to keep the glide slope constant at all times.
C (Manual IIA, fixed range)	All axis approach task with forcing function and torque on. The glide slope deviation computer range was fixed at 20,000 ft from threshold. The altitude and rate of climb were separated normal (varying range) to flight director.	Provides arbitrary all axis task performance data for comparison with split axis range varying, and flight director task.	Provides arbitrary all axis task performance data for comparison with split axis range varying, and flight director task.	Simulate a Category II manual IIA approach. There is some turbulence. Try to keep the glide slope and limiter variable constant at all times.
D (Manual IIA, varying range)	All axis approach task with forcing function and torque on. The range error deviation per unit altitude error increases with increasing range in flight director.	Provides conventional longitudinal task. Typical of "old format" cross pointer IIS display.	Provides conventional longitudinal task. Typical of "old format" cross pointer IIS display.	Simulate a Category II approach. There is some turbulence. The task director is to follow the approach path, keeping the glide slope and limiter variable constant. Pitch commands must be stopped immediately to avoid a standard. The glide slope and limiter reaction must be monitored.
E (Flight Director, fixed range)	All axis approach task with forcing function and torque on, and driven by forcing function. Same as Configuration C plus flight director.	Provides equalized, integrated display and arbitrary all axis task behavior. Flight Director also typical of modern practice.	Provides equalized, integrated display and arbitrary all axis task behavior. Flight Director also typical of modern practice.	Simulate a Category II approach. There is some turbulence. The task director is to follow the approach path, keeping the glide slope and limiter variable constant. Pitch commands must be stopped immediately to avoid a standard. The glide slope and limiter reaction must be monitored.
F (Flight Director, varying range)	All axis approach task with forcing function and torque on. The range error deviation per unit altitude error increases with increasing range in flight director.	Provides equalized, integrated display but conventional forcing function.	Provides equalized, integrated display but conventional forcing function.	Simulate a Category II approach. There is some turbulence. The task director is to follow the approach path, keeping the glide slope and limiter variable constant. Pitch commands must be stopped immediately to avoid a standard. The glide slope and limiter reaction must be monitored.
Vision Invariant	All axis approach task with forcing function and torque on. The range error deviation per unit altitude error increases with increasing range in flight director.	Provides equalized, integrated display but conventional forcing function.	Provides equalized, integrated display but conventional forcing function.	Simulate a Category II approach. There is some turbulence. The task director is to follow the approach path, keeping the glide slope and limiter variable constant. Pitch commands must be stopped immediately to avoid a standard. The glide slope and limiter reaction must be monitored.

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TABLE 3  
AVERAGE SCANNING STATISTICS\*  
(From Ref. 1)

CONF	SUBJ	NO PUBS AF3	INSTRUMENT 1, IAS						INSTRUMENT 2, ATT OR ATT/VD					
			$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_7$	$\bar{v}_8$	$\bar{v}_9$	$\bar{v}_{10}$	$\bar{v}_{11}$	$\bar{v}_{12}$
B	1	12	.57	.14	.09	.09	.01	.068	.61	.67	.29	.446	.896	.537
B	2	1	.63	.0	.002	.001	.002	.254	.97	.33	.211	.443	.453	
C	1	12	.59	.37	.095	.053	.066	.898	.81	.38	.540	.429	.451	
C	2	1	.48	.40	.015	.013	.013	.85	1.00	.45	.423	.429	.357	
E	1	14	.44	.15	.110	.06	.113	1.11	1.73	1.72	.488	.739	.438	
E	2	1	.13	.11	.043	.027	.070	.94	3.03	3.41	.876	.836	.454	
F	1	13	.15	.177	.099	.163	.147	1.50	1.36	.498	.737	.453	.453	
F	2	1	.10	.072	.039	.079	.37	2.19	1.80	.366	.80	.487	.487	

