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USEFULNESS OF HEART MEASURES IN FLIGHT SIMULATION

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ABSTRACT

The results of three studies performed at the NASA Langley Research Center are presented to indicate the areas in which heart measures are useful for detecting differences in the workload state of subjects. Tasks that involve the arousal of the sympathetic nervous system, such as landing approaches, were excellent candidates for the use of average heart-rate and/or the increase in heart-rate during a task. The latter of these two measures was the better parameter because it removed the effects of diurnal variations in heart-rate and some of the intersubject variability. Tasks which differ in the amount of mental resources required are excellent candidates for heart-rate variability measures. Heart-rate variability measures based upon power spectral density techniques were responsive to the changing task demands of landing approach tasks, approach guidance options, and 2 versus 20 second interstimulus-intervals of a monitoring task. Heart-rate variability measures were especially sensitive to time-on-task when the task was characterized by minimal novelty, complexity, and uncertainty (i.e., heart-rate variability increases as a function of the subjects "boredom").

INTRODUCTION

The Human Engineering (HEM) Group at Langley Research Center (LaRC) utilizes physiological measures to characterize the impact of various flight management displays and/or controls upon the pilot's mental state. Heart-rate parameters are being investigated for use in such display and control evaluations. Instantaneous and average heart-rate measures have been used quite successfully by other researchers in several flight studies to evaluate the effect of the steepness of an Instrument Landing System (ILS) flight path on pilot heart-rate (ref. 1). In addition, positive correlations between heart-rate and subjective estimates of workload has been reported (ref. 2). However, other types of tasks have not affected the heart-rate as systematically (ref. 3). In an effort to determine the advantages and limitations of these measures in the flight deck environment, and to establish protocols and guidelines for their application, the HEM Group has undertaken a series of piloted studies. This paper presents data from three studies and examines the usefulness of two classes of EKG measures, heart-rate and heart-variability. The discussion provides guidelines for choosing measures judiciously, as well as for evaluating circumstances for which particular choices of cardiac response measures are germane.

RATIONALE FOR USE OF HEART MEASURES

Measures of changes in average heart-rate reflect the synergistic action of sympathetic and parasympathetic nervous systems on the cardiovascular control system (ref. 4) and have been considered an index of general arousal (ref. 5). Therefore, it would be expected that any task having an affect on the autonomic nervous system would affect heart-rate. In addition, tasks involving physical activity will affect heart-rate.

A number of measures of heart-rate variability may also be derived from the electrocardiogram (EKG) signal. Unfortunately, the term "variability" can refer to any one of several methods of analysis of heart-rate variability. Such methods include statistical variability measures, such as the standard deviation, which may be derived over a number of inter-beat-intervals (IBIs) or a selected time interval, and spectral frequency analyses of the IBIs.

Spectral analysis of the IBI data has shown promise in the assessment of mental workload (ref. 6). From the spectral analysis the amount of power in a given frequency band may be calculated. Power in a frequency band from .05 to .15 Hz has been shown to reflect the action of neural processes on arterial blood pressure regulation mechanisms (ref. 7). Changes in power in this frequency band also show sensitivity to changes in task demands. The amount of heart-rate variability has been shown, under laboratory conditions, to decrease with increasing task difficulty. However, interpretation of phasic changes in the cardiac interval signal as a function of task demands is complicated by non-linearity in the relevant physiological control systems (ref. 7). This non-linearity means that a linear change in the heart-rate variability index should not be expected with a linear change in task demand. Despite this limitation, frequency spectral analysis of the signal is considered promising as an estimate of aircrew mental workload (ref. 8). Mental tasks, which require physical responses to implement a decision, reportedly produce changes in heart-rate variability (ref. 9). Therefore, heart-rate variability measures appear particularly appropriate for use in evaluating pilots' mental state during flight simulation tasks.

