Naval Aerospace Medical Research Laboratory

NAMRL-1403

CALCULATING A HELICOPTER PILOT'S INSTRUMENT SCAN PATTERN FROM DISCRETE 60-HZ MEASURES OF THE LINE OF SIGHT: THE EVALUATION OF AN ALGORITHM

L. A. Temme, J. Woodall, and D. L. Still

Naval Aerospace Medical Research Laboratory
51 Hovey Road
Pensacola, Florida 32508-1046

Reviewed and approved 6/17/98

C. G. ARMSTRONG, CAPT, MSC USN
Commanding Officer

This research was sponsored by the Naval Medical Research and Development Command under work unit 0603706N M0096.001-7208.

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Volunteer subjects were recruited, evaluated, and employed in accordance with the procedures specified in the Department of Defense Directive 3216.2 and Secretary of the Navy Instruction 3900.39 series. These instructions are based upon voluntary informed consent and meet or exceed the provisions of prevailing national and international guidelines

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ABSTRACT

In order to obtain data to develop and evaluate theories relating instrument scanning to flight performance we recorded the line of sight (LOS) of student naval helicopter pilots as they flew prescribed maneuvers in a motion-based, high fidelity, instrument training simulator. These LOS data were discrete, 60 Hz samples of eye pointing. For some types of analysis it is helpful to think of a scan pattern as a sequence of fixations, and to use an averaging algorithm to transform the 60 Hz data into such a sequence, a scan path. An appropriate algorithm was identified, developed and evaluated. As part of this evaluation, we developed a String Similarity (SS) measure, a measure of the similarity between two scan paths. The evaluation of the algorithm, consisting of observing the algorithm's output as a function of the algorithm's parameter values, showed that the algorithm behaved in a sensible fashion, logically consistent with the input data. This increased our confidence in our implementation of the fixation algorithm. The SS metric proved to be an informative, useful tool that we expect to use in the analysis of scanning behavior and flight performance.

ACKNOWLEDGMENTS

I wish to thank Dr. John Kolen of the University of West Florida's Institute of Human and Machine Cognition for helpful discussions concerning string editing procedures , the Commanding Officers of the Training Wing and staff, including the Squadron Commanding Officers, Executive Officers, Training Officers, Project Officers, instructor and student pilot volunteers, Ensigns, the many contractual personnel, the generous fine individuals associated with NAWC/TSD, NAMRL professional, technical and support staff, and as always, the administrative assistants, especially Ms. Shirley Dasho, without whom, nothing gets done.

INTRODUCTION

A competent instrument pilot can control the aircraft using information obtained from flight instrument displays. In order to develop competence with these flight instruments, student naval helicopter pilots undergo flight training as prescribed by the curriculum of the Naval Air Training Command (1, 2). According to this curriculum, student naval helicopter pilots receive more than 7 hours of basic flight instrument training distributed over 6 flights in motion-based, instrument training simulators. These simulator flights are followed by a set of flights in the TH-57C helicopter. After these helicopter flights, students return to the simulators for an additional 8 simulator flights, during which radio instrument skills are developed. The Master Curriculum Guide specifies the maneuvers to be mastered during each of the basic instrument and radio instrument training flights (3).

Flight instrument competence requires mastery of several piloting skills, including the ability to scan the flight instruments appropriate to the specific maneuver and situation, the ability interpret this information and the ability to use this information to maintain situational awareness. Despite the crucial role that instrument scanning plays in instrument flight, objective, scientific information and data about instrument scanning under realistic conditions are rare. There are several reasons for this, including the cost and the logistical and technical difficulties of making objective recordings of instrument scanning in a sufficiently non-invasive or non-obtrusive fashion during the limited time aviators can reasonably be available for study. Although there is little objective information about instrument scanning behaviors of pilots, all pilots we have spoken to concerning instrument scanning have clearly expressed strong feelings and intuitions based upon their experiences and introspection. Indeed, Flight Training Instruction for the TH-57 Helicopter Advanced Phase (1) prescribes certain types of instrument scanning strategies to be used for specific maneuvers.

It remains an open question whether the impressions of pilots, their subjective opinions and intuitions concerning their instrument scanning, are correct, and if so, whether additional scientific, objective information may lead to the development of tools that enhance instrument scanning and the acquisition of instrument pilot competency. In order to address these questions we have developed the capability of recording the instrument scan patterns in an essentially non-invasive fashion using a commercial eye tracker (4). We installed this eye tracker into one of the motion-based, high fidelity, instrument training simulators used to train student naval helicopter pilots. This installation provides a computer record of the instrument scanning behaviors of pilots, as well as a concurrent record of the flight path executed by the pilot. With this instrumentation we have assembled a database to characterize instrument scanning behaviors, instrument flight performance and the relation between the two. The instrumentation has been described elsewhere (5, 6).

The eye tracker sampled the LOS of the eyes of the pilot at 60 Hz. Since a normal human eye is constantly moving, even when it is looking at something (7), we needed a method to decide either that the differences in successive LOS data points were consistent with the eye maintaining a relatively constant view of a specific location on the instrument panel, or that the eye was doing something else. From the literature we identified and implemented an algorithm (8, 9) that was designed specifically to use 60 Hz LOS data as input to calculate sequences of fixations and fixation durations. Although the word "fixation" has different connotative and denotative meanings for different user communities and situations, we use it here to refer to the computed output of the algorithm. Thus, a fixation: a) has a definite beginning and end determined by the start and stop criteria of the algorithm, b) has a definite duration determined from the number of LOS data points between the start and stop criteria, and c) is directed toward a location in the visual field computed from the average locations of the data points between the start and stop criteria. In the present context, the use of the word 'fixation' does not imply that the eye was looking at the same location for an inappropriate or abnormally long time.

The fixation algorithm was a data reduction stage converting a string of 60 Hz LOS input data to a sequence of fixations, each fixation summarizing a segment of the 60 Hz data. This sequence of computed fixations may be thought of as a scan pattern or path.

The present paper reports an evaluation of the behavior of the fixation algorithm. Specifically, we assessed the affects on fixations computed for the same input LOS data sets as we systematically varied the fixation starting criteria of the algorithm. This evaluation of the fixation algorithm was undertaken to ensure that our implementation of the algorithm was adequate and that the algorithm processed the data in a reasonable fashion.

We were particularly interested in determining how the changes in starting criteria impacted the computed sequence of fixations, the scan paths. The dependence of the computed scan paths on the algorithm is important since the scan path should reflect the instrument scanning of the pilot and should be minimally affected by specific values assigned to algorithmic parameters.

In order to evaluate the output of the algorithm we implemented way to measure the similarity between pairs of scan paths which are really pairs of strings of successive fixations on the flight instruments (10, 11). The problem of quantifying the similarity between scan paths belongs to a class of problems that has confronted a variety of research areas including molecular biology, computer science, ethnology, geology, and others, each area developing its solutions (12). Over the past 15 years there has been a growing recognition that these independent solutions are implementations of similar strategies to solve similar problems and these have been classed together under the general topic of string editing issues (12).

The most common approach to measuring the similarity between two strings of events, such as a sequence pair of DNA macromolecules, or a pair of flight instrument scan patterns, is by noting the (usually minimum) number of operations required to convert one string of the pair into the other. The operations are simple and well defined and usually include the insertion of an element, the deletion of an element, and the replacement of one element by another. We implemented a string editing procedure based on an algorithm that computes the shortest sequence of replacement, insertion and deletion operations to convert one file string to another (14).

Following Stark and his colleagues (11) , we used the string editing technique to develop a measure of the similarity between pairs of scan paths. The present paper reports our use of String Similarity (SS) to measure the similarity between scan paths generated by the fixation algorithm from the same set of input data. This is the first use of string editing techniques to be applied to flight instrument scan patterns.

METHODS

Data: The data for each test subject consisted of a string of 1000 consecutive LOS data points (DPs) with each DP being of an x-y coordinate pair identifying a pixel location on the instrument panel. Since the string of LOS DPs was obtained at a 60-Hz sampling rate, the string of 1000 DPs is a segment of nearly 16 seconds duration. Data from 5 student helicopter pilots were used for the present evaluation of the algorithm. These data were selected on no other basis than they were most readily at hand at the beginning of the present analysis; the data had just been collected and were being archived at that time. Thus, these data are not a random sample, but they are most likely representative.

Instrument Panel Layout: The region of the instrument panel containing the flight instruments that the student pilot monitors and over which the LOS data are collected, was bitmaped into a Cartesian coordinate space of 512 by 256 pixels. A computer rendering of this bitmaped instrument panel, Figure 1, details the pixel dimensions of each gauge.

Although there is space between the instruments, our current analysis ignores this; boundaries were drawn midway between the instruments, to define regions around each instrument. A LOS DP was considered to be toward that instrument when the DP fell within the region, even though the LOS DP was on the instrument panel rather than on the instrument proper. The eye was about 27 inches from the instrument panel; but this is clearly only a very rough approximation since, even if a pilot's head is stabilized and left/right centered, it invariably was above the panel, so the LOS is not normal to the panel.

Apparatus: The eye tracking, flight simulator, data collection and data logging apparatus have been described elsewhere (5,6).

The Fixation Algorithm: The fixation algorithm starts at the beginning of the LOS data string and searches for 6 successive DPs, all of which remain within a spatial extent specified by the value of a parameter, called the Start Criterion (SC). Specifically, the algorithm has a averaging window 6 pixels wide and calculates the standard deviation of the x-y locations of the 6 DPs in the window. If the calculated standard deviation exceeds the SC, the window is shifted down the data string by one DP and the standard deviation is calculated with the new set of 6 data points. This procedure is repeated until the SD of the X and the Y values for 6 successive data points are less than or equal to the SC.

The algorithm then calculates the average X and Y coordinates for these 6 data points, selects the next DP in the string and compares the coordinates of this DP to inclusion/exclusion criteria established by the algorithm. If the DP meets the inclusion/exclusion criteria, the coordinates of the DP are noted and the next DP is tested. This process is repeated until the criterion that closes the fixation is met; i.e., the x-y coordinates of a sufficient number of DPs exceed dimensions set by the inclusion criteria. When this happens, the fixation is closed and the algorithm calculates the x-y coordinates of the fixation as the average of all the DPs that have met the tests for inclusion into that fixation. The duration of the fixation is also calculated. The algorithm then steps through the LOS data string testing for the beginning of the next fixation as determined by the SC.

For the present analysis, we evaluated the algorithm output as a function of SC values. These SC values ranged from 3 to 9 pixels horizontally, which correspond respectively to approximately 15- 45 minutes of arc horizontally. The sizes of the off-horizontal pixels were scaled proportionally.

Metrics: The output of the fixation algorithm was a string of fixations, or a scan path, consisting of a string of X, Y coordinate pairs indicating where on the instrument panel the eye was looking and the calculated duration of each look. From this string of fixations several dependent variables were calculated: (1) the number of output fixations calculated by the algorithm, (2) the number of DPs that were used to calculate fixations and the number that were excluded from the calculations, (3) the fixation duration, (4) the number of DPs that were allocated to fixations on different instruments, and (5) the or SS metric.

