N75 19158

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 crosscheck instrument scanning behavior. A companion paper, Ref. 2, shows the

*This research was sponsored by the U.S. Air Force under Contract No. F33615-71-C-1349.

†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

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
ν_i	Look fraction for ith instrument, determined as $\nu_i = \lim_{N \to \infty} N_i/N$*
q_{ij}	Link value (i.e., transition probability) for transitions <u>from</u> instrument i <u>to</u> instrument j, determined by $q_{ij} = \lim_{N \to \infty} N_{ij}/N$
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 $\bar{f}_s = \lim_{N \to \infty} N/T_R$, in looks/sec
$\bar{f}_{s_i}$	Average scanning frequency for the ith instrument, determined by $\bar{f}_{s_i} = \lim_{N \to \infty} N_i/T_R$, in looks/sec
η_i	Dwell fraction; the fraction of time which is spent looking at instrument i, determined by $\eta_i = \lim_{N \to \infty} T_i/T_R = \bar{T}_{d_i}\bar{f}_{s_i}$
$i \in B$	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

$$\sum_{i \in PUS} q_{ij} \equiv \nu_j$$

$$\sum_{j \in PUS} q_{ij} \equiv \nu_i$$

$$\sum_{i \in PUS} \nu_i \equiv \sum_{i,j \in PUS} q_{ij} \equiv 1$$

$$\sum_{i \in PUS} \bar{f}_{s_i} \equiv \bar{f}_s$$

*When values of ν_i are determined from experimental data, ν_i is calculated by $\nu_i = N_i/N$. A similar comment applies for q_{ij}, $\bar{f}_s$, $\bar{f}_{s_i}$, and η_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, $\bar{T}_{d_i}$, 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 <u>not being required</u> for the purpose of control and, in addition, by $\eta_i \doteq 0.4\, \bar{f}_{s_i}$ for those instruments when control-display system performance is optimized.

For the purpose of this paper, any instrument for which $\bar{T}_{d_i} \doteq 0.4$ sec will be treated as a secondary instrument. For example, the indicated airspeed instrument for an aircraft executing a landing approach on the "frontside" 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 $\bar{T}_{d_{IAS}} \doteq 0.4$ 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					
B		1	2	3	4	5	6		1	2	3	4	5	6
	1		0.012	0.004	0.008	0.043	0.004	1		0.016				
	2	0.051		0.024		0.278	0.016	2	0.416	0.016	0.008		0.451	
	3	0.004	0.020			0.559	0.008	3		0.008			0.008	
	4		0.012			0.438		4						
	5	0.055	0.506	0.059	0.012	0.008	0.012	5		0.451	0.008			0.008
	6			0.004		0.855		6					0.008	
	PILOT 1							PILOT 2					
C		1	2	3	4	5	6		1	2	3	4	5	6
	1		0.017	0.005	0.003	0.019		1		0.178				
	2	0.019	0.005	0.028	C.008	0.391	0.007	2	0.002	0.016	0.010	0.002	0.472	0.002
	3	0.008	0.019			0.042	0.007	3		0.006			0.004	
	4		0.002			0.003		4		0.002				
	5	0.081	0.366	0.C36		0.005	0.014	5		0.474			0.002	0.002
	6	0.002	0.008	0.002		0.023		6		0.002			0.002	
	PILOT 1							PILOT 3					
D		1	2	3	4	5	6		1	2	3	4	5	6
	1		0.034	0.005	0.002	0.027	0.002	1		0.004				0.009
	2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2			C.666		0.260	0.0CC
	3	0.00'	022			0.016	0.002	3		0.086			0.015	
	4	0.003						4						
	5	0.C14	0.390	0.010		0.002	0.005	5	0.004	0.877	0.015		0.004	0.106
	6		0.002	0.002		0.005		6	0.009	0.051			0.123	
	PILOT 1							PILOT 2					
E		1	2	3	4	5	6		1	2	3	4	5	6
	1		0.102	0.008	0.036	0.006		1		0.076				
	2	0.108	0.014	0.119	0.008	0.199	0.025	2	0.076	0.029	0.088	0.012	0.211	0.070
	3	0.006	0.187				0.008	3		0.094			0.006	0.006
	4	0.003	0 011					4		0.006			0.006	
	5	0.006	0.182	0.008			0.011	5		0.228	0.046			0.006
	6		0.036	0.005		0.006		6		0.058	0.0C.		0.018	
	PILOT 1							PILOT 3					
F		1	2	3	4	5	6		1	2	3	4	5	6
	1		0.165			0.010		1		0.081				
	2	0.165	0.010	0.109		0.175	0.020	2	0.081		0.041		0.391	0.014
	3		0.108			0.007	0.003	3		0.054				
	4							4						
	5	0.027	0.175	0.005			0.010	5		0.351	0.014			
	6		0.050			0.003		6		0.014				

