Visual Attention to Radar Displays

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Abstract

A model is described which predicts the allocation of attention to the features of a PPI radar display. It uses the growth of uncertainty and the probability of near collision to call the eye to a feature of the display. The main source of uncertainty is forgetting following a fixation, which is modelled as a two dimensional diffusion process. The model was used to predict information overload in intercept controllers, and preliminary validation obtained by recording eye movements of intercept controllers in simulated and live (practice) interception.

Introduction

The task of an intercept controller is to use the information displayed on a PPI radar to direct one or more fighters to the vicinity of one or more hostile aircraft. Because of the very low rates of change of the positions of ehcos at long radar range the kind of model for visual sampling which was proposed by Senders, et al. (1966) is inappropriate. The rate of generation of information (uncertainty) by the signal is slight compared with rate of generation of uncertainty by endgenous forgetting of the information acquired by fixations. The basic assumption of the model is therefore that the observer has an uncertainty threshold for his estimate of the position of the echos of aircraft, and when his uncertainty exceeds that threshold, he will again look at the echo (or other source of information) to reduce his uncertainty.

In order to model this process, we require an estimate of the rate of forgetting for radar-like information, and a model for its interaction with the operator's uncertainty threshold. A problem arises in how to validate such a model, since for a given interception there are many acceptable flight paths which will result in a successful interception. The model was therefore used not to predict the degree of success in completing an interception, but merely to predict the proportion of time spent in looking at different parts of the display, and statistics such as the mean first passage time for fixations.

Method

Two series of experiments were conducted. The first was to establish the form of the forgetting function. Intercept controllers were shown pictures of "radar-like" patterns for 10 seconds, (which was approximately the scan rate of the radar). The pictures consisted of one, two, or three small marks in a 8" diameter circle. The picture was removed, and the controller then was required to wait for a period from 3 seconds to thirty seconds. He was then shown a second, but blank, circle, and asked to mark the position(s) of the "echos". An estimate of the basic accuracy without forgetting was obtained by allowing the controller to mark the positions of echos on a blank circle while the stimulus was still visible, so that the only limitation on his accuracy was perceptual. Each operator performed the task for several different patterns, and several times for each pattern, at 5 recall delays, and with and without a map grid superimposed on the radar. Performance was measured in terms of the standard deviation of the estimate of the target position.

The second series of experiments consisted of recording the eye movements of interceptors while they conducted interceptions either in a simulator or with real aircraft. In the latter case, both aircraft were friendly but one played the role of intruder. The intruders did not take evasive action and no ECM were used. Data were collected from trainees and from experienced controllers, and on a variety of sorties. The data to be reported here are restricted to a series of simulated sorties in which a flight of 10 intruders approached, and were intercepted by 1-6 fighters. We were asked to predict which scenario would first lead to overload and a failure to complete interceptions.

The model was programmed in FORTRAN and run on a VAX computer.

Experiments on Forgetting

A summary of the results is shown in Figure 1. The latter shows forgetting curves for 1, 2, and 3 "echos", and for 3 "echos" with a superimposed reference grid. The results are pooled over all participants. The data from the several experiments are all described by the same equation,

$$sd(t) = a + b(t)^{3/2} \qquad \text{EQN (1)}$$

where $sd(t)$ is the standard deviation of the estimated position in millimetres after a recall delay of t seconds. All the data are well fitted by a value for $\underline{b}$ of 0.02. The constant $\underline{a}$ depends on the difficulty of the task, ranging from 8.25 for 1 echo to 11.0 for 3 echos, and falling 4.2 for 2 echos when a reference grid was provided.

It appears that forgetting proceeds at a constant rate independent of the complexity of the display, but that the uncertainty of the initial perceptual judgement is affected by complexity. The standard deviation when no memory was involved was 4.2 mm., so that approximately 86% of all estimates would fall within a circle 2 cm. in diameter, and 40% within a circle 1 cm. in diameter.

A Model for Visual Attention

Because new information appears only every ten seconds, and because the positions of the aircraft change only slightly each sweep on long range radar, we assume that most of the uncertainty is generated by forgetting. The effective bandwidth is too low for attention to be driven by the uncertainty in the display.