PILOTED STUDIES

The first two studies were performed in Langley's Visual/Motion Simulator (VMS). The VMS has a virtual image system to show the visual image taken of a model terrain board scene around a runway. The simulation tasks consisted of performing landing approaches. Reference 10 provides a more complete description of the simulation facility. The exterior of the simulator is shown in figure 1 and the interior is shown in figure 2. The cockpit was configured to simulate a jet transport. The experimenter performed the functions of the first officer in the right seat. Cardiac IBI data were collected for the pilots during flight simulation test runs. Each simulation run was preceded by a baseline period of several minutes duration, during which cardiac IBI data were collected. These baseline data were collected between simulation runs and may not represent truly "resting" conditions, because the subjects were either engaging in subjective workload assessment in the form of a verbal report or discussing conceptual aspects of the study or procedural aspects of the simulation task with the experimenter.

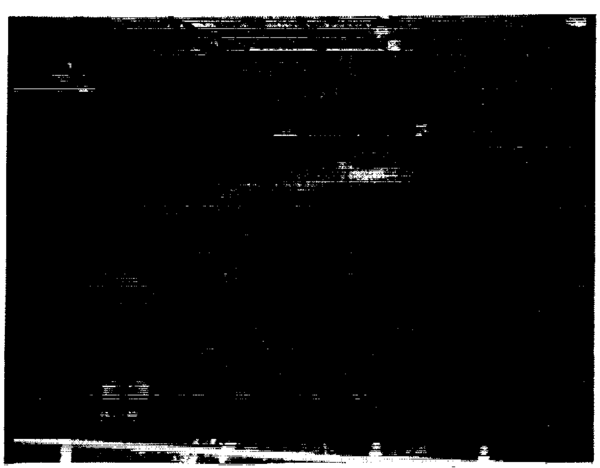

Figure 1. VISUAL MOTION BASE SIMULATOR

Figure 2. VISUAL MOTION BASE INSTRUMENT PANEL

The first study utilized five airline pilots and one NASA test pilot. Each completed 36 landing approach runs in the VMS for evaluation tests in flight along complex area navigation paths within the Microwave Landing System (MLS) signal environment. The primary independent variables were the type of flight path: ILS, RIVER, or HOOK. The ground track of the ILS path consisted of two straight lines, while that of the RIVER looked like the windings of a river with a short straight final to a landing, and that of the HOOK looked like a question mark. The task of flying the HOOK path was made even more difficult by removing the predictive elements from the guidance displays leaving the pilot to fly with reference to raw MLS data. Choice of these particular paths and control guidance configurations was based upon a prior set of tests that had shown these paths to have different Subjective Workload Assessment Techniques (SWAT) ratings (ILS was 14.6, RIVER was 31.8, and HOOK was 54.4).

The second study (a stereopsis/display format study) was also performed in the VMS, and utilized six United States Air Force transport pilots. Each pilot completed 24 landing approach simulation runs to evaluate the use of a perspective, stereo 3-D, path-in-the-sky display. The two main factors in the study were stereo versus non-stereo presentation and the type of pathway symbology. The pathway symbols were goalpost, monorail, and triangle-based monorail. Figure 3 shows a pilot in the simulator using goggles which alternatively transmit a left- and right-eye view, thereby providing stereopsis-type depth cues in the stereo version of the perspective display.

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Figure 3 STEREOGRAPHIC EQUIPMENT IN THE VISUAL MOTION SIMULATOR

The third study was a laboratory vigilance study concerned with physiological and performance assessment of subjects in a task underload scenario. Some preliminary data from this study were reported previously (ref. 11). In this study, subjects monitored a CRT display containing a schematic of a jet aircraft engine. The subjects were instructed to take corrective action by depressing a particular key on the keyboard anytime one of five areas turned red, thereby restoring the display to its normal condition. The engine schematic and key layout are shown in figure 4. The task lasted for 1 hour. The period between stimuli was either a fixed interval of 6 seconds or alternated between 2- and 20-second intervals with 5 minutes at each level.