*Format:

From Instrument	To Instrument					
	1	2	3	4	5	6
1						
2						
3	Transition Matrix					
4						
5						
6						

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

TABLE 2. EXPERIMENTAL CONFIGURATIONS (From Ref. 1)

CONFIGURATION	DESCRIPTION	PURPOSE	INSTRUCTIONS TO SUBJECTS
A (Pitch attitude regulation only)	Single axis tracking task with pitch attitude display and forcing function. Other instruments masked. Other axes controlled by autopilot. No flight director.	Tie in with single loop tracking data.	Simulates 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 (Split axis manual ILS, fixed range)	Three degree of freedom longitudinal task. Forcing functions and tracers on. Lateral axes under autopilot control, but meters visible. No flight director	Provide longitudinal scanning task, and basis for validating multiloop pilot response model.	Simulates a split-axis manual approach under Category II conditions. Control only the longitudinal motions An autopilot is controlling the lateral motions. There is some turbulence Try to keep the glide slope needle centered at all times
C (Manual ILS, fixed range)	All axis approach task with forcing functions and tracers on. The glide slope deviation computer range was fixed at 30,000 ft from threshold The altimeter and rate of climb meter appeared normal (varying range) No flight director	Provides stationary all axis task Reference case for comparison with split axis range varying, and flight director cases.	Simulates a Category II manual ILS approach There is some turbulence Try to keep the glide slope and localizer needles centered at all times
D (Manual ILS, varying range)	All axis approach task with forcing functions and tracers on. The range varied throughout the run Glide slope deviation per unit altitude error increases with decreasing range No flight director	Provides nonstationary longitudinal task. Typical of "old fashioned" cross pointer ILS display	
E (Flight Director, fixed range)	All axis approach task with forcing functions and tracers on Flight director on, and driven by forcing function Same as Configuration C plus flight director	Provides equalized, integrated display and stationary all axis task Reference flight director case Typical of modern practice	Simulates a Category II FD approach There is some turbulence Use the Director to follow the approach path, keeping the glide slope and localizer needles centered Pitch commands must be obeyed immediately to avoid a standoff The glide slope and localizer needles must be monitored
F (Flight Director, varying range)	All axis approach task with forcing functions and tracers Flight director on Glide slope component of FD forcing function attenuated with range by flight director computer Same as E, except range varying	Provides equalized, integrated display but nonstationary forcing function	
Visual Breakout	All axis approach task with Configurations D or F, except that the ... system was used to provide an external visual field display at 200 ft above ground Pilot looked up when told by copilot/experimenter. Breakout occurred some time after the 100 sec run	Exploratory investigation of the feasibility of measuring both visual field and panel EPP Used with only a few runs at the end of the experimental program	Same as D or F, except that copilot calls out altitude and says runway in sight" when visual acquisition occurs

ORIGINAL PAGE IS OF POOR QUALITY

TABLE 3

AVERAGE SCANNING STATISTICS*

(From Ref. 1)

