USE OF ELECTROMYOGRAM INFORMATION TO IMPROVE HUMAN OPERATOR PERFORMANCE

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THESIS

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USE OF ELECTROMYOGRAM INFORMATION TO IMPROVE HUMAN OPERATOR PERFORMANCE

THESIS

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by
Mark C. Kipperman Captain USAF Graduate Systems Management December 1979

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Preface

When Dr. Saul Young mentioned a possible thesis project involving biofeedback, the idea intrigued me. Although I had no personal experience with biofeedback, I had done some reading on the subject and thought that it would be a fascinating field of study. As it turned out, the process of experimentation and analysis, not just the biofeedback, was interesting and enlightening to me. I feel as if I have truly been immersed in the problems of experimental design, execution, and analysis.

This project involved a great deal of time and effort on the part of many people, and I would like to express my thanks to them. Andrew Junker and Saul Young developed the initial experimental protocol and gave invaluable advice and assistance along the way. Dr. Lynn Wolaver provided the biofeedback equipment. Grant McMillan, Marvin Roark, Warren Miller and Jim Ater at AMRL were very helpful in providing facilities and equipment with which to conduct the tracking experiments. Of course, my thanks also go to the experimental subjects, who volunteered so much of
their time. They are:

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Joe Cafarella Grant McMillan Dave Smedley
Dennis Dailey Rich McNally Bob Taylor
Bill Frazier Dick Mosbach Tom Wade
Gil Fried Bill Nusz Norbert Wagner
Mike Gusmus Jim Rechtorovic Bill Wise
Duane Johnson Art Ross

Finally I would like to thank my wife, Molly, for taking care of so many problems that I neglected while working on this thesis.

Mark C. Kipperman
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Abstract

This research was conducted to investigate the effects of electromyogram (EMG) biofeedback on learning and performance of a compensatory hand-eye tracking task. A total of twenty male subjects took part in the experiments, with each participating in at least 48 scored tracking runs on the Roll Axis Tracking Simulator.

The subjects were divided into three groups. The control group received no biofeedback, the first experimental group received biofeedback relaxation training and biofeedback while tracking, and the second experimental group received biofeedback relaxation training only. Comparisons across the three groups showed significant differences in muscle tension levels, but no significant differences in performing the tracking task.

Analysis of scores from each subject showed learning to have the most significant relationship to score, and demonstrated the log/log nature of the learning curve. When averages were taken across all subjects, 98 percent of the variance in logarithm of score was accounted for by the relationship with logarithm of run number.
USE OF ELECTROMYOGRAM INFORMATION TO IMPROVE HUMAN OPERATOR PERFORMANCE

I Introduction

The Air Force is always looking for ways to improve operational mission effectiveness, and the ability of pilots to perform their tasks is an important factor in the overall performance of the Air Force. No field of knowledge that could lead to improved pilot performance should be ignored.

In the last several years great advances have been made in aircraft instrumentation and avionics. The pilot of a modern aircraft can identify its location, altitude, speed, and direction, all in a very short time. The condition of the aircraft itself is also monitored in detail, with some systems even including automatic troubleshooting diagnostic routines. The one part of the weapons system that is not monitored is the pilot himself.

Techniques for monitoring automatic body functions and for learning voluntary control over them have existed for many years, but only recently have they been combined and scientifically studied. A new field of study called biofeedback has developed, concerned with "feeding back" physiological information to an individual to enable self-
monitoring and control of physiological processes (Brown, 1977:3). If biofeedback can improve pilot performance, it has tremendous potential for the Air Force.

Background

Concept. The original concept for this project came from two men at Wright-Patterson Air Force Base: LtCol George C. Young, Jr., a professor at Air Force Institute of Technology, and Mr. Andrew Junker, an engineer at Aerospace Medical Research Laboratory (AMRL). Young had been involved with clinical applications of biofeedback, and Junker had helped design a target-tracking simulator at AMRL. Their idea was to investigate the use of biofeedback during the tracking task to determine whether the biofeedback information could improve performance.