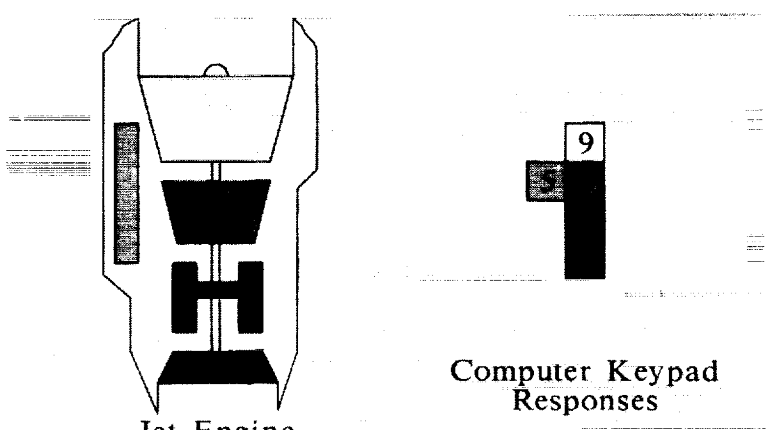

Figure 4. FAULT ACKNOWLEDGEMENT TASK

CARDIAC RESPONSE MEASURES

The electrocardiogram (EKG) signal (figure 5), from which the IBI, heart-rate, and heart-rate variability measures were derived, was obtained through active electrodes attached to the top of the sternum and the lower left rib cage. A reference electrode was attached to the left ankle. The EKG signal was fed through an optically isolated bioamplifier and routed to either signal processing equipment or magnetic tape depending on the requirements of the study. A level-sensitive Schmitt-trigger was used to determine the EKG IBI by timing and recording the duration of the intervals between successive cardiac contraction signals as they cross a preset level of the Schmitt-trigger hardware (figure 5). Although this technique does not detect the time of the actual peak of the "cardiac signal" the resulting error is much less than 3 milliseconds, which is of equal or greater precision compared to the timing of most other techniques in common usage. The series of inter-beat-intervals (IBI's), in units of milliseconds, is preserved in a file for later processing and analysis. The IBI data was used to calculate the average heart-rate (AHR).

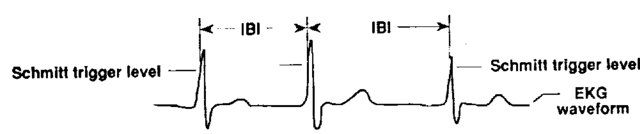

Figure 5. INTER-BEAT-INTERVAL DETECTION SCHEME

The spectral analysis measure of heart-rate variability was obtained from a Fourier analysis of the IBI data. Software algorithms convert the IBI data sequence into an equal-spaced time series sampled at 4 Hz (cardiotachogram step-function). A low-pass digital filtering algorithm (ref. 12) was then employed to filter the sampled cardiotachogram. Fourier analysis of the filtered cardiac event sequence yields a spectrum of frequency components in the range 0.0 Hz to approximately 0.5 Hz (the maximum frequency is actually limited by the heart-rate).

Two main summary measures of heart-rate variability are derived from the frequency spectral analysis: (1) total heart-rate variability (THRV), which is the total area under the power versus frequency (spectral density) curve (0.0 to 0.5 Hz) and (2) blood pressure component of heart-rate variability (BPHRV), which is the area under the power spectral density curve in the frequency range of 0.05 to 0.15 Hz. As noted previously, changes in this frequency band have been shown to reflect the action of arterial blood pressure regulation mechanisms (ref. 7).

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RESULTS

MLS Approach Paths

The first study compared heart measures for three different MLS approach paths (remember that the HOOK approach also involved the pilot's use of raw "path deviation" data instead of command guidance data). Table 1 presents the means and standard deviations of four heart measures (Total heart-rate variability - THRV, band pass heart-rate variability - BPHRV, Average heart-rate - AHR, and Average heart-rate minus Baseline heart-rate - AHR-BL) for the three approach paths. AHR and AHR-BL values were greatest for the HOOK approach and the THRV and BPHRV were lowest for the HOOK approach. The Analysis of Variance shows a significant difference in the AHR-BL parameter for the three approach paths ($p < .034$). The increase in heart-rate was sensitive to the workload change involved in the different paths (straight path of ILS and the multiple-curve path of the RIVER approach) as well as the increased mental stress of the combination of path without command guidance information of the HOOK approach. Even though the differences in the variability measures do not show statistical significance, the trend in the mean values follow the subjective workload ratings. Highest heart-rate variability with the lowest rated workload task and vice versa.