Assume that the observer makes an estimate of the position, course, and velocity of an echo, $\underline{x}$, at time t_0, and that thereafter he looks elsewhere. His uncertainty is represented by the s.d. of his estimate, and this increases with time,

$$U_x(t) = f(t)$$

where $\underline{t}$ is the time which has elapsed since x was fixated.

We make five assumptions.

1. For each source of information, $\underline{i}$, there is a threshold of uncertainty PTH_i. If this is exceeded due to forgetting (increasing $U_i(t)$) the observer will look back at $\underline{i}$ to reduce $U_i(t)$ to $U_i(t_0)$.

2. There is a PTH for all features of the display, each fighter, each intruder, and "console features" such as weather information, compass bearings, etc.

3. The value of PTH_i depends on the perceived value of the source of information as subjectively estimated by the controller.

4. Although the task of the controller is to bring aircraft into close proximity, (the "inverse Air Traffic Control" problem), it is not desirable to allow aircraft to approach too close for fear of collision. (This also applies to the relation of the fighter to any "strangers", that is aircraft not involved in the interception, which may be general aviation or commercial aircraft). We assume that the controller has a second threshold, CTH, which is related to the probability that two aircraft occupy the same position in air space. If CTH is exceeded, then he will look at both aircraft.

5. Following a pair of looks induced by CTH, PTH will be adjusted for each in such a way that PTH = a' + b'/exp(-d) where d is the separation of the aircraft. As the aircraft approach, the uncertainty threshold falls rapidly so that more attention will be paid to aircraft close to another.

The rate of forgetting was taken from the experiment described above.

The program provided a printout of the positions, courses, and speeds of each aircraft, the values of PTH and CTH, and the time since each source of information was last examined. If PTH or CTH called for a source of information to be examined, the source was flagged in the printout at the time it was examined. Importance values were tuned to some extent to improve the behaviour of the model.

Model outputs are shown in Tables 1 and 2. F1 - F4 are fighters, T1 - T4 are intruders. Other variables are "console variables". In Scenario 1, one fighter intercepted on intruder. In Scenario 2, two fighters intercepted two intruders, one fighter being launched thirty seconds after the other. In Scenario 3, three fighters (launched at 30 second intervals) intercepted three intruders. The tables give data for the early part of the sortie when the fighters were distant from the intruders, and also for the final minute as the interceptions were completed. "Console variables" model all sources of information other than aircraft which were fixated. "PTHs" for them were given typical values based on early empirical data.

From these data it is apparent that Scenario 3 is the first in which the mean first passage time rises substantially. The Scenario 3 MFPT, and the standard deviation are such that for a substantial proportion of the time more than 10 seconds will elapse between fixations. Looking back at Figure 1, it is after about 6 seconds that significant forgetting sets in, and we therefore predicted that overload would first occur at Scenario 3.

Note that in Scenario 2, a switch of attention is predicted. Early in the sortie, most attention is paid to two fighters, as they leave their base and begin the interception. Late in the sortie, Fighter 1 and Intruder 4 receive most attention as the interception is completed.

Experimental Data on Eye Movements

The same scenarios were programmed on the simulator at RAF Boulmer, and three controllers carried out the interceptions. They were given complete freedom to choose their own tactics. Their eye movements were recorded using a NAC eye mark recorder, modified to make its calibration more reliable. Summary data for these sorties are given in Tables 3,4 and 5. In these tables, the s.d. of the MFPT are the square root of the mean. As predicted, Scenario 3 is that in which MFPTs become unacceptably long. In fact, several interceptions failed, and one controller lost a fighter completely by flying it off the edge of the radar.

Switches of attention can be seen in Table 4. For example, in Scenario 2, two controllers showed strong bias early in the sortie but more equally distributed attention late in the sortie. In Scenario 3 Controller #1 shows a dramatic example of "cognitive tunnel vision".

Early in the sortie, there is a fairly uniform distribution of attention across the fighters, and a lower fairly uniform distribution over the intruders. Late in the sortie, 60% of attention is devoted to F2 and T2. The MFPT for these aircraft falls markedly and the fixation duration rises. We have seen even more dramatic examples of such "cognitive lockup" in real interceptions. In some cases, almost no attention is paid to anything except the two aircraft to the extent that they are allowed, for example, to wander into a civilian air traffic lane without the controller noticing. An example of such data is shown in Table 6 and 7. These are experienced controllers. Note the case of RHE who gives less than 10% of his attention to aircraft in the vicinity other than the interception. The model also shows this behaviour under certain conditions, particularly if the importance weighting function is inappropriately high.