Literature Review. In her book *New Mind, New Body*, Barbara Brown presents a detailed explanation of the field of biofeedback and its historical development. She explains that biological feedback systems within the body have been known for some time, but the breakthrough in biofeedback came with the introduction of an external portion of the feedback loop. Brown explains,

The real biological feedback drama unfolded when it was discovered that we could tap the hidden secrets of the completely internal, life-governing functions of the body, that we could capture the internal signals and transform them into externalized, information-bearing signals.
that could be sensed, perceived, recognized, and acted upon by our brain's control system (Brown, 1974:5).

One of the externalized signals to which Brown refers is the electromyogram (EMG), a measure of muscle tension level. Physiologist Edmund Jacobson pointed out the existence of residual tension, that tension a person maintains even when apparently at complete rest. Jacobson noted that residual tension can be measured by measuring the amount of muscle electrical activity (Brown, 1974:141). That measurement is accomplished by the EMG.

Robert Benshoff's report on self-regulation is much more cautious about the applications of biofeedback than is Brown's book. Benshoff points to several research efforts that found little promise in the use of biofeedback for improved performance. Stoyva and Budzynski, for example, compared subjects with and without muscle relaxation training at six different tasks, and found no significant difference between the two groups (Benshoff, 1976:15-18).

Benshoff sums up his position by saying, "Until further research establishes a discrete relationship between specific physiological events and performance, or until new techniques for biofeedback become more efficient, further efforts toward the utilization of self-regulation to performance enhancement do not appear reasonable (Benshoff, 1976:12)." It was decided to proceed with the project despite Benshoff's caution, modifying it to include more
emphasis on learning, EMG measurement, and the search for a relationship between tension level and performance.

Statement of the Problem

The EMG provides information which may be of value in improving human operator performance. This information is not currently being used in US Air Force aircraft because the value of EMG information in this area has not been demonstrated.

Objectives

Primary Objectives. Investigate possible advantages of employing electromyogram information during learning of a hand-eye tracking task.

Investigate possible advantages of employing EMG information during performance of a previously learned hand-eye tracking task.

Secondary Objectives. Investigate the relationship of EMG tension levels and performance of a hand-eye tracking task.

Increase understanding of learning curves and the nature of the learning process.

Personal Objectives. Become familiar with some practical research methods.

Develop a detailed understanding of statistical analysis techniques.
Scope, Limitations, and Assumptions

Scope. This thesis is restricted to the study of a single physical task: pitch tracking on the Roll Axis Tracking Simulator (RATS) at the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. Conclusions drawn from this study would not necessarily apply to other tasks.

The tracking task consisted of attempting to keep a target image in the center of a television screen by applying pressure on a control stick. The target would move vertically based on computer-generated disturbance signals and control stick inputs. Each tracking run was scored for 180 seconds.

There were twenty subjects in the study, with each one accomplishing 48 tracking runs. Thirteen subjects received biofeedback relaxation training, with seven also receiving active EMG feedback during their scoring runs, and five received no relaxation training at all. The other two subjects, both considered to be expert trackers, received relaxation training followed by active biofeedback on half their runs.

Four subjects continued past 48 scoring runs, receiving active biofeedback on half of their subsequent runs.

Limitations. Scheduling limitations and computer availability restricted the number of subjects to twenty.
This small number of subjects makes it more difficult to identify significant differences between groups.

Biofeedback relaxation training consisted of one 30-45 minute session per subject. This training was reinforced with 5-10 minutes of biofeedback prior to each tracking session. It could be argued that more intensive biofeedback training, such as one hour a day for two weeks, might lead to different experimental results.

Assumptions. The 18 subjects were assumed to be randomly selected into their three groups, with the exception of attributes specifically identified in the linear regression model. Each subject was assumed to be tracking to the best of his ability during each tracking run.

Organization

This thesis is divided into five chapters. Chapter I introduces the topic and provides background information. Chapter II describes the equipment used in the experiments. Chapter III discusses the experimental design and the methods used to gather, treat, and present the data. Chapter IV is an analysis and discussion of experimental results, and Chapter V presents a summary, conclusions, and recommendations. Appendices provide the experimental data and some computer analyses of results.
II Experimental Equipment

Two separate sets of equipment were used in these experiments. A tracking simulator was used to generate the tracking task and compute error scores, and biofeedback equipment was used to compute muscle activity levels and to provide audio biofeedback.