The calculation of SS is illustrated in Figure 2. Two strings of fixation sequences are presented, one as the Original (O) and the other as the Target (T). String T has 14 elements and String O 15 elements; note that the strings do not need to be the same length to measure SS. String O can be changed to String T with

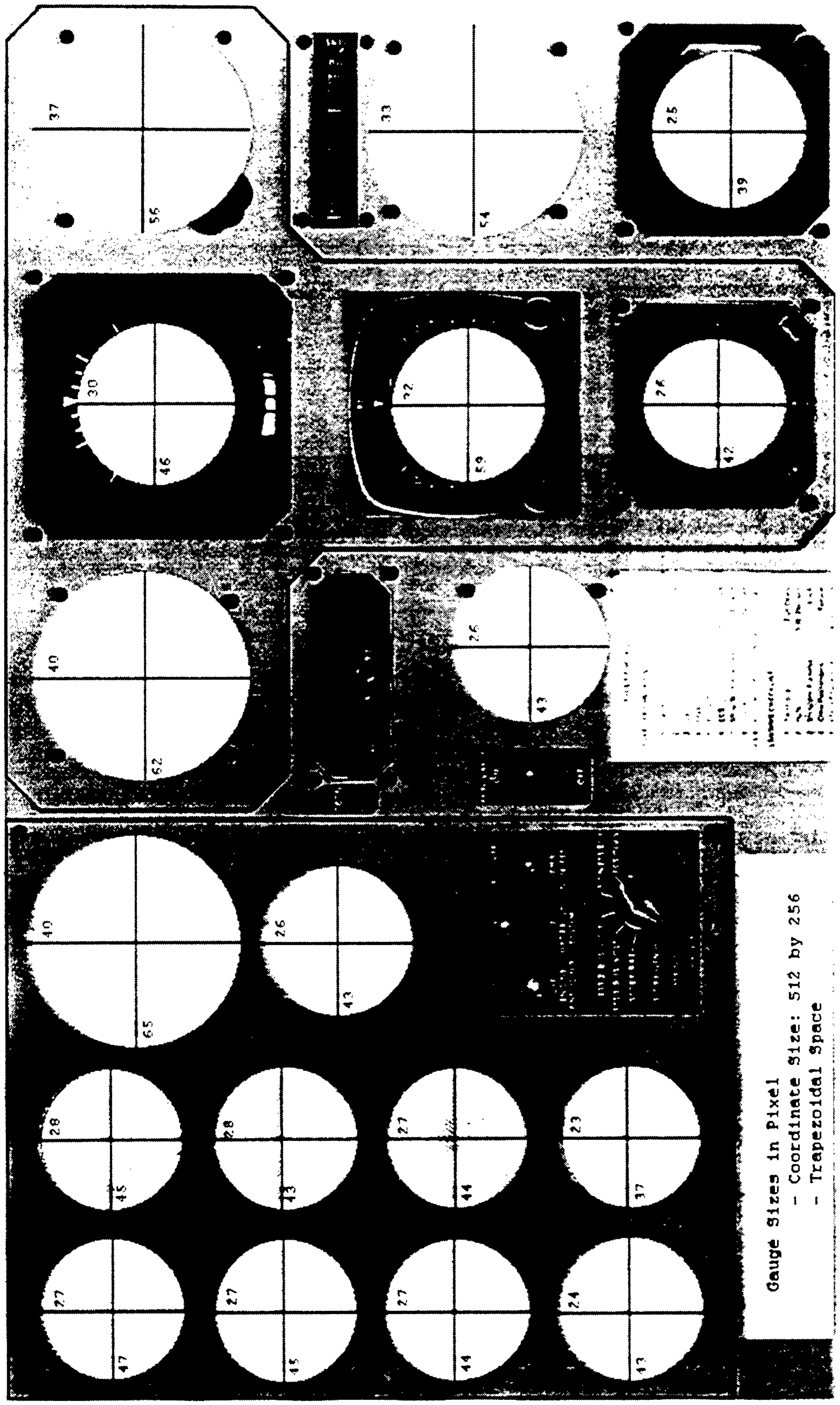
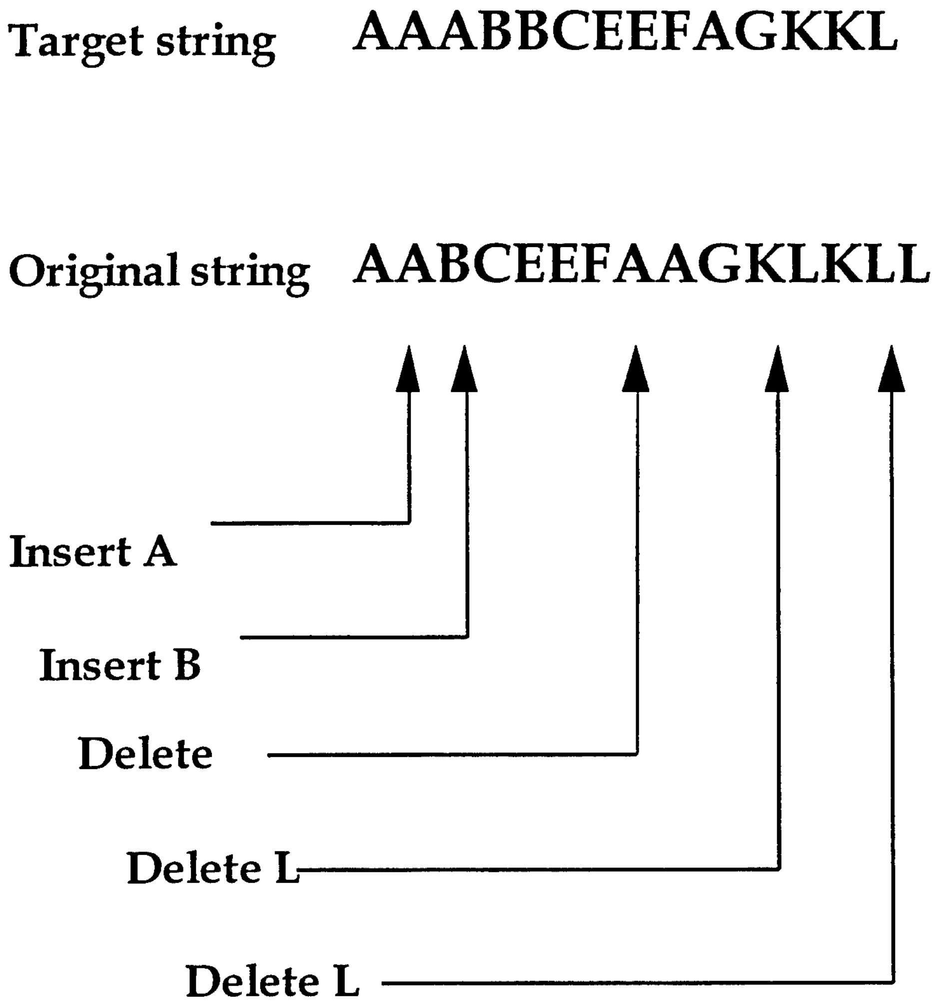


Figure 1. Gauge Sizes in Pixels

2 insertion and 3 deletion operations, a total of 5 operations; a sum that is divided by the total number of elements in String T, 14. This ratio is subtracted from 1, to produce a positive number that ranges from 0 to 1 and which reflects the number of operations (proportional to string length) needed to convert one string to the other. It should be noted that, because the number of operations is normalized to the number of elements in the T string, the SS between two strings of unequal length depends upon which string is identified as the T string and which the O string; thus in our implementation, we identify the O and the T strings.



Target string length = 14 elements
Original string length = 15 elements
5 operations
String Similarity (SS) = 1 - 5/14 = 0.643

Figure 2. Illustration of the calculation of String Similarity

TABLE I

		SC=3	SC=4	SC=5	SC=6	SC=7	SC=8	SC=9
0	1111111111	+	+	+	+	+	+	+
1	1	+	+	+	+	+	+	+
2	1	+	+	+	+	+	+	+
3	1	+	+	+	+	+	{ RMI RMI }	{ RMI RMI }
4	1	+	+	+	{ RMI RMI }	{ RMI RMI }	RMI RMI	RMI RMI
5	1	+	{ RMI RMI }	{ RMI RMI }	RMI RMI	RMI RMI	RMI RMI	RMI RMI
6	1	+	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI
7	1	+	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI
8	1	+	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI
9	1	+	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI	RMI RMI
10	1	+	{ RMI RMI }	{ RMI RMI }	{ RMI RMI }	{ RMI RMI }	{ RMI RMI }	{ RMI RMI }
11	1	+	+	+	+	+	+	+
12	1	+	+	+	+	+	+	+
13	1	+	+	+	+	+	+	+
14	1	+	+	+	+	+	{ HSIHSI }	{ HSIHSI }
15	1	+	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI
16	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
17	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
18	1	+	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
19	1	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
20	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
21	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
22	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
23	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
24	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }
25	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }
26	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
27	1	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI
28	1	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI
29	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
30	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
31	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
32	1	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
33	1	+	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
34	1	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
35	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }
36	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	{ HSIHSI }	{ HSIHSI }
37	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
38	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
39	1	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
40	1	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
41	1	+	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }
42	1	+	+	+	+	+	+	+
43	1	+	+	+	+	+	+	+
44	1	+	+	+	+	+	+	+
45	1	+	+	+	+	+	+	+
46	1	+	+	+	+	+	+	+
47	1	+	+	+	+	+	{ HSIHSI }	{ HSIHSI }
48	1	+	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI
49	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
50	1111111111	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
51	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
52	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
53	1	+	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
54	1	+	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }
55	1	+	+	+	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }
56	1	+	+	{ HSIHSI }	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI
57	1	+	{ HSIHSI }	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
58	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
59	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
60	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
61	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
62	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
63	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
64	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
65	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
66	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
67	1	+	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI	HSIHSI
68	1	+	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }	{ HSIHSI }
69	1	+	+	+	+	+	+	+
70	1	+	+	+	+	+	+	+
71	1	+	+	+	+	+	+	+
72	1	+	+	+	+	+	+	+
73	1	+	+	+	+	+	+	+
74	1	+	+	+	+	+	+	+
75	1	+	+	+	+	+	{ AG }	{ AG }
76	1	+	+	{ AG }	{ AG }	{ AG }	AG	AG
77	1	{ AG }	{ AG }	AG	AG	AG	AG	AG
78	1	AG	AG	AG	AG	AG	AG	AG
79	1	AG	AG	AG	AG	AG	AG	AG
80	1	AG	AG	AG	AG	AG	AG	AG
81	1	AG	AG	AG	AG	AG	AG	AG
82	1	AG	AG	AG	AG	AG	AG	AG
83	1	AG	AG	AG	AG	AG	AG	AG
84	1	AG	AG	AG	AG	AG	AG	AG
85	1	AG	AG	AG	AG	AG	AG	AG
86	1	AG	AG	AG	AG	AG	AG	AG
87	1	AG	AG	AG	AG	AG	AG	AG
88	1	AG	AG	AG	AG	AG	AG	AG
89	1	AG	AG	AG	AG	AG	AG	AG
90	1	AG	AG	AG	AG	AG	AG	AG
91	1	AG	AG	AG	AG	AG	AG	AG
92	1	AG	AG	AG	AG	AG	AG	AG
93	1	AG	AG	AG	AG	AG	AG	AG
94	1	AG	AG	AG	AG	AG	AG	AG
95	1	AG	AG	AG	AG	AG	AG	AG
96	1	AG	AG	AG	AG	AG	AG	AG
97	1	AG	AG	AG	AG	AG	AG	AG
98	1	AG	AG	AG	AG	AG	AG	AG
99	1	AG	AG	AG	AG	AG	AG	AG

RESULTS

Table I is a sample of a spreadsheet we designed to visualize the effects of the fixation algorithm on the LOS data. Table I contains only the first 100 of the 1000 DPs from Subject S-71. The first column of the spreadsheet numbers the DPs starting with 0. The second column contains tick marks with the string "1111111111" entered at every fiftieth DP and a "1" for all the intervening DPs. The remaining seven columns identify the fixations calculated by the algorithm when the SC assumed the value listed at the top of each column. The column entries identify the beginning and end of each fixation that the algorithm calculated, as well as the flight instrument the algorithm concluded the subject had viewed during that fixation.