CONF	SUBJ	NO RUNS AVG.	N_1	$\bar T_{d_1}$	σ_{T_1}	$\bar T_{e_1}$	η_1	ν_1	N_2	$\bar T_{d_2}$	σ_{T_2}	$\bar T_{e_2}$	η_2	ν_2
			INSTRUMENT 1, IAS						INSTRUMENT 2, ATT OR ATT/FD					
B		2	18	.57	.18	.09	.011	.068	85	.67	.29	.446	.896	.537
B	1	1	2	.94	.09	.02	.013	.015	61	.82	.36	.607	.498	.462
		5	25	.69	.28	.05	.034	.042	238	.74	.33	.474	.353	.397
	2	5	1	.63	0	.002	.001	.002	254	.9	.35	.511	.463	.453
[illegible]		1	49	.69	.35	.085	.059	.066	282	.81	.38	.540	.32	.451
[illegible]	1	2	3	.98	.40	.015	.013	.013	85	1.00	.45	.423	.425	.357
E	1	4	44	[illegible]	.15	.110	.06	.115	111	1.73	1.72	.428	.739	.458
E	2	5	13	[illegible]	.11	.043	.023	.070	94	3.03	3.41	.276	.836	.494
F		5	53		.15	.177	.099	.163	147	1.50	1.56	.492	.757	.453
[illegible]	[illegible]		[illegible]	[illegible]	.10	.079	.035	.079	37	2.19	1.80	.366	.80	.487

CONF	SUBJ	NO RUNS AVG.	N_3	$\bar T_{d_3}$	σ_{T_3}	$\bar T_{e_3}$	η_3	ν_3	N_5	$\bar T_{d_5}$	σ_{T_5}	$\bar T_{e_5}$	η_5	ν_5
			INSTRUMENT 3, PALT						INSTRUMENT 5, HSI/GSD					
B		-	23	.38	.12	.115	.044	.087	111	1.08	.80	.557	.567	.481
B	[illegible]		2	.17	.04	.02	.011	.015	57	.78	.25	.567	.443	.432
[illegible]	[illegible]	4	40	.42	.16	.08	.034	.067	255	1.09	.72	.508	.551	.485
[illegible]	2	4	[illegible]	.41	.15	.01	.004	.009	242	.98	.40	.486	.476	.431
C	1	5	27	.4	.22	.054	.024	.041	265	.84	.43	.527	.444	.405
[illegible]	3	2	9	.44	.15	.045	.020	.038	96	.93	.51	.479	.443	.403
E		4	[illegible]	.4	.10	.28	.051	.131	76	.57	.80	.190	.109	.195
E	2	[illegible]	18	.50	.11	.059	.03	.097	41	.51	.12	.135	.069	.222
F		3	34	.35	.07	.113	.039	.105	59	.46	.13	.197	.090	.181
F	1		4	.34	.05	.04	.013	.053	27	.54	.45	.267	.145	.355

CONF	SUBJ	NO RUNS AVG.	N_6	$\bar T_{d_6}$	σ_{T_6}	$\bar T_{e_6}$	η_6	ν_6		N_N	$\sum \nu_i$	$\bar T_s$	
			INSTRUMENT 6, IVSI						ALL INSTRUMENTS				
B		4	10	.40	.14	.05	.020	.038		264	200	1.32	
B	[illegible]		1	.55	0	.01	.005	.008		152	101	1.31	
[illegible]		5	16	.38	.07	.038	.012	.027		600	502	1.19	
	[illegible]	[illegible]	2	.47	.23	.004	.002	.004		561	497	1.13	
	[illegible]	5	[illegible]	.40	.18	.010	.004	.008		694	503	1.30	
[illegible]	3	2	43	.45	.14	.214	.095	.181		238	200	1.19	
E		4	16	.44	.11	.04	.018	.041		390	400	.976	
E	2	5	14	.49	-	.046	.023	.076		185	505	.607	
	[illegible]	3	3	.35	.12	.033	.012	.031		385	300	1.08	
	3	1	1	.49	0	.01	.005	.013		76	101	.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_{ii}/ν_i with respect to unity. The largest value occurs for Instrument No. 2 (flight director/attitude indicator) for configuration .-2 for which:

$$q_{22}/\nu_{22} = 0.029/0.454 = 0.064 << 1$$

The next largest value of this ratio occurring in the data is less than 0.036.