Biofeedback Equipment

Electromyogram (P303, Cyborg Corporation, 1977). The Cyborg P303 Clinical EMG was used to provide audio signals to those subjects receiving biofeedback and to measure muscle activity for all subjects. The subjects would hear a repetitive tone in their earphones. The pitch and repetition rate of the tone would increase with increasing EMG activity, with pitch variation possible from 100 Hz to 1000 Hz. Figure 1 is a diagram of the EMG controls.

![Figure 1. Cyborg P303 Clinical EMG (P303, Cyborg Corporation, 1977)]
Threshold level and range multiplier could be adjusted to allow for individual differences in tension level. Ranges available were 0.1-10 microvolts, 1-100 microvolts, and 10-1000 microvolts. Threshold level, the lowest level at which audio feedback is generated, could be selected within each range. Volume of audio feedback was also adjustable.

The Cyborg Q700 RMS Data Accumulator was used to transform the continuous EMG readings into averages that could be used in data analysis. The Q700 used Time Period Integration, the averaging of a signal over a period of time. A reset button was pressed to start the averaging process, and EMG data was averaged for a preset time period. At the end of the time period the average EMG level was displayed on light-emitting diodes, and averaging automatically began for the next time period. Figure 2 shows the front panel of the Data Accumulator.

Fig 2. Cyborg Q700 RMS Data Accumulator (Q700, Cyborg Corporation, undated)
Time periods available on the Q700 were ten seconds, one minute, and ten minutes. During tracking runs, readings were taken at one-minute intervals for three minutes.

Roll Axis Tracking Simulator

All tracking runs were performed and scored on the Roll Axis Tracking Simulator (RATS) at Aerospace Medical Research Laboratory, Wright-Patterson AFB. Although the simulator was capable of motion and disturbance in the roll axis, the preliminary benchmark experiments employed in this study used only pitch tracking with no motion.

Hardware. The simulator was a basic cockpit design with a pilot's seat and a control stick. The stick was a forward-back force control stick located approximately 30 cm to the right and 25 cm in front of the subject; an arm rest was located at a comfortable height to provide support for the subject's arm. The stick was approximately 14 cm high, and the subjects could use a combination of finger and thumb grips or their entire hand to manipulate it.

An 8-inch-diagonal television screen was used for the tracking display. The display was centered in azimuth approximately 70 cm from the subject's eyes, and within ten degrees of each subject's eye level.

Computers used to generate signals, integrate stick inputs, and provide scores were a Digital Equipment Corporation PDP 11/40 digital computer and an Electronics
Associates Incorporated 580 analog computer. The digital computer drove an X-Y oscilloscope, and a camera was used to convert the image on the oscilloscope to a video signal, which was transmitted by coaxial cable to the television screen in the simulator (Roark, 1979).

**Software.** The tracking task was an adaptation of a compensatory tracking task design by Bolt Beranek and Newman Incorporated (Roark, 1979). The design began with a human operator model, and added system dynamics to form a model of the overall tracking task.

The human operator model for processing continuous information is shown in Figure 3. System dynamics are described by $\mathbf{x}(t)$, the vector which describes the state of the system, and $\mathbf{w}(t)$, a noise or disturbance vector. Display, $\mathbf{y}(t)$, is a function of the state of the system, and
\( y(t) \) represents observation noise, the difference between the actual display and the perceived display. After a perceptual time delay, the operator reacts to the perceived display \( y_p(t) \) by estimating the state of the system \( x(t) \) and formulating a response activity \( y(t) \). In the case of a closed-loop continuous control system, the response activity is a control input to the system (Zacharias and Levison, 1978:5-6).

Using the human operator model just described, the tracking task was designed to meet two specific objectives:

a. Overall sensitivity of the task to changes in operator behavior induced by environmental stressors, and
b. Differential sensitivity of the task to qualitatively different stressors (Zacharias and Levison, 1978:5).

The objectives were chosen to enable measurement and identification of changes in performance due to slight changes in task environment.

One of the most basic determinants of performance is the set of dynamics used in the tracking task. If the dynamics are easy to control, tracking performance tends to be insensitive to environmental changes; if they are difficult to control, performance level can be highly sensitive to the same changes (Zacharias and Levison, 1978:16).