For example, column 3 lists the fixations calculated by the algorithm with SC = 3. The + entered for DP 0 through DP 18 indicates that the algorithm concluded that these DPs did not meet the start criteria defined by SC = 3; that is, the standard deviation of 6 consecutive DPs exceeded 3 pixels.

The algorithm computed the first fixation to begin with DP 19. This fixation was toward the Horizontal Situation Indicator (HSI) identified in the table as HSIHSI. All the consecutive DPs from 19 to 32, inclusively, were considered to belong to this fixation. The brackets around cell entry identify the first and last DPs of a fixation; thus the table shows that this fixation was 14 DPs long and, since each DP represents an interval of approximately 16.67 ms, the duration of this fixation was about 238 ms (14 X 16.67 ms.).

The + entered for DP 33 indicates that the algorithm did not assign this DP to a fixation; it fell between the closing criteria of the one fixation and the opening criteria of the subsequent fixation, which began with DP 34. This was a refixation to the HSI which terminated with DP 40, a fixation of about 117 ms (7 X 16.67 ms) duration. Thus, the fixation algorithm produced scan paths that included successive fixations onto the same flight instrument.

Data prints 41 through 76 did not meet the start criteria of a fixation; in other words, the standard deviation of every group of 6 consecutive DPs in all 41-76 exceeded 3 pixels. Thus, they were excluded from fixations, as indicated in the table by the string of plus signs.

The next fixation began with DP 77 and continued beyond DP 99. This fixation was toward the Attitude Gyro, identified in the table as AG. Thus, with SC =3, of the first 100 DPs 44 were grouped into 3 fixations and 56 DPs were not assigned to any fixations.

With SC = 4, illustrated in the next column of the table, the algorithm considered the first fixation to start with DP 5 and end with DP 10. This fixation was to the Radio Magnetic Indicator, identified in the table as RMI RMI. This fixation was followed by a string of DPs that were not assigned to any fixation. The second fixation began with DP 18 and ended with DP 32, as indicated by the brackets around the HSIHIS entered for that DP's cell. The brackets around the HSIHIS for DP 33 indicates that this began the next fixation, which was a refixation on the HSI which ended with DP 40.

None of the DPs from 41 through 56 met the criteria to begin a fixation; but DP 57 began a fixation to the HSI that continued through DP 68. DPs from 69 through 76 did not form a fixation; DP 77 began a fixation toward the Attitude Gyro that extended beyond DP 99.

The differences between the fixation sequences calculated by the algorithm when SC = 3 and SC = 4 are understandable when it is remembered that the larger the value SC assumed, the more loose was the algorithm's criteria for starting a fixation. Data with greater variability met the looser starting criteria, thus fixations could begin earlier with the larger SC values, DP 18 versus DP 19 and DP 33 versus DP 34. Furthermore, with the looser criteria, the algorithm identified fixations where none had been found with the stricter SC criteria; the fixations with DP 5 through DP 10 and DP 57 to DP 68.

The increase in SC values from 4 through 9 successively relaxed the start criteria of a fixation so that the first fixation began earlier, DP 5 with SC = 4 and 5; and DP 3 with SC = 8 and 9.

Even though the SC value directly controlled only the beginning of the fixation, it indirectly affected the closing of the fixation. For example, DP 15 initiated the fixation on the HSI with SC = 5 and 6, whereas DP 18 initiated the HSI fixation with SC = 4. Although the rules to close the fixation were not changed by the changes in SC, different DPs, with different x-y locations, marked the beginning of the fixation. These different DPs established a different location for the algorithm to evaluate its closing criteria. Fixations computed with SC = 5 and 6 included DPs that were not included with SC = 4. Thus the closing criteria were satisfied with different DPs. When fixations closed with different DPs, the sequence of fixations calculated from the same LOS DPs fell out of register. For SC values of 5, 6, and 7, DP 41 closed the second successive fixation onto the HSI whereas with SC values of 8 and 9 this same DP, 41, closed the third successive fixation onto the HSI.