Table 1. Heart Measures

	THRV ms*ms	BPHRV ms*ms	AHR BPM	AHR-BL BPM @
	Mean (Standard Deviation)			
ILS	60.43	22.81	72.24	0.70
	(22.44)	(8.10)	(6.00)	(1.88)
RIVER	55.17	20.65	73.51	2.36
	(20.22)	(6.65)	(5.92)	(1.81)
HOOK	53.70	19.73	74.29	3.18
	(25.23)	(9.18)	(7.24)	(3.00)

@ $p < .034$

Stereopsis/Display Format

The stereopsis/display format piloted simulation study involved the pilots' use of perspective, path-in-the-sky displays for curved, decelerating, descending approach-to-landing under turbulent wind conditions. Figure 6 shows the heart-rate of one pilot making a landing approach. Characteristic features of this heart-rate time history show a constant heart-rate at the beginning of the approach until the introduction of winds, and followed by flight maneuvers involving a reduction in airspeed, a curved path to aligning up with the runway, and a final straight segment leading to a touchdown and subsequent stopping on the runway. Table 2 lists the difference in heart-rate at touchdown and the heart-rate at the beginning of the landing approach (AHR-BL) for the two experimental manipulations of stereopsis and displayed pathway. This measure is used in lieu of the heart-rate at touchdown, because it reduces some of the between-subject variability. Unfortunately, it does not eliminate that variability entirely. On the average, the AHR-BL was less with stereo than without stereo. There was a significant difference in the AHR-BL measure for the stereopsis factor ($p < .027$), with a significantly smaller change in AHR-BL with the use of stereo. This shows that the level of arousal or stress was decreased through the use of the stereo display. Differences in AHR-BL between the pathway symbology types were not significant. Pilot comments were likewise ambivalent concerning the effects of the pathway symbology.

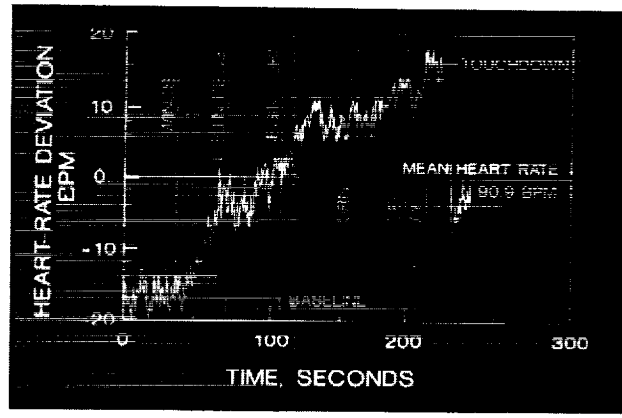

Figure 6. HEART RATE RESPONSES

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Table 2. AHR-BL Heart Measures

Stereopsis @	On	Off	
	9.67	11.44	
	(5.87)	(6.22)	
Pathway	Goalpost	Monorail Triangle-Base	Simple Monorail
	10.06	12.66	8.93
	(5.52)	(8.77)	(5.94)

@ $p < .027$

Stereopsis effects on the variability measures, THRV and BPHRV, are shown in figure 7 for overlapping time periods during the landing approach. The data show a consistent decrease in the variability measures from the first to the last of the run. This decrease in the heart rate variability parallels the increases in task difficulty of the landing approaches brought on by winds and required changes in aircraft state as the airplane proceeded toward a landing. While there were no statistically significant differences in the THRV or BPHRV measures for the stereopsis effects, there were differences during the landing approach.