General Comments

The model is a very rough first approximation, and no time was available for tuning it or for sensitivity analysis. It appears able to capture the general features of intercept controller attention, including switching attention, cognitive lockup, etc. The forgetting function seems to generate eye movement statistics of the right order of magnitude with little parameter twiddling.

The empirical data are of great interest, and show some very interesting features. They confirm the model's prediction that cognitive lock up can occur, and may reach levels which while sensible from the point of view of interception, may be hazardous to other aircraft. (It would be interesting to collect similar data on air traffic controllers). It is also interesting that fixation times are remarkably short. Taken with the MFPT, this means that within the 10-second period during which the antenna completes a rotation, each echo is examined as many times as possible, although no new information arrives. This suggest that controllers are very sensitive to forgetting and try to minimise forgetting by a repeated rapid superficial scan, rather than using an intense examination to minimise initial uncertainty which would result in a rise and fall of uncertainty over a large range.

More data are available through the author, and the eye movement recordings are lodged at RAF Farnborough, U.K. See also Moray, Richards and Low (1980) and Moray, Neil and Brophy (1983).

ACKNOWLEDGEMENTS

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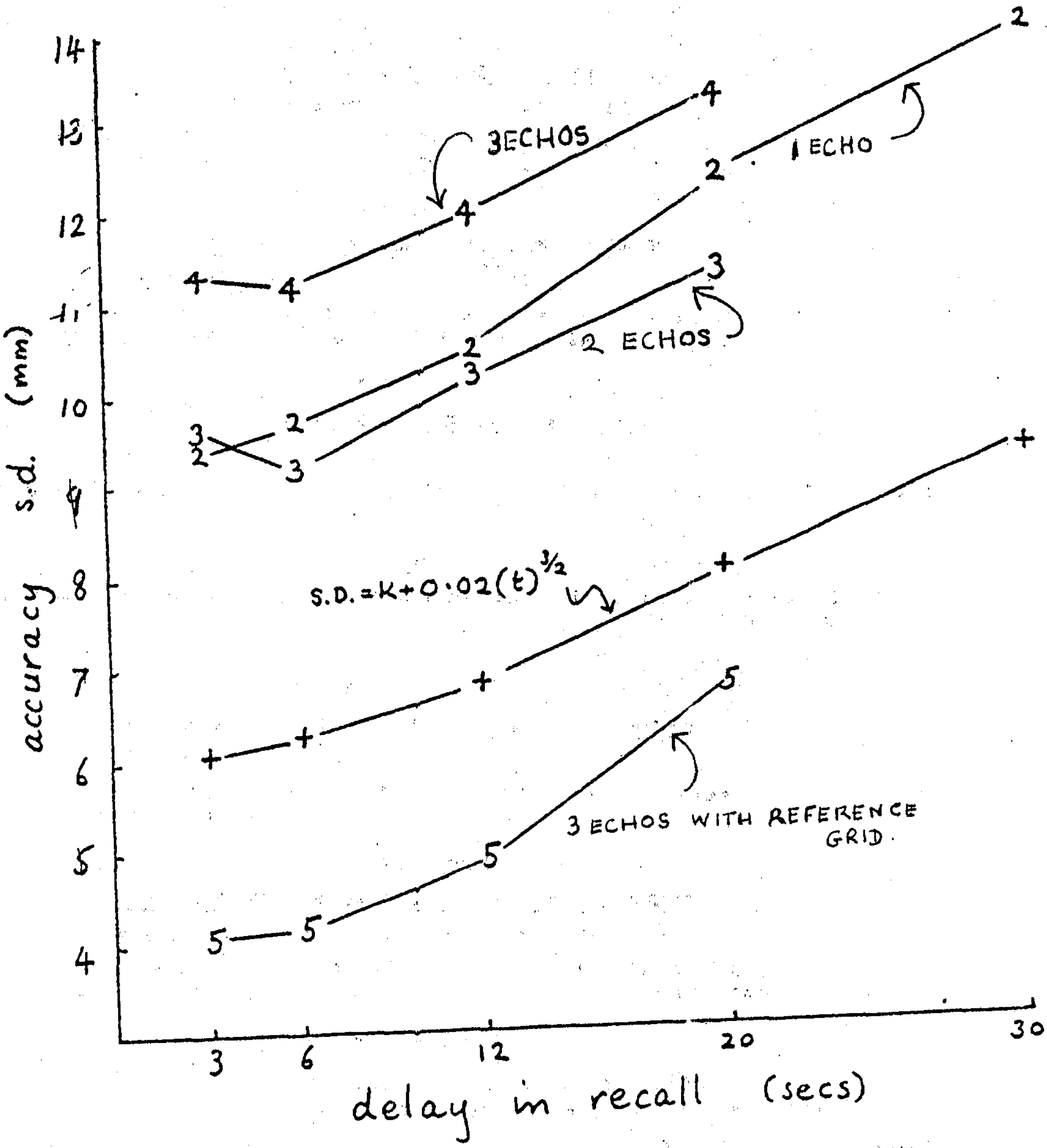