The RATS used unstable dynamics with a fixed instability, together with a loop input disturbance signal.
The general form of plant dynamics $P(s)$ is given by the following Laplace transform with transformation variable $s$:

$$P(s) = \frac{L}{s-L}$$

The plant pole location $L$ was equal to 2.0 radians per second. Score sensitivity tests conducted by Bolt Beranek and Newman showed this value to be a good compromise between insensitivity ($L=1.0$) and loss of control ($L=4.0$) (Zacharias and Levison, 1978:26).

The purpose of the loop input disturbance signal is to continuously move the target and necessitate continuous compensatory control actions by the human operator. It is important that the disturbance signal appear to the operator to be random; otherwise, the operator may begin to perceive a pattern and anticipate disturbances instead of reacting to them (Zacharias and Levison, 1978:21).

High-frequency disturbance signals can present extremely difficult tracking problems, but those signals can be attenuated in power through the use of a power spectral density (PSD) function. To combine high-frequency attenuation with random-appearing signals, the RATS input disturbance signal was constructed from 13 sinusoids whose PSD approximated the following continuous PSD function:

$$\phi_{dd}(w) = \frac{2a}{w^2 + a^2}$$
where "w" equals 25 Hz and "a" equals 0.5 radians per second (Zacharias and Levison, 1978:21,39).

Figure 4 is a block diagram of the tracking task. The RATS differs from the original model in that stick gain is incorporated into the plant dynamics and the disturbance signal is generated in the digital computer rather than the analog computer (Roark, 1979).

The specific plant dynamics used in these experiments were as follows:

\[ P(s) = \frac{KL}{s - L} e^{-t_0 s} \]

The stick gain K was used to convert from pounds of stick force to centimeters of plant command, and was set to 10 cm/pound. Thus, full-scale deflection of the target represented a force of approximately 0.6 pounds. The plant
dead-time (time delay) $t_0$, a processing and interface delay inherent in the simulator, was equal to 65 milliseconds (Roark, 1979).

A typical tracking display is shown in Figure 5. The display consisted of three horizontal lines, each 3.3 cm long. The two outer lines were centered vertically on the television screen, while the third line (the target) could move up and down between them. The target was also differentiated by a small vertical pip in its center.

Error scores were based on mean square displacement from the center of the screen, with samples taken 25 times.
per second for the duration of the scored run. Displace-
ment was measured in raster grid units, with one unit equal
to 0.02 cm. Thus, an average (weighted) displacement of
1.0 cm would produce a score of 50^2, or 2500; an average
(weighted) displacement of 0.4 cm would produce a score of
20^2, or 400. Scores were displayed on the television screen
after the conclusion of each run.
III Experimental Procedures

Data Gathering

Questionnaires. Each experimental subject filled out a short questionnaire prior to beginning the experiments. Questionnaire information was used to identify demographic variables, such as age and pilot experience, that might affect experimental outcomes. Additional information was gathered to allow for more detailed follow-on analysis and possible use of a tracking simulator with motion. A sample questionnaire is shown in Appendix A.

Twenty male subjects were used for the experiments. The youngest was 18 years of age, and the oldest was 36. Nineteen were right-handed or ambidextrous, and all had vision that was normal or corrected to normal.

Initial Experimental Protocol. The initial experimental design called for the subjects to be divided into two groups, an experimental group and a control group. Both groups would receive initial biofeedback training and reinforcement prior to each scoring session, but only the experimental group would receive active biofeedback; that is, audio biofeedback during the actual tracking runs. Each individual would have seven sessions in the simulator: one for biofeedback training and six for tracking, with eight scored tracking runs in each tracking session.
Biofeedback training and the subsequent use of the EMG were conducted with electrodes on the subject's forehead to measure the electrical activity of the frontalis muscles. In order to avoid confusing generalized tension measurements with active voluntary muscle activity, it was necessary to record activity from some muscle(s) not directly involved in the tracking task; for example, muscle activity in the right arm would not be indicative of general tension level in these experiments (Bolt Beranek and Newman Inc., 1979:29). Precedent for use of the frontalis muscles is found in Stoyva and Budzynski's research on tension headaches. Brown cites several advantages in their selection of the frontalis muscles: high tension levels of the frontalis were associated with tension headaches, relaxation of the muscles is relatively difficult, and biofeedback-associated relaxation effects spread to other muscles of the upper body, such as the shoulders and neck (Brown, 1974:154-155). Cyborg Corporation also recommends use of the frontalis for general relaxation training (P303, Cyborg Corp., 1977).