TABLE II

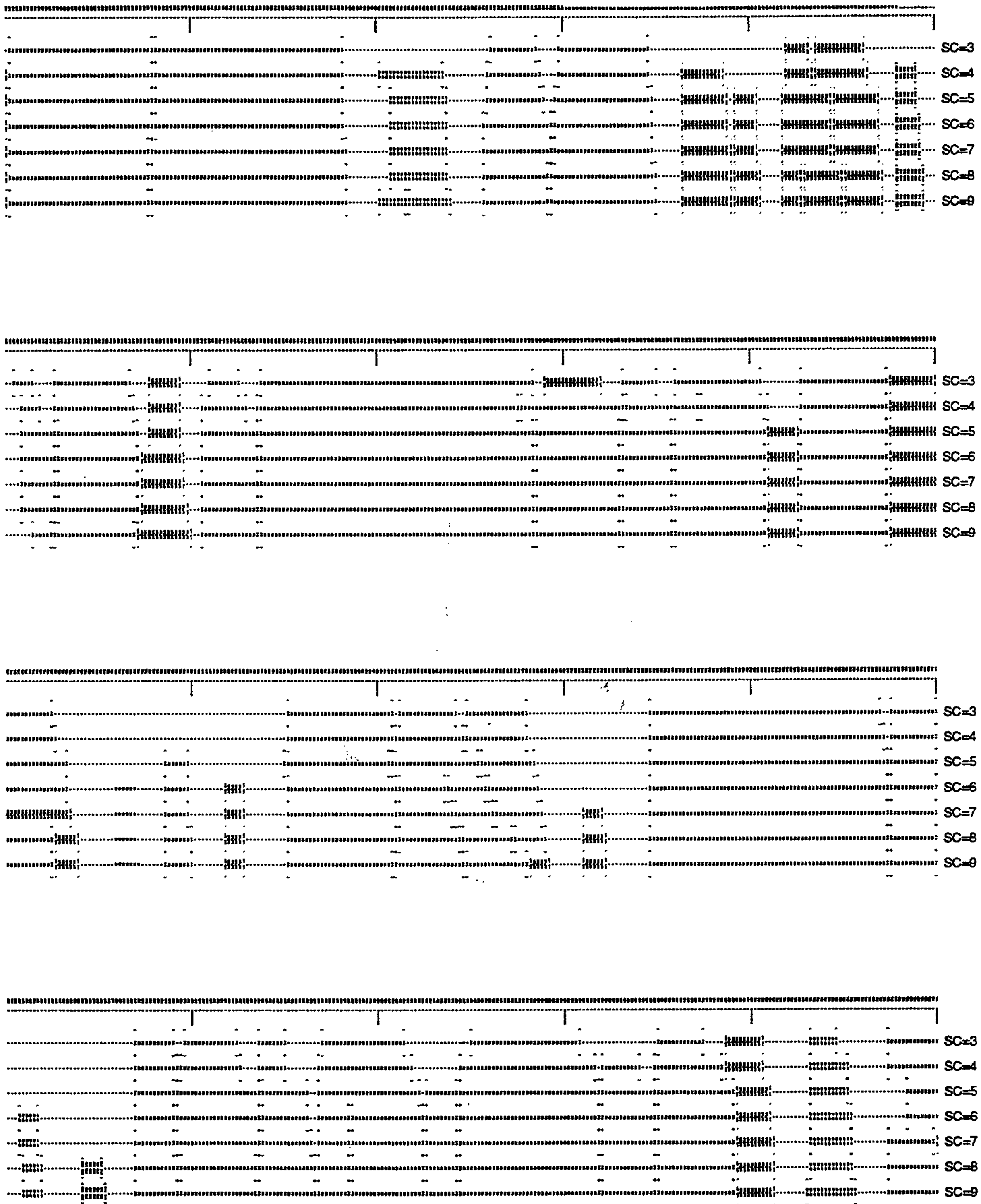

SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9

TABLE III

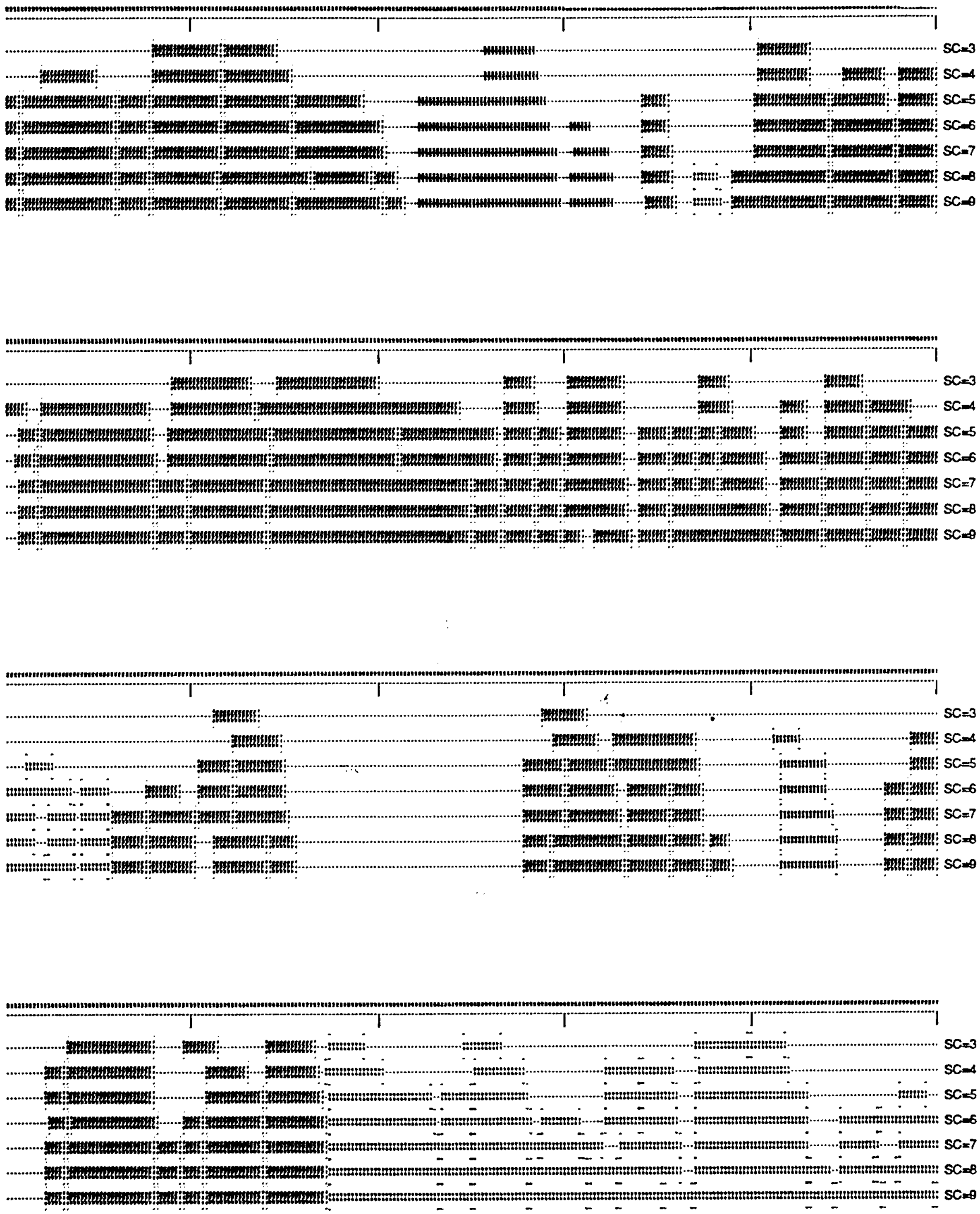
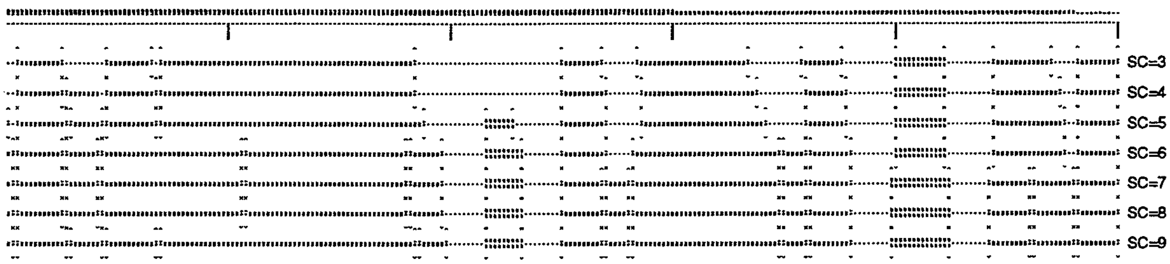

SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9

TABLE IV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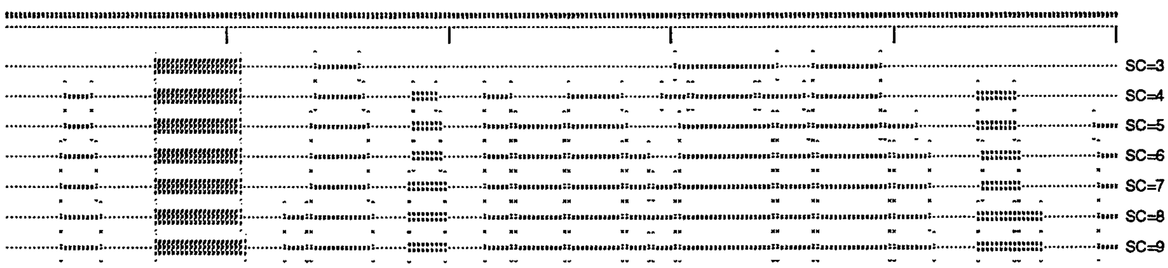
SC=8
SC=9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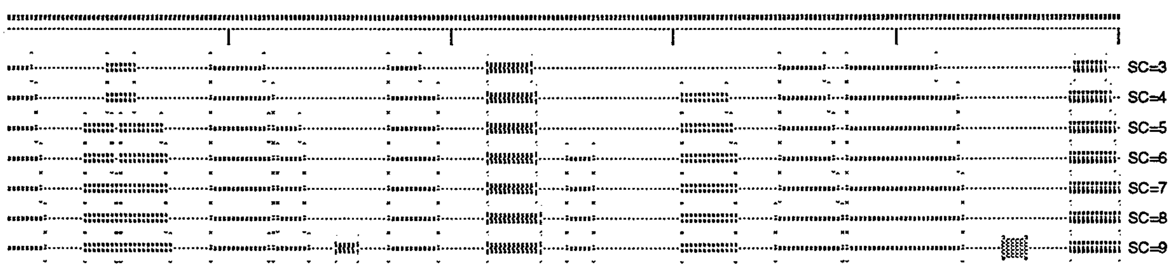
SC=9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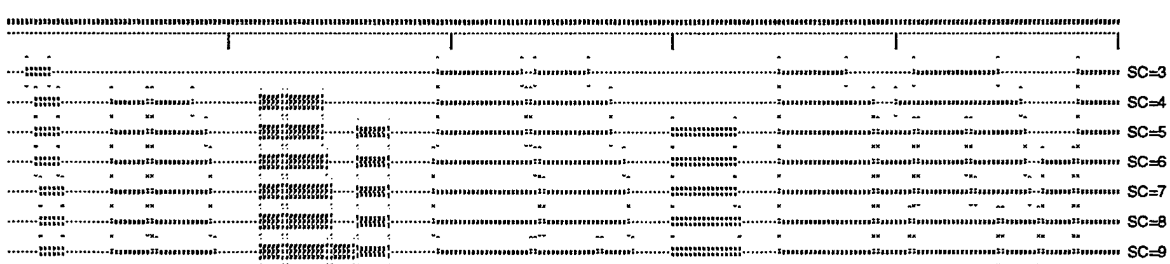
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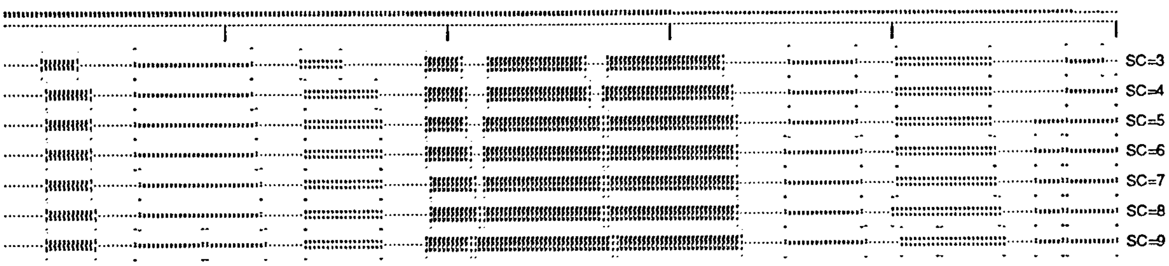
TABLE V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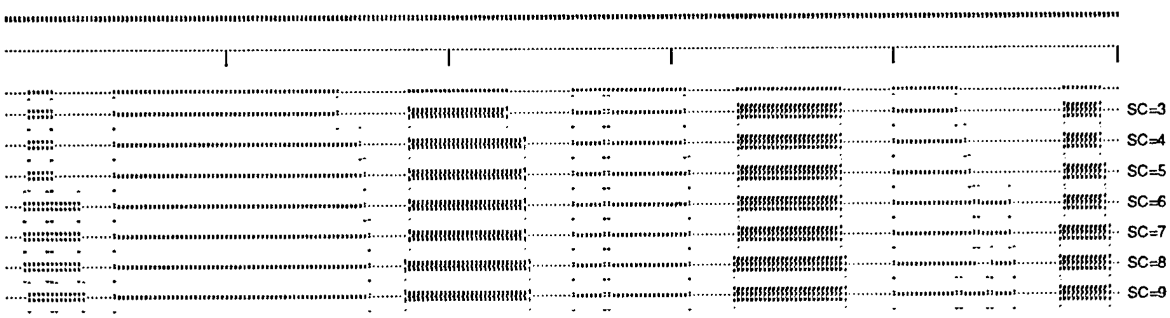
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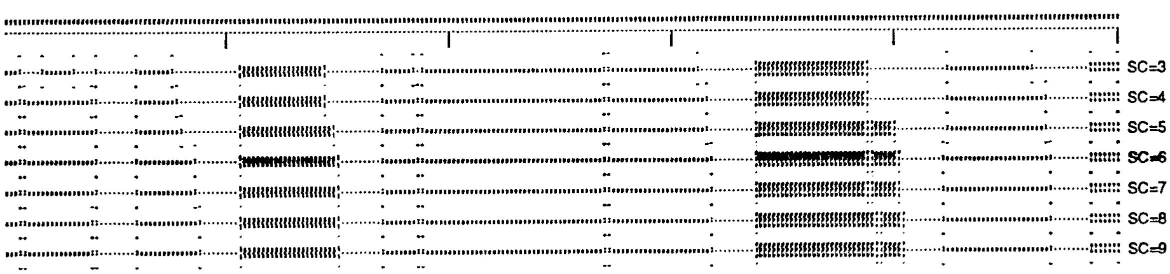
SC=9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SC=9

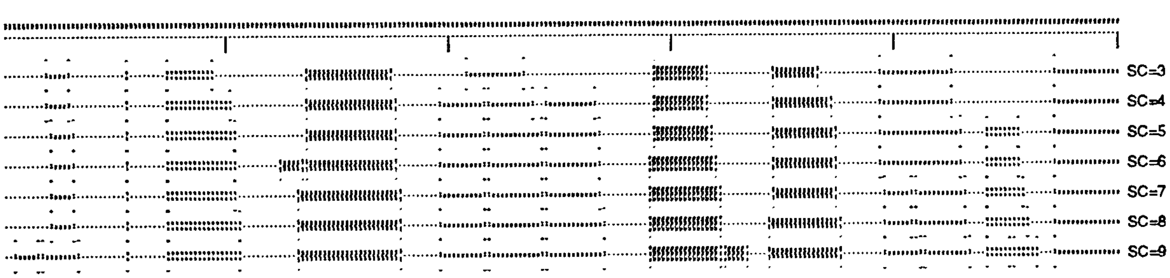
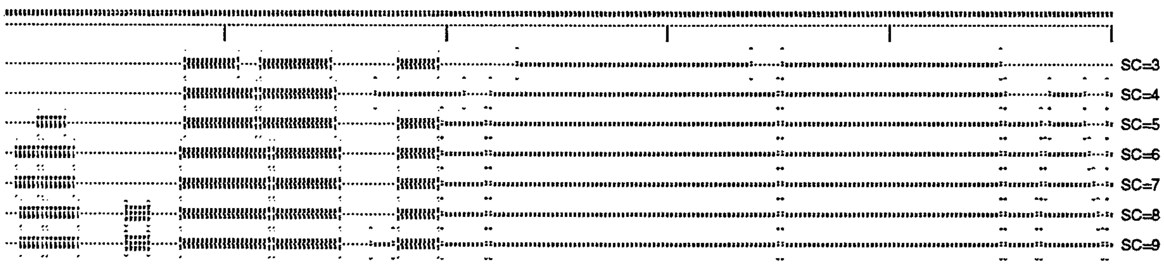

SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9

TABLE VI


SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9


SC=3
SC=4
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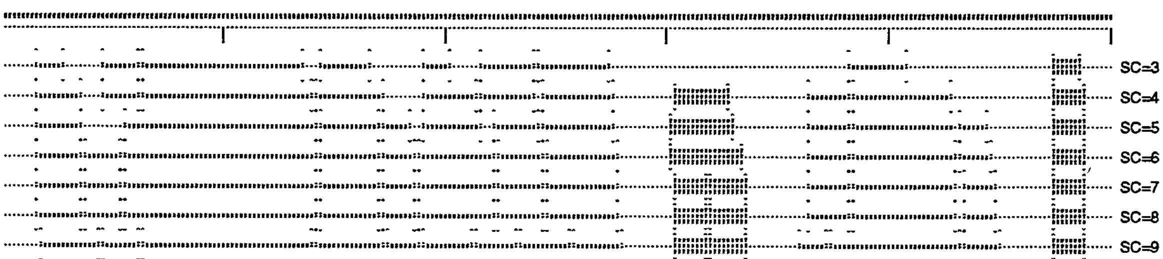
SC=7
SC=8
SC=9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SC=5
SC=6
SC=7
SC=8
SC=9

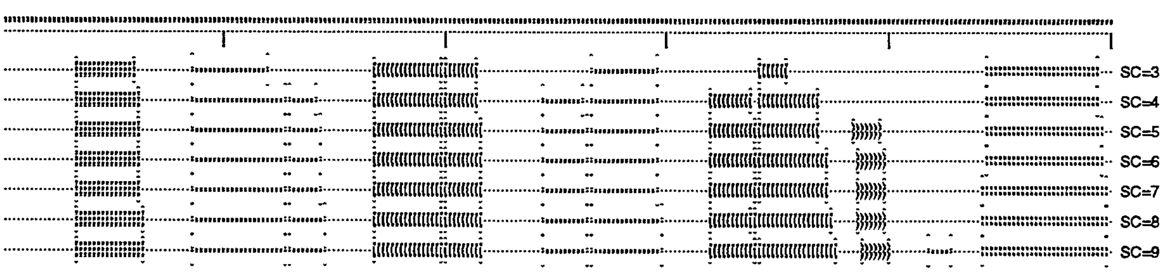
SC=3
SC=4
SC=5
SC=6
SC=7
SC=8
SC=9

Table II is a chart containing all 1000 DPs for S 71, including those presented in Table I, on a greatly reduced scale. Table II contains four groups of 9 columns each. The first group of columns includes the material of Table I and extends it through to DP 249. On this scale, identifying a DP's approximate number is possible with the tick marks in the second column, the long tick mark indicating every 50th DP. The second group of 9 columns displays DPs 250 through 499, the third group of columns DPs 500 through 749 and the fourth group DPs 750 through 999.

Obviously, the great reduction in scale makes it impossible to read alphanumeric entries in the table; but the scale reduction causes the identifiers coding the different flight instruments to have distinguishable shapes. Thus, from Table II it is possible to appreciate, for the different SC values, where fixations began and ended, the relative durations of fixations, whether the same DPs were allocated to fixations toward the same or toward different instruments, the relative number of fixations and the relative number of DPs excluded from any fixation.

One of our major concerns was that the algorithm would assign the same DP to different instruments depending upon the value of SC. Table II demonstrated that, for these data, the algorithm was consistent in its assignment of DPs to instruments. The overwhelming number of DPs were either allocated to a fixation onto same instrument or the DP was excluded from any fixation. Specifically, of the 1000 DPs, 41 were allocated to different instruments by the algorithm, depending upon SC value. These differences invariably occurred with strings of DPs. An example can be seen in the second group of columns in the Table II, around DP 350. With SC = 3 a string of DPs (340-355) formed a fixation toward the HSI; whereas with SC = 4 through 9 these same DPs were incorporated into an ongoing fixation to the AG. What happened in this case was that the algorithm, for all SC values, closed the previous fixation (onto the AG) with the same DP, 334. With SC values from 4 through 9 the algorithm immediately opened a re-fixation onto the AG with DP 335. However, with the more restrictive fixation start criteria of SC = 3, the fixation did not begin until DP 340, 5 DPs later. When this fixation did begin, the algorithm calculated the fixation to be toward the HSI. Thus with SC = 3 the algorithm determined that the string of 16 DPs from 340 through 355 were directed toward the HSI; whereas with SC = 4 to 9 these same DPs were incorporated in the ongoing fixation toward the AG. Figure 1 shows that the AG is right above the HSI on the instrument panel.

A similar situation can be seen to have occurred about middle of the third set of columns, DPs 604 - 609. With the SC=9, these 6 DPs were allocated to a fixation toward the HSI, whereas with the other SC = 3 - 8 these 6 DPs were either excluded from a fixation (SC = 3, 4) or were incorporated into a fixation toward the AG (SC = 5, 6, 7). What happened in this situation was that DP 604 met the most relaxed start criteria (SC = 9), and this fixation continued until its end criterion was met with DP 609. However, the more rigorous starting criteria were satisfied with DPs subsequent to 605 and these were incorporated in fixations to the AG.

The other DPs that were assigned to different instruments were the 18 between DP 733 through 750. Again, the difference occurred because the algorithm began the fixations with different DPs, thus the closing criteria were compared against a different average location. The allocation of DPs to different instruments was limited to a string of consecutive DPs and was again confined to a confusion between the HSI and the AG.

The one remaining DP, 295 ends fixations on the HSI when SC = 5 through 9 but begins fixation on the AG when SC = 4, and is not included in any fixation when SC = 3.

Tables III, IV V and VI show the complete 1000 DP spreadsheets for the subjects 75, 79, 83 and 85, respectively, in a format identical to Table II. The patterns coding the identity of the various flight instruments were consistent across these Tables, although the specific identities of instruments and the sequences of fixations are not relevant for the purposes of the present paper.

A careful inspection of these datasets showed that for the different SC value there were no DPs assigned to different instruments for S 75, S 79, and S 83. For S 85, the string of 10 DPs from 402 to 411 were allocated to the AG with the SC value of 4, or to the HSI when SC assumed other values.

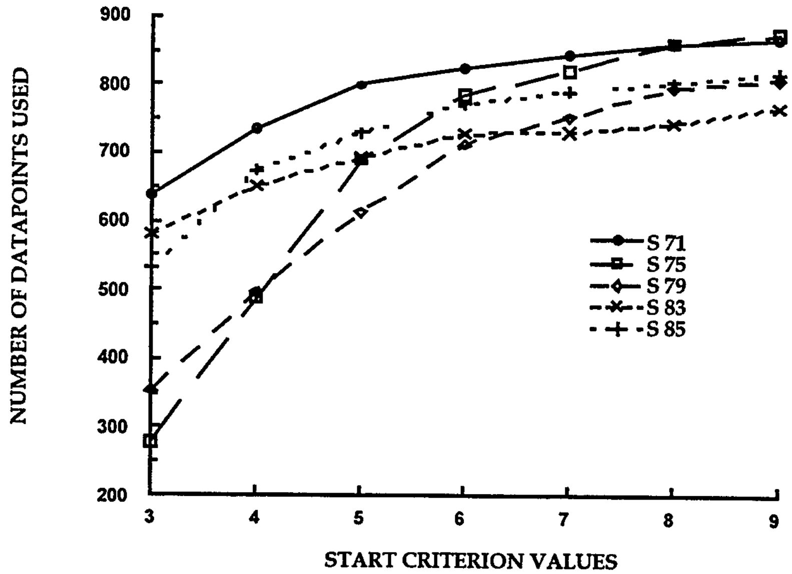

FIGURE 3. The number of DPs used to calculate fixations as a function of the Start Criterion value for each subject.

The larger the value of SC, the more loose was the criterion for beginning a fixation; so, for a given set of data, the easier it was for the algorithm to conclude that a fixation had begun, and therefore, the more DPs were included in the calculations of fixations. This relationship is illustrated in Figure 3, showing the number of DPs the algorithm used to calculate fixations as a function of the SC values for each subject. For every subject, the fewest DPs occurred with SC = 3; the most occurred with SC = 9, with intermediate points generally connected by monotonically increasing functions. For S 75 and S 79 SC values of 3 and 4 exclude more than half of the DPs. With SC values of 6 or greater, there was only a slight increase in the number of DPs used to calculate fixations.

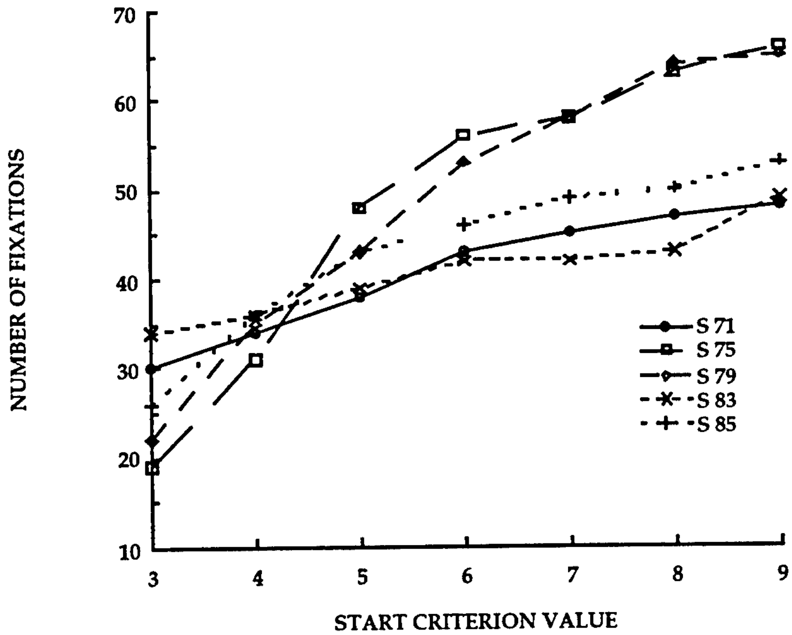

FIGURE 4. The number of fixations calculated from the 1000 DPs for each Start Criterion value for the individual subjects.