FIGURE 1

data pooled over all subjects

SCENARIO #1

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

	F1	T1	Console Variables			
EARLY	1.81	2.65	67.43	25.22	36.89	62.78
LATE	2.07	2.03	81.61	26.36	36.56	81.29

SCENARIO #2

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

	F1	F2	T1	T2	Console Variables			
EARLY	3.00	3.26	6.02	5.38	82.25	31.70	47.09	83.77
LATE	3.20	6.42	5.43	3.39	18.03	43.14	105.32	16.83

SCENARIO #3

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

	F1	F2	F3	F4	T1	T2	T3	T4	Console Variables			
EARLY	6.40	7.02	7.77	7.71	12.98	13.87	7.27	5.56	101.28	49.97	110.61	115.68

Table 1

Summary of Mean First Passage Times in Seconds for Eye Movements as Predicted by the Model.

SCENARIO #1

PROPORTION OF TIME SPENT ON SOURCES OF INFORMATION

	F1	T1	Console Variables			
EARLY	0.43	0.43	0.01	0.06	0.04	0.01
LATE	0.44	0.44	0.01	0.05	0.05	0.01

SCENARIO #2

PROPORTION OF TIME SPENT ON SOURCES OF INFORMATION

	F1	F2	T1	T2	Console Variables			
EARLY	0.30	0.30	0.15	0.15	0.01	0.04	0.04	0.01
LATE	0.24	0.16	0.18	0.26	0.06	0.03	0.02	0.06

SCENARIO #3

PROPORTION OF TIME SPENT ON SOURCES OF INFORMATION

	F1	F2	F3	F4	T1	T2	T3	T4	Console Variables			
EARLY	0.15	0.15	0.13	0.13	0.07	0.07	0.13	0.12	0.01	0.02	0.02	0.01

Table 2

Summary of Distribution of Attention as Predicted by Model

SCENARIO #1

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

		F	T	OL	CON	S	INFO	U
CONTROLLER #1	EARLY	2.37	1.09	3.50	24.08	7.50	---	---
	LATE	1.12	1.12	19.18	---	73.00	12.63	---
CONTROLLER #2	EARLY	1.64	2.00	1.31	---	---	---	79.39
	LATE	1.14	1.14	5.38	---	37.45	---	---
CONTROLLER #3	EARLY	1.77	0.85	5.65	61.02	60.69	---	---
	LATE	1.18	1.18	5.12	34.41	---	---	---
CONTROLLER #4	EARLY	1.14	1.15	---	---	42.08	---	22.81
	LATE	1.05	1.05	---	---	12.35	---	---

SCENARIO #2

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

		F1	F2	T1	T2	OL	S	U	INFO
CONTROLLER #1	EARLY	2.93	5.52	2.45	3.75	2.82	14.92	---	---
	LATE	1.92	2.63	1.93	2.64	13.06	---	---	101.53
CONTROLLER #2	EARLY	1.49	6.39	3.33	10.62	3.45	13.72	72.52	---
	LATE	2.93	2.54	2.62	2.52	3.09	40.72	---	---
CONTROLLER #3	EARLY	3.37	2.36	3.68	7.16	1.51	---	---	---
	LATE	2.82	1.87	2.82	1.82	---	---	---	---

SCENARIO #3

MEANS OF MEAN FIRST PASSAGE TIMES (SECONDS)