CONF	SUBJ	NO PUBS AF3	INSTRUMENT 3, PALT						INSTRUMENT 4, HSI/SPD					
			$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_7$	$\bar{v}_8$	$\bar{v}_9$	$\bar{v}_{10}$	$\bar{v}_{11}$	$\bar{v}_{12}$
B	1	23	.38	.12	.115	.084	.087	1.11	1.08	.80	.557	.507	.481	
B	2	1	.17	.04	.02	.011	.015	.57	.78	.28	.567	.443	.438	
C	1	40	.42	.18	.08	.056	.067	.955	1.09	.78	.508	.551	.480	
C	2	1	.15	.01	.004	.009	.262	.98	.40	.486	.476	.431		
D	1	27	.4	.22	.054	.028	.041	.805	.84	.43	.587	.444	.405	
D	2	1	.44	.15	.042	.020	.031	.96	.93	.51	.479	.443	.403	
E	1	11	.6	.10	.08	.051	.151	.76	.57	.80	.190	.109	.190	
E	2	1	.18	.11	.059	.03	.097	.41	.51	.12	.139	.069	.088	
F	1	16	.35	.07	.113	.074	.105	.59	.46	.13	.197	.090	.181	
F	2	1	.4	.05	.013	.053	.27	.54	.45	.887	.145	.395		

CONF	SUBJ	NO PUBS AF3	INSTRUMENT 5, TWSI						ALL INSTRUMENTS		
			$\bar{v}_1$	$\bar{v}_2$	$\bar{v}_3$	$\bar{v}_4$	$\bar{v}_5$	$\bar{v}_6$	$\bar{v}_7$	$\bar{v}_8$	$\bar{v}_9$
B	1	10	.40	.14	.05	.000	.038	.364	.200	1.32	
B	2	1	.55	0	.01	.005	.008	.132	1.01	1.31	
C	1	16	.38	.07	.038	.012	.027	.600	.508	1.19	
C	2	1	.47	.23	.004	.002	.004	.561	.497	1.13	
D	1	1	.40	.18	.010	.004	.008	.654	.503	1.36	
D	2	1	.45	.14	.214	.095	.181	.838	.800	1.19	
E	1	14	.44	.11	.04	.018	.041	.390	.400	.976	
E	2	1	.49	.11	.046	.023	.076	.185	.305	.607	
F	1	3	.35	.12	.035	.012	.031	.380	.300	1.08	
F	2	1	.49	0	.01	.005	.013	.76	1.01	.758	

\*There were transitions to and from, but no dwells on instrument 4, the Mach meter." (Ref. 1)

link values for the primary instruments are very small in comparison to the look fraction for the respective primary instruments. The numerical comparisons are made in terms of  $q_{11}/v_1$  with respect to unity. The largest value occurs for Instrument No. 2 (flight director/attitude indicator) for configuration -2 for which:

$$q_{22}/v_{22} = 0.029/0.454 = 0.064 \ll 1$$

The next largest value of this ratio occurring in the data is less than  $0.016$ .

Since the values of this ratio are very much less than unity, we shall draw the idealized conclusion that, in effect, there are no self-transitions. Mathematically, this is expressed by:

$$q_{11} = 0 \quad i \in P \cup S \quad (1)$$

Scans Between Secondary Instruments

To test the hypothesis that the pilot's eye fixation transitions to a primary instrument after fixating a secondary instrument, we will compute the conditional probability,  $\mathcal{P}$ , that, given a fixation on an instrument in the secondary group, the next fixation will be upon an instrument in the secondary group.

Let  $N_S$  be the total number of transitions from all secondary instruments. Let  $N_{SS}$  be the total number of transitions from all secondary instruments which terminate on any secondary instrument. Then the probability that pilot's eye fixation transitions to a primary instrument after fixating a secondary instrument is given by  $(1 - \mathcal{P})$  where:

$$\mathcal{P} = N \lim_{N \rightarrow \infty} \frac{N_{SS}}{N_S} = N \lim_{N \rightarrow \infty} \frac{\sum_{i \in S} \sum_{j \in S} N_{ij}}{\sum_{i \in S} \sum_{j \in P \cup S} N_{ij}} = \frac{\sum_{i \in S} \sum_{j \in S} q_{ij}}{\sum_{i \in S} v_i} \quad (2)$$

Computations of  $(1 - \mathcal{P})$  on the basis of the experimental data in Tables 1 and 3 are summarized in Table 4. The computations are based upon using  $1 - \sum_{i \in P} v_i$  in place of its theoretical equivalent,  $\sum_{i \in S} v_i$ . (See Eq. 6.)