Since larger SC values made it easier for the algorithm to consider that a fixation had begun, increasing the SC value increased the number of fixations that the algorithm identified from the same set of data. This relationship between SC value and the number of fixations is illustrated in Figure 4. For SC values of 3, about 20 fixations were identified from the datasets of subjects 75 and 79; and with SC values of 9 the algorithm identified more than 60 fixations from the same datasets. The increase in the number of fixations for the other 3 subjects was more gradual, increasing from about 30 to about 40. These relationships can be seen in Tables I through VI, particularly for the data from S 75 and S 79.

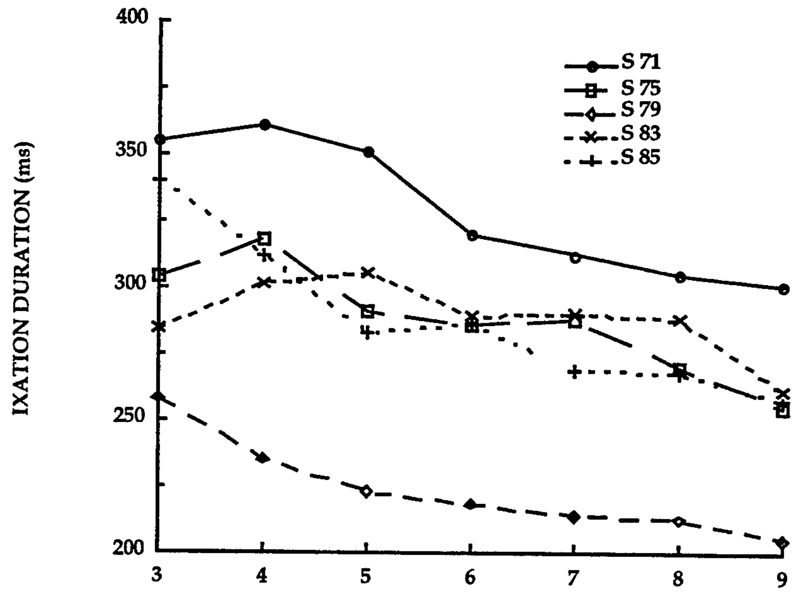

FIGURE 5. The mean duration of the fixations calculated for each Start Criterion value for individual subjects.

The average duration of the fixations was calculated for each subject for each SC value. These are illustrated in Figure 5. Variability is not indicated for the sake of clarity but standard deviations ranged from a high of about 360 ms for S71 to a low of about 69 ms for S79. What was most interesting about these results was the decrease in average duration as SC values increased. This unanticipated inverse relationship between duration and SC value was found to be statistically significant for four of the five subjects with the simple linear regression statistics as summarized in Table VII.

SUBJECT	p-Value	R-Squared
71	0.0012	0.896
75	0.0039	0.836
79	0.0032	0.849
83	0.156	0.357
85	0.0021	0.871

TABLE: VII Linear regressions and R-squared computed for the data in Figure 5.

For S 71 the average fixation duration calculated with SC = 3 was about 355 ms whereas with SC = 9 the average duration was about 301 ms. Why average fixation duration decreased with increased values of SC can be seen from Table II. When SC was small, there were several long sequences of LOS DPs for which the algorithm failed to define any fixations, for example, DPs 40 through 76. With SC = 4, the algorithm calculated a single fixation from these DPs, and with SC $\geq$ 5 the algorithm calculated two fixations from these DPs. These fixations were relatively short, reducing the length of the average fixation. For S 71 the same phenomenon occurred several times involving DPs: 119 - 157, 287 - 295, 255 - 609, 674 - 736, 965 – 999, with the smaller SC values, the algorithm failed to identify fixations where it found fixations when it assumed larger SC values although the fixations were relatively short ones. The same phenomena can be seen for S 75 in Table III, S79 in Table IV and S 85 in Table VI but was not evident in the LOS data of S 83 in Table V.

STRING COMPARISON

The fixation algorithm computed scan paths from the LOS data, different SC values resulting in different paths from the same LOS data. We used the string editing technique to measure the String Similarity (SS) between pairs of scan paths in order to characterize the dependence of the paths on the values SC assumed.

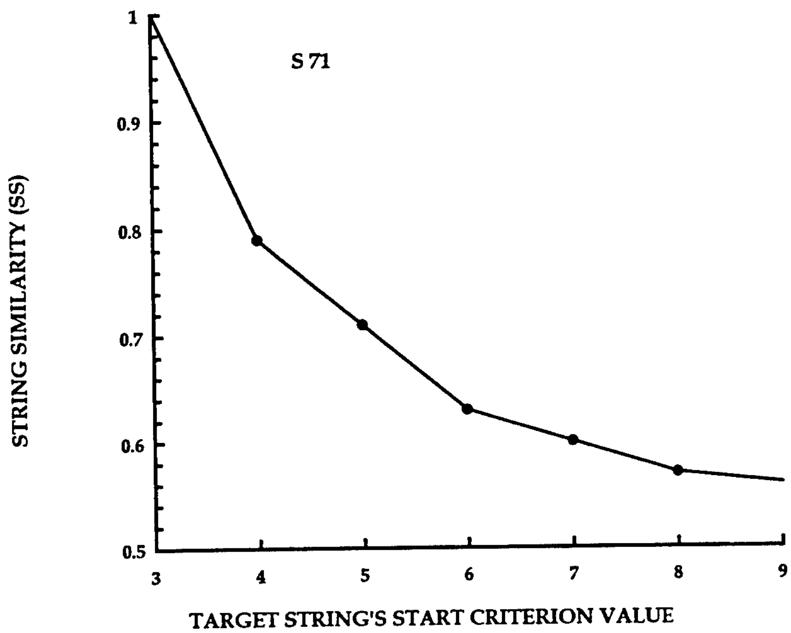

FIGURE 6: String similarity (SS) between pairs of scan paths for S 71, the O String generated with SC=3 and the T String generated with the SC values indicated on the abscissa.

Figure 6 shows SS measured between pairs of scan paths calculated from the same LOS data recorded from S 71. Each point in Fig. 6 shows SS on the ordinate as a function of the T String indicated the abscissa. For all data points in Figure 6 the O String was obtained with SC = 3 .

SS is 1.0 when the T and O strings were both obtained with the SC = 3, that is, the two strings were identical and no string editing operations were needed to convert the string to itself.

With the T String obtained with SC= 4, the SS to the O String was approximately 0.79. This SS was calculated by noting that a minimum of 7 operations were required to change the SC = 3 scan path to the SC = 4 scan path, dividing the number of operations by the length of the T String and subtracting from unity [1 - (7/34) = 0.79...]. As Fig. 6 shows, SS decreased to a low of about 0.59 as the SC values of the T string become increasingly different from SC = 3.

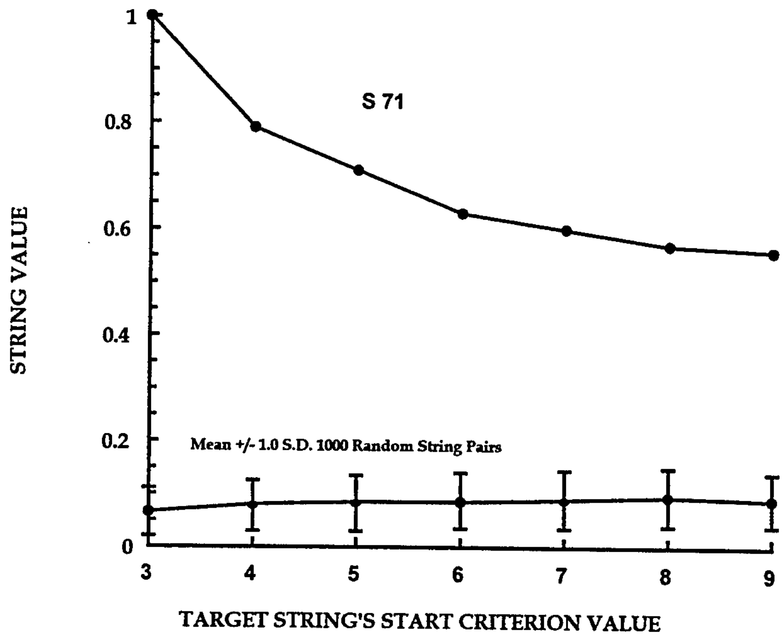

FIGURE 7. The same data as in Figure 6 with the addition of the mean and standard deviations of 1000 SS calculated from 1000 pairs of random strings of appropriate lengths where O string SC = 3 and T string SC assumes the values 3 through 7 on the abscissa.

In order to provide a statistical framework with which to evaluate the observed SS; we generated for each of the O-T scan path pairs, 1000 pairs of random scan paths of appropriate lengths and calculated the SS for each random pair. The mean SS (+/- 1.0 standard deviation) of these SS are plotted in Figure 7. The mean SS values ranged from 0.066 (S.D. = 0.044) to 0.097 (S.D. = 0.054). Clearly, SS between the pairs of random scan paths was several standard deviations smaller than the SS found with the scan paths calculated from the LOS data.

These random pairs of fixation strings were generated by randomly sampling all 11 instruments into which the instrument panel was divided, that is, sampling all the instruments toward which the subject could look. This sampling assumed that the instruments all had an equal probability of being viewed by the subject. However, the data show that S 71 did not look at all the instruments during this segment of the flight. With SC = 3, the fixation algorithm concluded that S 71 looked at only 3 flight instruments, with SC = 4 through 7 the algorithm concluded that S 71 viewed 4 flight instruments and with SC = 8, 9 the algorithm concluded that S 71 viewed 5 flight instruments. Thus, the number of instruments the algorithm considered the subject to look at depended upon the value of SC, the larger the SC value, the more instruments Subject 71 viewed.

Since Subject 71 did not view all the instruments, we repeated the procedure of generating pairs of 1000 random scan paths of appropriate lengths and sampling only the instruments that the fixation algorithm identified as viewed by the subject. The mean (+/- 1.0 standard deviation) of these distributions are presented as the open circles in Figure 8. For ease of comparison, the material presented in Figure 7 is also presented in Figure 8.

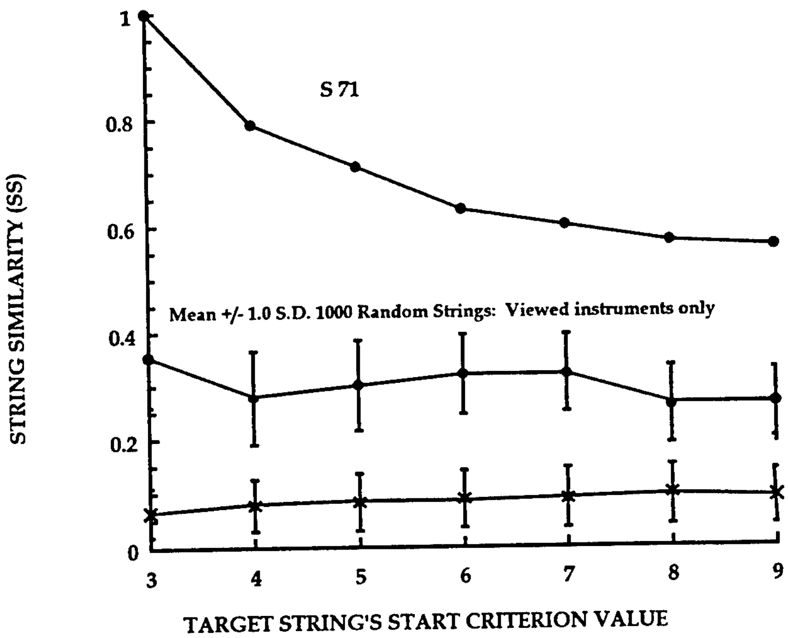

Figure 8: The same data as presented in Figure 7 with the addition of the mean and standard deviations of 1000 SS calculated from 1000 pairs of random strings of appropriate lengths sampling only the instruments that were actually viewed by the subject. For the O string SC = 3 and for the T string SC assumes the values 3 through 7 on the abscissa.