		F1	F2	F3	F4	T1	T2	T3	T4	OL	S
CONTROLLER #1	EARLY	5.48	4.73	4.25	4.17	39.61	9.56	8.74	19.81	2.66	72.09
	LATE	6.73	1.96	5.85	9.55	6.73	1.91	5.85	9.55	---	----
CONTROLLER #2	EARLY	6.58	4.70	4.43	6.72	6.55	4.70	4.43	6.22	3.74	---
	LATE	7.60	5.52	8.92	9.83	7.39	5.60	11.52	28.18	2.10	104.83
CONTROLLER #3	EARLY	4.48	5.64	3.02	6.79	4.54	70.38	4.22	18.16	3.90	---
	LATE	4.42	5.11	8.82	2.73	4.42	5.11	8.82	2.23	44.58	---

TABLE 3

SCENARIO #1

PROPORTION OF TIME SPENT ON FEATURES OF DISPLAY

		FIGHTER	TARGET	OL	CON	SEARCH	INFO	UNKNOWN
CONTROLLER #1	EARLY	0.19	0.49	0.22	0.02	0.07	--	--
	LATE	0.56	0.46	0.03	--	0.05	0.01	--
CONTROLLER #2	EARLY	0.30	0.27	0.42	--	--	--	0.01
	LATE	0.44	0.44	0.10	--	0.01	--	--
CONTROLLER #3	EARLY	0.34	0.52	0.13	0.01	0.01	--	--
	LATE	0.43	0.43	0.12	--	0.02	--	--
CONTROLLER #4	EARLY	0.55	0.40	0.02	--	--	--	0.03
	LATE	0.48	0.48	0.04	--	--	--	--

SCENARIO #2

PROPORTION OF TIME SPENT ON FEATURES OF DISPLAY

		F1	F2	T1	T2	OL	S	U	INFO
CONTROLLER #1	EARLY	0.18	0.13	0.22	0.13	0.29	0.05	--	--
	LATE	0.28	0.19	0.28	0.19	0.05	--	--	<0.01
CONTROLLER #2	EARLY	0.40	0.08	0.23	0.05	0.19	0.04	0.01	--
	LATE	0.18	0.20	0.21	0.21	0.18	0.01	--	--
CONTROLLER #3	EARLY	0.16	0.22	0.15	0.08	0.39	--	--	--
	LATE	0.20	0.30	0.20	0.30	--	--	--	--

SCENARIO #3

PROPORTION OF TIME SPENT ON FEATURES OF DISPLAY

		F1	F2	F3	F4	T1	T2	T3	T4	OL	S
CONTROLLER #1	EARLY	0.12	0.12	0.13	0.12	0.01	0.06	0.09	0.04	0.31	0.01
	LATE	0.07	0.30	0.08	0.05	0.07	0.30	0.08	0.05	--	--
CONTROLLER #2	EARLY	0.07	0.11	0.08	0.09	0.10	0.12	0.06	0.02	0.35	0.01
	LATE	0.09	0.12	0.12	0.09	0.09	0.12	0.12	0.19	0.15	--
CONTROLLER #3	EARLY	0.11	0.10	0.17	0.09	0.12	0.01	0.16	0.03	0.21	--
	LATE	0.14	0.10	0.06	0.20	0.14	0.10	0.06	0.20	0.01	--

TABLE 4

SCENARIO #1

FIXATION DURATIONS (SECONDS)

		F	T	OL	CON	S	INFO	U
CONTROLLER #1	EARLY	0.76	1.19	1.03	0.50	0.55	--	--
	LATE	0.93	0.93	0.62	--	0.66	0.50	--
CONTROLLER #2	EARLY	0.76	0.71	1.01	--	--	--	0.50
	LATE	0.91	0.91	0.62	--	0.50	--	--
CONTROLLER #3	EARLY	0.78	1.06	0.89	0.50	0.50	--	--
	LATE	0.90	0.90	0.68	--	0.53	--	--
CONTROLLER #4	EARLY	0.96	0.69	--	--	1.00	--	0.75
	LATE	0.96	0.96	--	--	0.54	--	--

SCENARIO #2

FIXATION DURATIONS (SECONDS)