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TABLE 4  
EXPERIMENTAL VALUES OF  $(1 - P)$

CONFIGURATION-PILOT	$(1 - P)$
B-1	0.868
B-2	1.000
C-1	0.893
C-2	1.000
D-1	0.884
D-3	0.922
E-1	0.876
E-2	0.900
F-1	0.934
F-3	0.973

The values of  $(1 - P)$  are nearly unity for all configurations. On this basis, we shall draw the idealized conclusion that, in effect, there are no transitions which originate on one secondary instrument and terminate on a secondary instrument. Mathematically, this is expressed by:

$$q_{i,j} \equiv 0 \quad i, j \in S \quad (3)$$

#### NEW LINK VALUE ESTIMATOR

The several observed experimental facts listed in the introductory section can be used as the basis for development of a link value estimator.

We shall use the following assumptions:

- Stationarity:  $q_{ij}(t) = \text{const}$ , for all  $t$
- No self-transitions:  $q_{ii} \equiv 0$ ,  $i \in P \cup S$
- No transitions between secondary instruments:  $q_{ij} \equiv 0$ ;  $i, j \in S$
- Scans from a secondary instrument to a primary instrument are made at random according to distributions given by the relative look fractions for the instruments.

- Scans from a primary instrument to a secondary instrument are made at random according to distributions given by the relative look fractions for the instruments.
- Scans within the primary group are a random selection from among the other primary instruments according to distributions given by the relative look fractions for the instruments.

The first four assumptions are used to develop an estimator of the link values for transitions from a secondary instrument to a primary instrument.

$$q_{ij} = \frac{v_i}{\sum_{k \in S} v_k} \left( \sum_{k \in S} v_k \right) \frac{v_j}{1 - \sum_{k \in S} v_k} = \frac{v_i v_j}{1 - \sum_{k \in S} v_k} \quad (4)$$

$$i \in S, j \in P$$

Consider the intermediate expression for  $q_{ij}$ .  $\frac{\sum_{k \in S} v_k}{\sum_{k \in S} v_k}$  is the probability that a transition is from the secondary instrument group to the primary instrument group.  $\frac{v_i}{\sum_{k \in S} v_k}$  is the probability that a transition from the secondary instrument group originates from the  $i$ th secondary instrument.  $\frac{v_j}{1 - \sum_{k \in S} v_k}$  is the probability that a transition to the primary instrument group terminates upon the  $j$ th primary instrument.

The next assumption is used in developing an estimator of the link values for transitions from a primary instrument to a secondary instrument.

$$q_{ij} = \frac{v_i}{1 - \sum_{k \in S} v_k} \left( \sum_{k \in S} v_k \right) \frac{v_j}{\sum_{k \in S} v_k} = \frac{v_i v_j}{1 - \sum_{k \in S} v_k} \quad (5)$$

$$i \in P, j \in S$$

Consider the intermediate expression for  $q_{ij}$ .  $\frac{\sum_{k \in S} v_k}{\sum_{k \in S} v_k}$  is the probability that a transition is from the primary instrument group to the secondary instrument group.  $\frac{v_i}{1 - \sum_{k \in S} v_k}$  is the probability that a transition from a primary group instrument originates from the  $i$ th primary

instrument.  $v_j \sum_{k \in S} v_k$  is the probability that a transition to the secondary instrument group terminates upon the  $j$ th secondary instrument.

If the  $q_{ij}$  are considered as elements of a matrix, it must also be true that the  $j$ th secondary instrument column elements must sum to the look fraction,  $v_j$ . Similarly, the  $i$ th secondary instrument row elements must sum to  $v_i$ . This leads directly to the requirement that:

$$\sum_{i \in P} v_i = 1 - \sum_{k \in S} v_k \quad (6)$$

which is merely a statement of one of the basic identities given above. Furthermore, it must be true that:

$$\sum_{i \in P \cup S} \sum_{j \in P \cup S} q_{ij} = 1 \quad (7)$$

However, since  $q_{ij} = 0$  for  $i, j \in S$ , it is evident that:

$$\sum_{i \in P} \sum_{j \in P} q_{ij} = 1 - 2 \sum_{k \in S} v_k \quad (8)$$

It is also evident that  $(1 - 2 \sum_{k \in S} v_k)$  is the probability that a transition originates and terminates on primary instruments.