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:

$$q_{ii} \equiv 0 \qquad i \in P \cup S \tag{1}$$

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:

$$\mathcal{P} = \lim_{N \to \infty} \frac{N_{ss}}{N_s} = \lim_{N \to \infty} \frac{\sum_{i \in S} \sum_{j \in S} N_{ij}}{\sum_{i \in S} \sum_{j \in PUS} N_{ij}} = \frac{\sum_{i \in S} \sum_{j \in S} q_{ij}}{\sum_{i \in S} \nu_i} \tag{2}$$

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 $1 - \sum_{i \in P} \nu_i$ in place of its theoretical equivalent, $\sum_{i \in S} \nu_i$. (See Eq. 6.)

TABLE 4

EXPERIMENTAL VALUES OF $(1 - \mathcal{P})$

CONFIGURATION-PILOT	$(1 - \mathcal{P})$
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 $(1 - \mathcal{P})$ 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:

$$q_{ij} \equiv 0 \qquad i,j \in S \tag{3}$$

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.

$$q_{ij} = \frac{\nu_i}{\sum\limits_{k \in S} \nu_k} \left(\sum_{k \in S} \nu_k \right) \frac{\nu_j}{1 - \sum\limits_{k \in S} \nu_k} = \frac{\nu_i \nu_j}{1 - \sum\limits_{k \in S} \nu_k} \tag{4}$$

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

Consider the intermediate expression for q_{ij}. $\sum_{k \in S} \nu_k$ is the probability that a transition is from the secondary instrument group to the primary instrument group. $\nu_i / \sum_{k \in S} \nu_k$ is the probability that a transition from the secondary instrument group originates from the ith secondary instrument. $\nu_j / (1 - \sum_{k \in S} \nu_k)$ is the probability that a transition to the primary instrument group terminates upon the jth 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.

$$q_{ij} = \frac{\nu_i}{1 - \sum\limits_{k \in S} \nu_k} \left(\sum_{k \in S} \nu_k \right) \frac{\nu_j}{\sum\limits_{k \in S} \nu_k} = \frac{\nu_i \nu_j}{1 - \sum\limits_{k \in S} \nu_k} \tag{5}$$

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

Consider the intermediate expression for q_{ij}. $\sum_{k \in S} \nu_k$ is the probability that a transition is from the primary instrument group to the secondary instrument group. $\nu_i / (1 - \sum_{k \in S} \nu_k)$ is the probability that a transition from a primary group instrument originates from the ith primary instrument. $\nu_j / \sum_{k \in S} \nu_k$ is the probability that a transition to the secondary instrument group terminates upon the jth secondary instrument.

If the q_{ij} are considered as elements of a matrix, it must also be true that the jth secondary instrument column elements must sum to the look fraction, ν_j. Similarly, the ith secondary instrument row elements must sum to ν_i. This leads directly to the requirement that:

$$\sum_{i \in P} \nu_i = 1 - \sum_{k \in S} \nu_k \tag{6}$$

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

$$\sum_{i \in P \cup S} \sum_{j \in P \cup S} q_{ij} \equiv 1 \tag{7}$$

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

$$\sum_{i \in P} \sum_{j \in P} q_{ij} = 1 - 2 \sum_{k \in S} \nu_k \tag{8}$$

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

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

$$q_{ij} = \frac{\nu_i}{1 - \sum_{k \in S} \nu_k} \left(1 - 2 \sum_{k \in S} \nu_k\right) \frac{\nu_j}{1 - \nu_i - \sum_{k \in S} \nu_k} \tag{9}$$

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

$\nu_i/(1 - \sum_{k \in S} \nu_k)$ is the probability that a transition from a primary group instrument originates from the ith primary instrument. $\nu_j/(1 - \nu_i - \sum_{k \in S} \nu_k)$ is the probability that the transition originating from the ith primary

instrument and terminating in the primary group, terminates upon the jth 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:

$$\nu_i = \frac{1 - \sum_{k \in S} \nu_k}{p} \qquad i \in P \tag{10}$$

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 $\nu_{(\ )}$ by the quantity $\bar{f}_{s(\ )}/\bar{f}_s$. 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:

$$q_{ii} = 0 \qquad i \in P \cup S \tag{11}$$

$$q_{ij} = \frac{\bar{f}_s - 2 \sum_{k \in S} \bar{f}_{s_k}}{p(p-1)\bar{f}_s} \qquad i \in P \cap j,\ j \in P \tag{12}$$

$$q_{ij} = 0 \qquad i,j \in S \tag{13}$$

$$q_{ij} = \frac{\bar{f}_{s_j}}{p\bar{f}_s} \qquad i \in P,\ j \in S \tag{14}$$

$$q_{ij} = \frac{\bar{f}_{s_i}}{p\bar{f}_s} \qquad i \in S,\ j \in P \tag{15}$$

COMPARISON OF LINK VALUE ESTIMATORS WITH EXPERIMENTAL DATA

The link value estimators given in Ref. 3 are:

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

$$i,j \in P \cup S;\ i \neq j$$

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 ... ng experimental values of the dwell fractions, η_i, for all instrumen ... e q_{ij} used for comparison pu poses will be computed using the experim ... alues of the fractions, ν_i, for the secondary instruments only. ... n values for ... onfiguration-pilot combinations C-1 and F-3 are given in ... 5 and 6, respectively. Numerical values for q_{ij} in these tables should ... ilar 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 e... ator, 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	ν_i
1	0	.019	0	0	.022	0	.041
2	.019	0	.031	.002	.363	.012	.427
3	0	.031	0	0	.034	0	.063
4	0	.002	0	0	0	0	.005
5	.022	.363	.034	.003	0	.014	.436
6	0	.012	0	0	.014	0	.026
							.988

b) Ref. 3 Link Value Estimator

	1	2	3	4	5	6	ν_i
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	.021
							.952

Format:

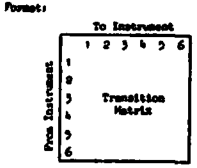


TABLE 6

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

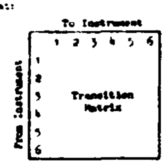
a) New Link Value Estimator

	1	2	3	4	5	6	
1	0	.077	0	0	0	0	[illegible]
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	.013
							.976

b) Ref. 3 Link Value Estimator

	1	2	3	4	5	6	ν_i
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	.015
							.988

Format:



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:

$$\nu_{FD} = \sum_{k \in S} \nu_k = 1/2 \tag{17}$$

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

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

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:

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

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.

REFERENCES

1. Weir, D. H., and R. H. Klein, The Measurement and Analysis of Pilot Scanning and Control Behavior During Simulated Instrument Approaches, NASA CR-1535, June 1970.

2. Clement W. F., L. G. Hofmann, and D. Graham, A Direct Procedure for Partitioning Scanning Workload in Control Display System Design, presented at the Ninth Annual Conf. on Manual Control, MIT, 23-25 May 1973.

3. McRuer, D. T., H. R Jex, W. F. Clement, and D. Graham, A Systems Analysis Theory for Displays in Manual Control, JANAIR/Systems Technology, Inc., Tech. Rept. 163-1, June 1968.

4. Clement, W. F., and L. G. Hofmann, A Systems Analysis of Manual Control Techniques and Display Arrangements for Instrument Landing Approaches in Helicopters. Vol. I: Speed and Height Regulation, JANAIR Rept. 690718 (Systems Technology, Inc., Tech. Rept. 183-1).

5. Milton, J. L., R. E. Jones, and P. M. Fitts, Eye Fixations of Aircraft Pilots: Frequency, Duration, and Sequence of Fixations When Flying the USAF Instrument Low Approach Systems (ILAS), USAF Tech. Rept. No. 5839, Oct 1949.

6. Milton, J. L., B. B. McIntosh, and E L. Cole, Eye Fixations of Aircraft Pilots: Fixations During Day and Night ILAS Approaches Using an Experimental Instrument Panel Arrangement, USAF Tech. Rept. 6570, Oct. 1951.

7. Watts, A. F. A., and H. C. Wiltshire, Investigation of Eye Movements of an Aircraft Pilot under Blind Approach Conditions, College Note No. 26, The College of Aeronautics, Cranfield Eng., May 1955.

8. Hofmann, L. G., and K. V. Smith, Re-Examination of Eye Scanning Data for Segments of Flight Director Runs, Systems Technology, Inc., Working Paper [illegible], 20 May 1971.