		F1	F2	T1	T2	OL	S	U	INFO
CONTROLLER #1	EARLY	0.66	0.78	0.65	0.59	1.16	1.75	--	--
	LATE	0.72	0.66	0.72	0.66	0.64	--	--	0.50
CONTROLLER #2	EARLY	1.02	0.61	0.90	0.62	0.82	0.50	0.50	--
	LATE	0.64	0.62	0.71	0.68	0.68	0.50	--	--
CONTROLLER #3	EARLY	0.68	0.70	0.63	0.59	0.03	--	--	--
	LATE	0.76	0.79	0.71	0.79	--	--	--	--

SCENARIO #3

FIXATION DURATIONS (SECONDS)

		F1	F2	F3	F4	T1	T2	T3	T4	OL	S
CONTROLLER #1	EARLY	0.68	0.56	0.62	0.58	0.50	0.56	0.75	0.70	1.08	0.50
	LATE	0.50	0.78	0.52	0.50	0.50	0.78	0.52	0.50	--	--
CONTROLLER #2	EARLY	0.61	0.65	0.63	0.63	0.61	0.65	0.63	0.63	0.65	--
	LATE	0.54	0.64	0.71	0.85	0.68	0.64	0.80	0.50	0.95	0.50
CONTROLLER #3	EARLY	0.50	0.62	0.54	0.54	0.61	1.00	0.64	0.50	0.91	--
	LATE	0.67	0.60	0.52	0.67	0.67	0.60	0.52	0.67	0.62	--

TABLE 5

Controller	Early in Sortie			Late in Sortie		
	F	T	S	F	T	S
SBU(L)	3.12	2.71	6.04	1.79	1.41	19.03
SBU(L)	1.78	1.55	3.75	1.12	0.91	10.95
SBS(S)	1.45	1.75	1.81	1.12	1.18	2.45
RH(L)	1.45	2.25	4.55	1.29	1.60	4.32
RHE(S)	2.04	1.51	7.43	1.52	1.59	38.19
PH(S)	1.93	1.13	11.16	1.28	1.07	8.14
PH(L)	3.18	1.63	-	1.37	1.31	9.52
PH(L)	1.62	0.97	51.05	0.96	0.93	6.33
STH(S)	1.35	1.02	1.52	0.93	0.89	3.13

Table 6. MFPT for Fighter, Target and Stranger in Live and Simulator Sorties. Time in seconds.

Experienced Controllers

Controller	Early in Sortie			Late in Sortie		
	F	T	S	F	T	S
SBU(L)	21	25	11	39	43	3
SBU(L)	25	27	12	39	41	4
SBS(S)	31	25	25	34	33	18
RH(L)	33	26	12	35	28	12
RHE(S)	30	41	9	45	46	1
PH(S)	29	45	5	35	47	6
PH(L)	21	42	0	38	40	6
PH(L)	28	37	1	37	38	8
STH(S)	32	37	24	41	40	15

Table 7. Proportion of time spent on Fighter, Target, and Stranger, in Live (L) and Simulator (S) sorties.

Controller	Early in Sortie			Late in Sortie		
	F	T	S	F	T	S
SBU(L)	3.12	2.71	6.04	1.79	1.41	19.03
SBU(L)	1.78	1.55	3.75	1.12	0.91	10.95
SBS(S)	1.45	1.75	1.81	1.12	1.18	2.45
RH(L)	1.45	2.25	4.55	1.29	1.60	4.32
RHE(S)	2.04	1.51	7.43	1.52	1.59	38.19
PH(S)	1.93	1.13	11.16	1.28	1.07	8.14
PH(L)	3.18	1.63	-	1.37	1.31	9.52
PH(L)	1.62	0.97	51.05	0.96	0.93	6.33
STH(S)	1.35	1.02	1.52	0.93	0.89	3.13

Table 6. MFPT for Fighter, Target and Stranger in Live and Simulator Sorties. Time in seconds.

Experienced Controllers

Controller	Early in Sortie			Late in Sortie		
	F	T	S	F	T	S
SBU(L)	21	25	11	39	43	3
SBU(L)	25	27	12	39	41	4
SBS(S)	31	25	25	34	33	18
RH(L)	33	26	12	35	28	12
RHE(S)	30	41	9	45	46	1
PH(S)	29	45	5	35	47	6
PH(L)	21	42	0	38	40	6
PH(L)	28	37	1	37	38	8
STH(S)	32	37	24	41	40	15

Table 7. Proportion of time spent on Fighter, Target, and Stranger, in Live (L) and Simulator (S) sorties.