These results,  $q_{ii} = 0$ , and the last assumption are used to develop an estimator of the link values for transition from one primary instrument to another primary instrument.

$$q_{ij} = \frac{v_i}{1 - \sum_{k \in S} v_k} \left( 1 - 2 \sum_{k \in S} v_k \right) \frac{v_j}{1 - v_i - \sum_{k \in S} v_k} \quad (9)$$

$$i \in P \cap j, j \in P$$

$(1 - \sum_{k \in S} v_k)$  is the probability that a transition from a primary group instrument originates from the  $i$ th primary instrument.  $v_j / (1 - v_i - \sum_{k \in S} v_k)$  is the probability that the transition originating from the  $i$ th primary

instrument and terminating in the primary group, terminates upon the  $j$ th primary instrument.

It can be verified that all row summations for the resultant  $q_{ij}$  matrix are equal to their respective row instrument look fractions when the restriction given by Eq. 6 is observed. However, when the number of primary instruments,  $p$ , exceeds one, the summation of column elements for the resultant  $q_{ij}$  matrix requires the additional restriction:

$$v_i = \frac{1 - \sum_{k \in S} v_k}{p} \quad i \in P \quad (10)$$

in order that the summations be equal to their respective column instrument look fractions.

All of the above equations are readily expressed in terms of average scanning frequencies by the simple expedient of replacing  $v_i$  by the quantity  $\bar{F}_{Si} / \bar{F}_S$ . The link values are most conveniently expressed in terms of average scanning frequencies when the results are to be used as part of a control-display analysis model, e.g., Refs. 3 and 4.

To summarize, the new link value estimators given by Eqs. 1, 3, 4, 5, and 9, subject to the requirements imposed by Eqs. 6 and 10, may be written in terms of the average scanning frequencies and the number of primary instruments as:

$$q_{ii} = 0 \quad i \in P \cup S \quad (11)$$

$$q_{ij} = \frac{\bar{F}_S - 2 \sum_{k \in S} \bar{F}_{Sk}}{p(p-1)\bar{F}_S} \quad i \in P \cap j, j \in P \quad (12)$$

$$q_{ij} = 0 \quad i, j \in S \quad (13)$$

$$q_{ij} = \frac{\bar{F}_{Sj}}{p\bar{F}_S} \quad i \in P, j \in S \quad (14)$$

$$q_{ij} = \frac{\bar{F}_{Si}}{p\bar{F}_S} \quad i \in S, j \in P \quad (15)$$

COMPARISON OF LINK VALUE ESTIMATORS  
WITH EXPERIMENTAL DATA

The link value estimators given in Ref. 3 are:

$$\tilde{q}_{ij} = \frac{\eta_i \eta_j}{1 - \sum_{k \in PUS} \eta_k^2} \quad (16)$$

$$i, j \in PUS; i \neq j$$

We shall compare the estimates given by  $\tilde{q}_{ij}$  and the estimates given by  $q_{ij}$  in the previous section with experimentally measured link values. The experimental data is for configurations which have one and two primary instruments.

The comparisons will be made on the basis of  $\tilde{q}_{ij}$  computed using experimental values of the dwell fractions,  $\eta_i$ , for all instruments. The  $q_{ij}$  used for comparison purposes will be computed using the experimental values of the fractions,  $v_i$ , for the secondary instruments only. The look fraction values for configuration-pilot combinations C-1 and F-3 are given in Tables 5 and 6, respectively. Numerical values for  $q_{ij}$  in these tables should be similar to the corresponding entries for configuration-pilot combinations C-1 and F-3 in Table 1. The look fractions should correspond to entries in Table 3. The sum of the look fractions should be unity.

The numerical values computed using either the new link value estimator or the Ref. 3 link value estimator, generally have about the same degree of similarity to the experimental values. However, the new link value estimator appears to be somewhat more accurate for the link values involving secondary instruments. The look fractions for the secondary instruments determined by the new link value estimator appear to be superior, but this is because that estimator is merely parroting the experimental values which were used in that computation.