The SS between the random scan paths generated with only the instruments that were actually viewed by Subject 71 ranged from 0.26 to 0.36. These scan paths were all more similar to each other than were the random scan paths obtained with all the flight instruments. Nonetheless, the SS between the scan paths calculated by the fixation algorithm were still several standard deviations greater than the random paths, even when the fixation algorithm output was most dissimilar (S = 0.56).

The SS values plotted in Figures 6, 7, and 8 reflected only the O String obtained with SC = 3. In actuality, this curve was only one of a family of seven curves, one curve for each of the seven SC values used to generate a O String. The complete family of comparisons are presented in Figure 9.

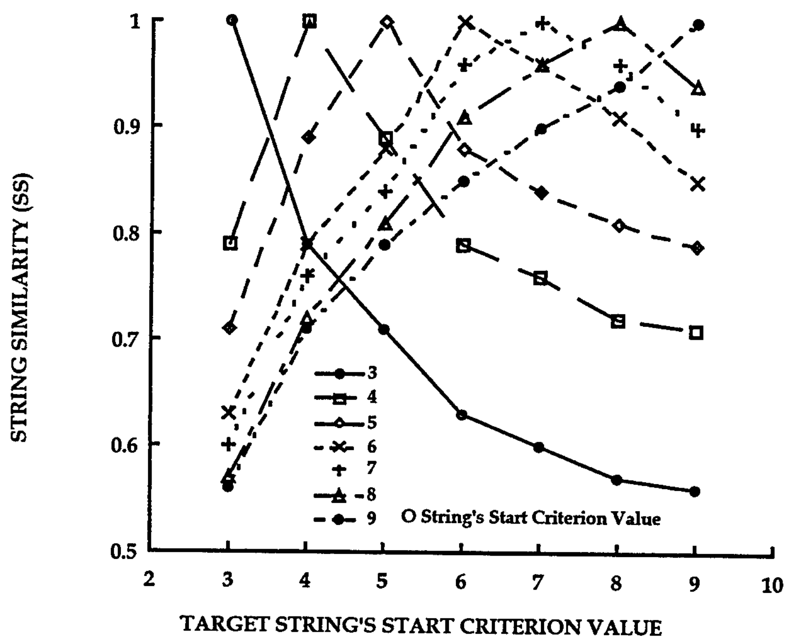

FIGURE 9: String Similarity for all combinations of T and O strings calculated with S 71's data.

Figure 9 presents the SS between all scan paths calculated from LOS data by the fixation algorithm for S 71. The data presented in Figure 6 are in Figure 9 as the open circles. The open squares reflect the SS of the scan paths when the O String was obtained with SC = 4, and the T String obtained with the SC values indicated on the abscissa. Since this function peaks with a SS of 1.0 with the abscissa value of 4, the two scan paths obtained with SC = 4 were identical and no operations were required to convert the one into the other. SSs decrease as the T String SC values become increasingly different from 4. This pattern of decreasing SS is evident for every one of the functions plotted in Figure 9. For each of the seven curves in the figure, SS peaks at 1.0, when the SC values are the same for both the O and T scan patterns, and SS decreases with increased difference between the SC values.

It should be pointed out that data presented in Figure 9 were obtained from a seven by seven square matrix; however, this matrix is not symmetric; SS reflects the sum of operations to convert the O to the T String normalized with respect to the length of the T String. Since the strings of different SC values have different lengths, (see Figure 4) the SS calculated when the T String was obtained with SC = 3 (29 fixations) and the O String was obtained with SC = 4 (34 fixations) is slightly different from the similarity calculated when the T and O strings were reversed.

For each of the 49 SS values plotted in Fig. 9, two sets of 1000 random scan paths of appropriate length were generated, one set obtained by a random sample of all possible 11 instruments, and the second set obtained by a random sample of only the instruments that were actually viewed. The means of these two sets of 49 distributions are plotted in Figure 10. These mean SS are clearly analogous to those plotted in Figure 8. For the sake of clarity, the standard deviations are not included but were observed to be comparable to those plotted in Figure 8.

Figures 11 through 14, all in the same format as Figure 10, are the comparable SS calculated for Ss 75, 79, 83, and 85. A comparison of Figure 10 through 14 shows that for the five subjects, SS peaked with a value of SS = 1 which occurs when the T and the O Strings were generated with equal SC values. Furthermore, for all five subjects, SS decreases with the increasing difference between the SC values. Subject 75 (Fig 11) showed the greatest decrease in SS, reaching values about of 0.29 whereas Subject 85 (Fig 14) showed the least dependence with S values reaching 0.69.

The fixation algorithm identified the flight instruments the subject actually monitored while flying. The numbers of instruments identified as viewed are indicated in Figures 10 through 14. Four instruments were viewed by Subject 75, 79, and 83; five instruments by Subject 71, and seven instruments by Subject 85. These were the instruments that were used to calculate the random scan paths when sampling was restricted to only the sets of flight instruments that were actually viewed. The SS obtained with these restricted sets of flight instruments were also included in Figures 10 through 14. For Subjects 71, 83 and 85 these SS were always less than the SS obtained with the observed scan paths. For Subjects 75 and 79, the SS measured from the random samples of the restricted set of flight instruments were comparable with the SS obtained with the observed scan paths when the SC values of the T and O scan paths were most different. For example, with Subject 75 the SS measured between the O String obtained with SC = 3 and the T Strings with SC $\geq$ 5, (the open squares) were all indistinguishable from the random scan paths sampling the four viewed instruments. Furthermore, for this subject, with the O String obtained with SC = 4 and the T String with SC = 9, the SS values were comparable between the observed scan path data and the random scan sampling the four instruments. A similar situation can be seen to have occurred with Subject 79.

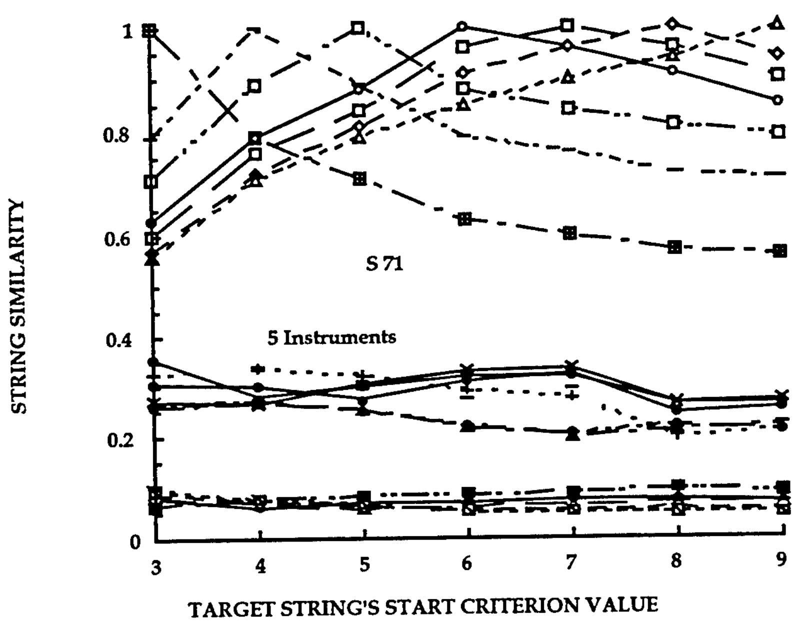

Figure 10: Contains all the SS obtained with data of S 71, including the random strings.

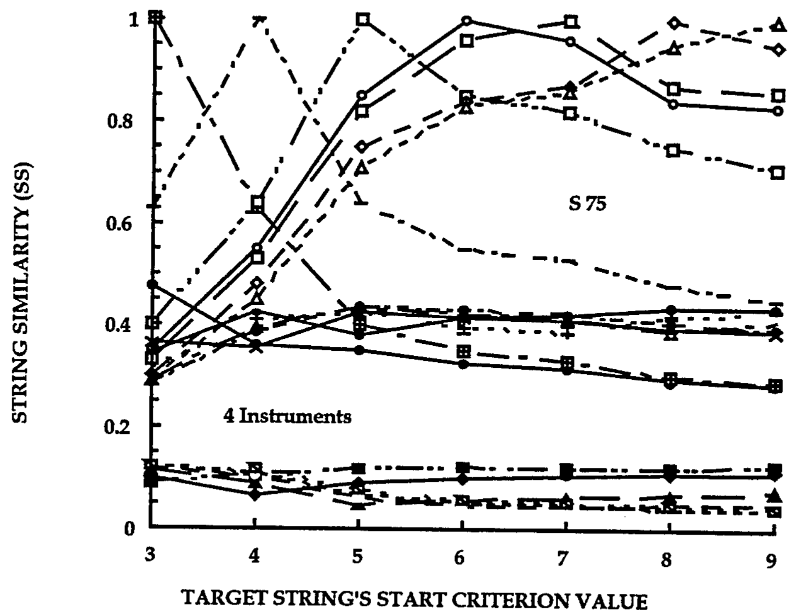

FIGURE 11: Data from Subject 75 in the same format as Figure 10.

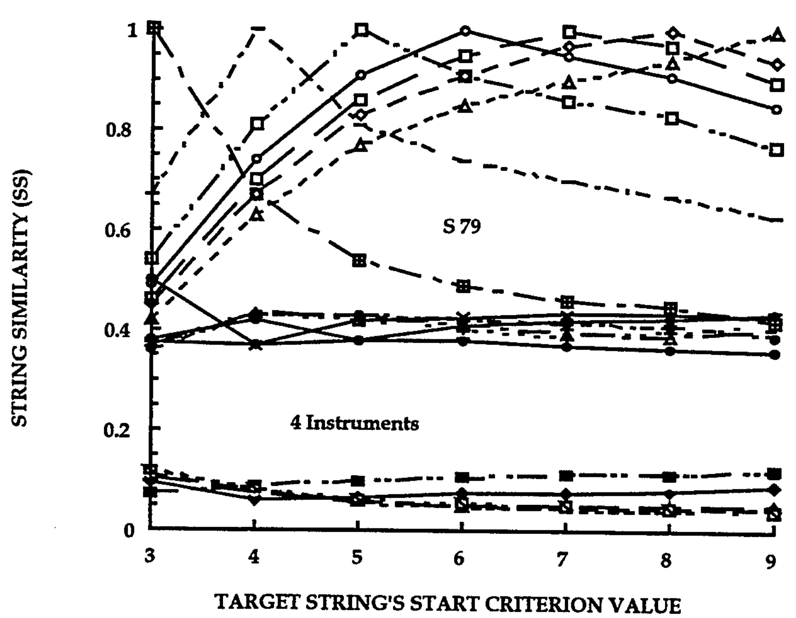

FIGURE 12: Data from Subject 79 in the same format as Figure 10.