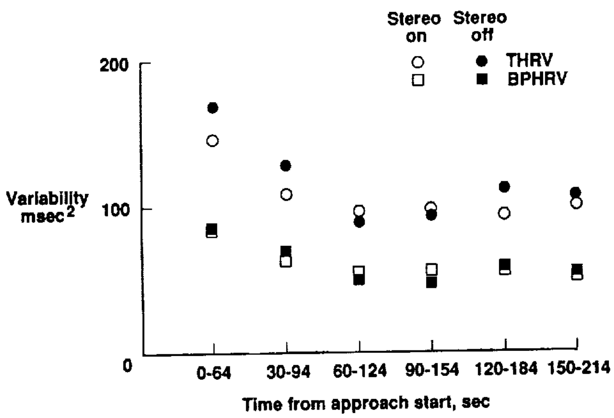

Figure 7. STEREOPSIS EFFECT ON HEART RATE VARIABILITY

Pathway effects on the variability measures, THRV and BPHRV, are shown in figure 8 for overlapping time periods of the landing approach. These data also show a consistent decrease in the measures from the first three segments with a vary slight increase in the last segments. Consistent with pilot comments, the statistical analysis showed no significant effect of the type of pathway upon either THRV or BPHRV. A consistent trend for the first three time segments of the data was that the heart-rate variability for the triangle pathway was consistently lower than the other pathways. This would indicate a higher mental workload associated with that pathway symbology during those phases of the flight.

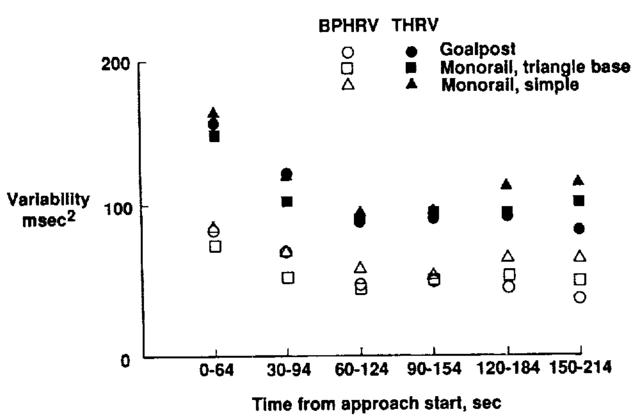

Figure 8 PATHWAY EFFECTS ON HEART-RATE VARIABILITY

Task Underload

For the task underload study, the subjects spent 1 hour monitoring a display to respond to fault indications with the press of a button. Three heart-rate parameters were derived (AHR-BL was omitted) for consecutive 5-minute blocks of a 1-hour task. Data were collected for two different inter-stimulus-interval (ISI) conditions, constant 6 seconds and alternating 5-minute blocks of 2 and 20 seconds.

Figures 9 thru 11 show AHR, THRV, and BPHRV parameters for each 5-minute block of the two ISI schedules. The ANOVA analysis of these data are presented in Table 3. The two variability parameters, THRV and BPHRV, statistically differentiated the block factor.