In every case, the sum of the look fractions in Tables 5 and 6 is less than unity. This arises because the look fractions and dwell fractions in Table 3 do not each sum to unity. In other words, there were extraneous looks at places other than the instruments during the experiment. This

TABLE 5

COMPARISON LINK VALUES FOR C-1  
(Instruments 2 and 5 are Primary)

a) New Link Value Estimator

	1	2	3	4	5	6	$v_1$
1	0	.019	0	0	.022	0	.041
2	.019	0	.031	.002	.363	.012	.427
3	0	.031	0	0	.034	0	.065
4	0	.002	0	0	0	0	.005
5	.022	.363	.034	.003	0	.014	.436
6	0	.012	0	0	.014	0	<u>.026</u>
							.988

b) Ref. 3 Link Value Estimator

	1	2	3	4	5	6	$v_1$
1	0	.021	.002	~0	.033	.001	.057
2	.021	0	.021	.001	.342	.007	.392
3	.002	.021	0	~0	.033	.001	.057
4	~0	.001	~0	0	.002	~0	.003
5	.033	.342	.033	.002	0	.012	.422
6	.001	.007	.001	~0	.012	0	<u>.021</u>
							.952

Format:

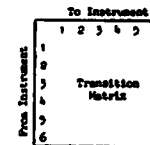


TABLE 6  
COMPARISON LINK VALUES FOR F-3  
(Instrument 2 is Primary)

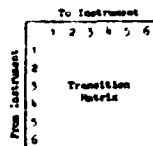
a) New Link Value Estimator

	1	2	3	4	5	6	
1	0	.077	0	0	0	0	.17
2	.077	0	.052	0	.346	.01	.438
3	0	.052	0	0	0	0	.052
4	0	0	0	0	0	0	.000
5	0	.346	0	0	0	0	.346
6	0	.013	0	0	0	0	<u>.013</u> .976

b) Ref. 3 Link Value Estimator

	1	2	3	4	5	6	$v_1$
1	0	.083	.001	0	.015	.001	.100
2	.083	0	.031	0	.343	.012	.469
3	.001	.031	0	0	.006	~0	.038
4	0	0	0	0	0	0	.000
5	.015	.343	.006	0	0	.002	.366
6	.001	.012	~0	0	.002	0	<u>.015</u> .988

From:



makes entirely consistent comparison of the data and the link value estimators impossible, but the effects of the inconsistencies would appear to be small because the sums of the look fractions and dwell fractions approach unity.

CONCLUSIONS

A new link value estimator has been developed which is based upon two deterministic features found in actual pilot eye scanning data. The new link value estimator is developed in terms of event-related quantities (i.e., looks) whereas the previous link value estimator is in terms of time-related quantities (i.e., dwell times). Since the link values are event-related statistics, it is inappropriate that the previous link value estimators should be in terms of time-related quantities.

The new link value estimator appears to adequately emulate experimental data for cases wherein there are one or two primary instruments. However, the data base used for comparison is admittedly small.

When there is but one primary instrument (designated here as a flight director, FD), then the new link value estimator can be used to show that:

$$v_{FD} = \sum_{k \in S} v_k = 1/2 \quad (17)$$

If this result is expressed in terms of average scanning frequencies, thus:

$$\bar{f}_{s_{FD}} = \sum_{k \in S} \bar{f}_{s_k} = \bar{f}_s/2 \quad (18)$$

In other words, the flight director scanning frequency and the sum of secondary instrument scanning frequencies are equal. This feature is shown in Ref. 2 to considerably simplify application of the control-display theory of Refs. 3 and 4 for this case. This is by virtue of eliminating iteration in the computational procedure.

For the more general case wherein there are multiple primary instruments, a modest simplification of the control-display theory computations results.



This simplification is that the average scanning frequencies for all primary instruments are equal. That is:

$$\bar{f}_{s_i} = (\bar{f}_s - \sum_{k \in S} \bar{f}_{s_k}) / p \quad i \in P \quad (19)$$

The effect, in this case, is to reduce by  $(p - 1)$  the number of parameters over which the pilot-control-display-vehicle system must be optimized. Experimental data for the two primary instrument case confirms Eq. 19. However, no experimental data based upon the use of contemporary flight instruments has been found for cases involving three or more primary instruments.

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