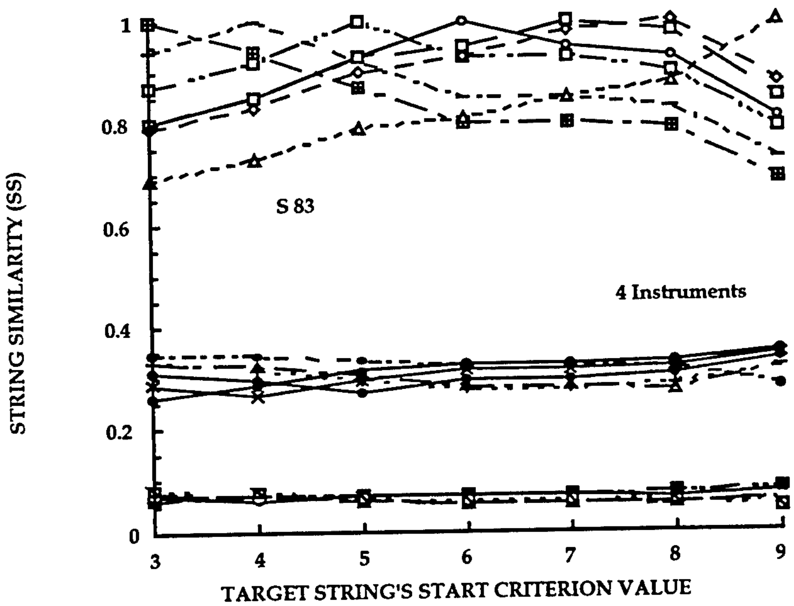

FIGURE 13: Data from Subject 83 in the same format as Figure 10.

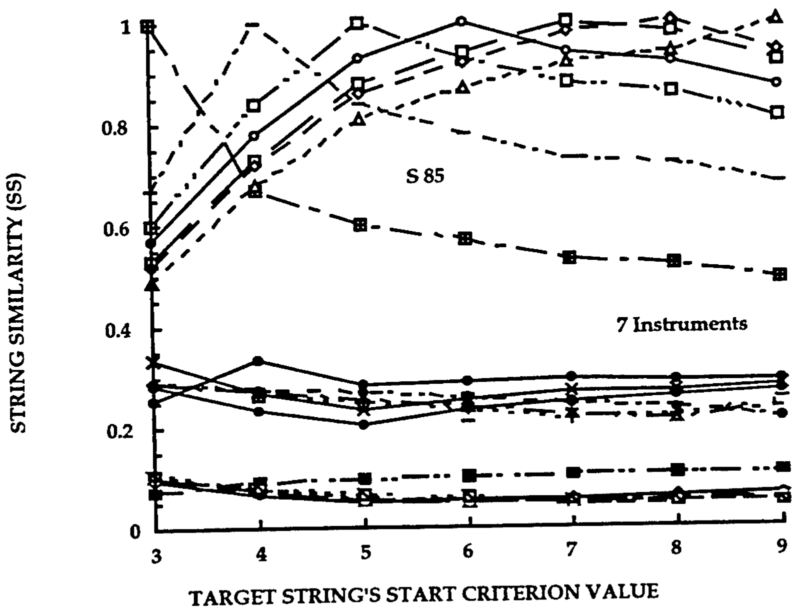

FIGURE 14: Data from Subject 85 in the same format as Figure 10.

DISCUSSION

The present paper reports the evaluation of data analysis and data visualization tools designed developed and implemented to support the study of instrument scanning in the helicopter training simulator.

One tool is the fixation algorithm which uses the 60 Hz LOS data to compute a scan path which is the sequence of flight instruments viewed. Since the fixation algorithm is used as a filter to reduce the volume of data, averaging the LOS data points into larger units considered to be fixations, it was important to determine that the algorithm was well behaved and did not introduce biases that could compromise subsequent data analysis.

The algorithm has three parameters; the first, the SC, determines the beginning of a fixation; the other two parameters set the criteria for datapoint inclusion/exclusion from the fixation and the termination of that fixation. Specifically, SC is the spatial extent within which the standard deviation of six successive LOS data points must be contained for the algorithm to consider that the data points begin a fixation. Once the algorithm determined that a fixation has begun, it computed the arithmetic average location of the six LOS data points. This average is the provisional location of the fixation and the location of each subsequent LOS data point is compared to this provisional location. If the data point falls within the spatial extent set by the inclusion/exclusion criteria, then the data point is identified as belonging to that fixation. The algorithm cLOSes the fixation when a defined number of data points exceeded the inclusion/exclusion limits. When all the LOS data points to be included into the fixation have been identified, the location of that fixation is computed as the average of all included LOS data points. Note that the provisional fixation location is based only on the six initial data points that mark the beginning of the fixation, and this provisional location does not change as the various data points are compared to it. It is only after the algorithm determines that no more data points are to be included into the fixation that the location of the fixation is computed.

The SC value defines a measure of acceptable variability. The larger SC, the greater the variability among the six successive LOS data points that the algorithm will recognize as a fixation. Thus we anticipated that the more strict the start criteria, the fewer LOS data points that would be included into the calculations and the fewer the fixations that would be calculated. These two expectations were met. We were particularly concerned, however, that the algorithm be consistent in its assignment of LOS data points and instruments. Specifically, the SC value influenced whether a data point was included or excluded from a fixation; but once included in a fixation, that data point should be allocated to the same instrument, regardless of SC values. The fixation algorithm would be extremely suspect if different SC values caused the same data point to be relegated to different instruments. We are encouraged since this was a rare event that occurred with 4.1% of the LOS data points for S 71 and 1% of the data points for S 85; it did not occur at all with the other 3 subjects. Furthermore, all of the confusions occurred between two instruments, the AG (attitude Gyro and the HSI (Horizontal situation Indicator), two instruments that were next to each other and to which most of the individual DPs were directed. These results show that the fixation algorithm is consistent in its allocation of LOS data points to instruments.

The spreadsheets in Tables II through VI are a visualization tool we developed to aid understanding how SC values affected the calculated fixations. With these tables we were able to see for S 71 and 85 those instances when the same LOS data were allocated to different instruments. These spreadsheets also helped to understand what was an unanticipated and initially perplexing relationship, average fixation duration decreased as SC values increased. From Tables II through VI it was apparent that the increase in SC values made it increasingly easy for the algorithm to discover relatively short fixations of greater variability in the expanses of LOS data that were not incorporated into other fixations.

The development of the String Similarity measure (SS) is important. It provides a tool with which to measure the similarity between pairs of instrument scan patterns. The tests and evaluations we conducted on the scan paths the algorithm generated with different SC values lend credence to both the algorithm as well as to SS; they behaved in a completely orderly and logically self-consistent fashions that were in agreement with reasonable expectations for the algorithm's output.

The SS measurement between string pairs has a potentially important role in the future analysis of the instrument scan paths. For the present analysis we used Monte Carlo methods to create random strings that had specified characteristics and used them to generate SS frequency distributions. These distributions provided the statistical models with which to compare and evaluate the observed SS. This technique is powerful and promises to have great potential for measuring the amount of similarity between pairs of scan patterns. The first random model we constructed was based on the assumption that all flight instruments had an equal probability of being viewed during the flight segment. The second model we constructed recognized that the during the flight segment only a subset of instruments were viewed, but all the instruments in this reduced set were equally likely to be viewed. We stopped with this model since we had demonstrated the development of this new measurement capability, SS, and had used it to measure the effects of SC on the algorithm's computed the scan paths and carrying it any further with these datasets seemed of little value.

In the present paper, SS is obtained from a normalized score; i.e., the number of string operations to convert the O string into the T string is divided by the T's length and this ratio is then subtracted from 1. When the O and T strings are of different length, the SS computed between the two strings depends upon which is taken to be the O and which the T, since the ratio depends upon which string length is used as the denominator. This implies that SS is not derived from a measure of the distance between the two strings since distance should be the same from O to T and T to O. This is a problem with symmetry (12) and is usually dealt with in the literature by formally defining the distance as the minimum distance which, for the present application, means always normalizing with respect to the longer of the two strings, resulting in the smaller ratio, the smaller distance (14). The distance measurement is the ratio which, when subtracted from one, produces the SS, an index of the similarity between the strings. Our future applications of these editing procedures will incorporate this definition of distance

Future work includes the use of the SS to measure the between pilot and the within pilot differences in the instrument scan paths associated with various identified flight maneuvers. We are particularly interested in the SS between scan paths of different pilots flying the same maneuvers, the same pilots flying different maneuvers, the differences between scan patterns associated with good versus poor execution of the maneuvers as well as the effects of flight experience and training.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
17 June 1998

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Calculating A Helicopter Pilot's Instrument Scan Pattern From Discrete, 60-Hz Measures Of The Line-Of-Sight:

5. FUNDING NUMBERS
0603706N
M0096.001-7208

6. AUTHOR(S)
Leonard A. Temme and David L. Still

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY
51 HOVEY ROAD
PENSACOLA FL 32508-1046

8. PERFORMING ORGANIZATION REPORT NUMBER
NAMRL-1403

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Medical Research and Development Command
National Naval Medical Center
Building 1, Tower 12
8901 Wisconsin Avenue
Bethesda, MD 20889-5606

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
In order obtain data to develop and evaluate theories relating instrument scanning to flight performance we recorded the line of sight (LOS) of student naval helicopter pilots as they flew prescribed maneuvers in a motion-based, high fidelity, instrument training simulator. These LOS data were discrete, 60 Hz samples of eye pointing. For some types of analysis it is helpful to think of a scan pattern as a sequence of fixations and to use an averaging algorithm to transform the 60 Hz data into such a sequence, a scan path. An appropriate algorithm was identified, developed and evaluated. As part of this evaluation, we developed a String Similarity measure, SS, a measure of the similarity between two scan paths. The evaluation of the algorithm, consisting of observing the algorithm's output as a function of the algorithm's parameter values, showed that the algorithm behaved in a sensible fashion, logically consistent with the input data. This increased our confidence in our implementation of the fixation algorithm. The SS metric proved to be an informative, useful tool that may have addition uses in the analysis scanning behavior and flight performance.

14. SUBJECT TERMS
Pilot performance, Instrument scanning, Eye movements, Visual search, Scan patterns, String editing, Helicopter instrument flight, Pilot training

15. NUMBER OF PAGES
33

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102