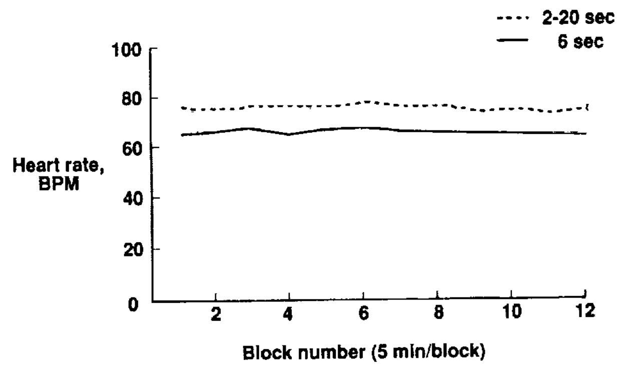

Figure 9. AVERAGE HEART RATE VERSUS TIME ON TASK

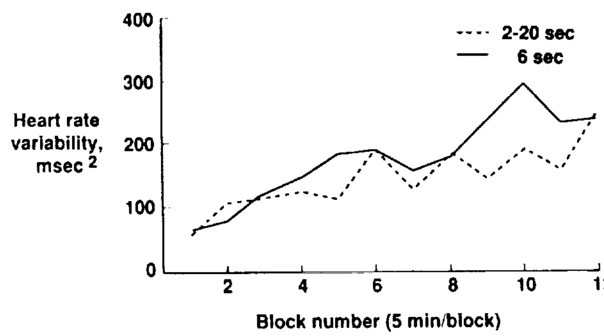

Figure 10. HEART RATE VARIABILITY VERSUS TIME ON TASK

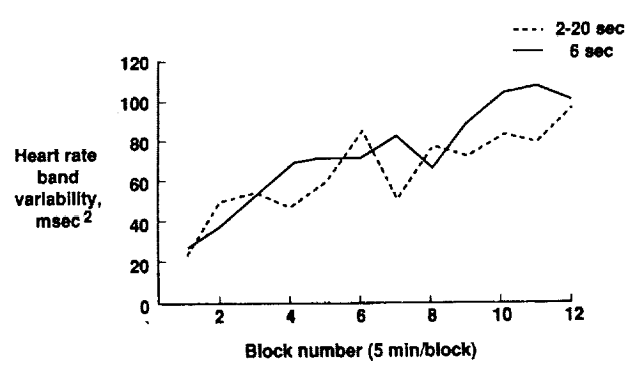

Figure 11. HEART RATE VARIABILITY (.05 - .15 HZ BAND) VERSUS TIME ON TASK

Generally, THRV and BPHRV measures were greater with increasing time on task (block number). The ISI alternating condition of 2-20 seconds was marginally significant for the THRV parameter. The differences in the mental workload of the 2-20 seconds ISI blocks is evident in the changes in the heart-rate variability measure but not in the heart-rate measure. Since there were no changes in the task demands with block number (except alternately for the 2-20 seconds ISI) the largest changes in heart-rate variability was that of block number (time-on-task). This indicated something about the mental state of the subjects as a function of time on the task and suggests that the mental resources devoted to the task were decreasing. This effect was shown by the increases in the heart-rate variability measures with block number.

Table 3. ANOVA significance levels

Factor	THRV	BPHRV	AHR
Blocks(6 SEC)	<.001	<.001	ns@
Blocks(2-20 SEC)	<.043	<.019	<.053
ISI (2-20 SEC)	<.073	ns@	ns@

@ ns = not significant (p > .10)

CONCLUSIONS

Taken together the results of these three studies can be used to indicate the areas in which heart measures are useful in measuring differences in the workload state of subjects.

Tasks that involve the arousal of the sympathetic nervous system, such as the landing approaches used in the first two experiments, are excellent candidates for the use of the two heart-rate measures: (1) average heart-rate (AHR) and (2) increase in heart-rate during a task (AHR-BL). Of these two measures, AHR-BL is the better parameter, because it removes the diurnal variations in heart-rate, and it tends to reduce some of the inter-subject variability. In order to measure the AHR-BL parameter some provision has to be made for taking a baseline measurement, either preceding the data run, as in the case of the first experiment, or by designing the data run to include a non-demanding period (a reference heart-rate), as in the second experiment. This latter technique has the advantage of controlling the activity of the subject while taking the baseline measure.

In addition to heart-rate, heart-rate variability measures are also very responsive during the landing approach tasks. Although heart-rate increases during the landing approach and heart-rate variability decreases during the landing approach, both sets of measures reflect the increasing task demands of the landing maneuver.

Heart-rate variability measures show sensitivity to some task demand changes (2-20 ISI, MLS approach guidance options, and stereopsis effects). In addition, increases in heart-rate variability have also been used successfully in the evaluation of changes in the boredom level during a test run of tasks which can be characterized by minimal novelty, complexity, and uncertainty (i.e., heart-rate variability increases as a function of "boredom").

Neither one of the two heart-rate variability measures seem to be the more sensitive measure. In one of the tests, THRV was the more sensitive parameter, in another test, the BPHRV was the more sensitive parameter, and in a third test, both THRV and BPHRV were sensitive measures. At this point in time, it cannot be predicted which of the two variability measures will be the more sensitive. Either parameter can be derived in the Fourier analysis of the data. The researcher will have to derive and analyze both parameters.

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