Each subject received an initial 30-45 minute biofeedback training session. The nature of the experiment and the equipment was described, and electrodes were secured to the subject's forehead with a head strap and electrode paste. The subject was then seated in the simulator, and earphones were put on. The subject was told to try to...
vary the biofeedback tone by changing the amount of forehead tension, trying to become more aware of what bodily changes accompanied a lowering of tension. EMG threshold levels were adjusted for each individual to insure that changing tension levels produced changing audio tones. Subjects were encouraged to note the effects of the following variables on tension: slackness of jaw, eyes open or closed, hand on or off the control stick, and amount of control stick pressure.

Tracking sessions consisted of five minutes of relaxation with biofeedback, followed by two blocks of four 3-minute scored tracking runs each. Time between runs varied from fifteen seconds to one minute, and time between blocks was approximately five minutes. Tracking sessions were scheduled for one hour, and were normally completed within 45 minutes.

Before each scoring run, the scoring control switch was in the "off" position and the autopilot was on. Immediately before the run, the autopilot would be turned off to activate control stick inputs. When the subject indicated he was ready for the run, scoring was initiated and the Data Accumulator was reset. EMG readings were recorded at one-minute intervals during the run, and tracking error score was recorded from the television screen after the end of the run.
The subjects were given two objectives for the tracking sessions. First, learn to track and minimize tracking error score. Second, if getting biofeedback while tracking, use the biofeedback to relax as much as possible. If not getting active biofeedback, try to relax as much as possible while tracking, using what was learned in previous biofeedback training.

**Changes in Experimental Design.** Two of the volunteers for the experiments had had a great deal of experience in tracking tasks similar to this one, and were considered tracking experts. It was decided to treat these individuals separately rather than including them in one of the two original groups. Each tracking session for these individuals would consist of four runs with biofeedback and four runs without biofeedback.

Three other subjects volunteered for additional experiments. After their original 48 tracking runs, they continued on to a maximum of 80 runs in all. Half of the extra runs were conducted with biofeedback and half without it. These changes allowed separate analysis with each of these individuals functioning as his own control.

Preliminary analysis of results early in the experimental program revealed no significant differences in performance between the control group and the experimental group. It was decided that merely varying the method of achieving a relaxed state might be too narrow a difference.
The question arose as to whether any conscious relaxation effort would result in improved performance.

To help resolve that question, it was decided to expand the scope of the study by adding a third group of subjects. Electrodes and earphones were used for EMG measurement and standardization of physical conditions, but no audio feedback or biofeedback training was given. These subjects were given only one objective for their six tracking sessions: learn to track and minimize tracking error score.

Data Treatment

Computer Data File. Data from each tracking run was punched onto a computer card in the following format:

<table>
<thead>
<tr>
<th>Column</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Subject number (01-20)</td>
</tr>
<tr>
<td>3</td>
<td>Dominant hand (0=right-handed or ambidextrous; 1=left-handed)</td>
</tr>
<tr>
<td>4-5</td>
<td>Age in years</td>
</tr>
<tr>
<td>6</td>
<td>Pilot or tracking experience (0=no previous experience; 1=some previous experience)</td>
</tr>
<tr>
<td>7</td>
<td>Experimental group (0=received training, but not active biofeedback; 1=received active biofeedback; 2=did not receive biofeedback training)</td>
</tr>
<tr>
<td>8-9</td>
<td>Total number of completed runs</td>
</tr>
<tr>
<td>10</td>
<td>Number of runs completed in current session</td>
</tr>
<tr>
<td>11-14</td>
<td>Tracking error score (to nearest integer)</td>
</tr>
<tr>
<td>15-17</td>
<td>Sum of three 1-minute EMG readings (times ten microvolts)</td>
</tr>
</tbody>
</table>

Information for columns three through seven was obtained from completed questionnaires. Individuals who indicated any experience in either piloting or tracking were classified as experienced in column six.
After all cards were punched, the data was catalogued on a computer disk file for ease of handling. The file contained 1,070 cases (cards). All subsequent computer runs, except those involving summary data, used the disk file rather than the punched cards.

Computer Analysis Techniques (Nie et al, 1975). Statistical Package for the Social Sciences (SPSS) program was used for all data analysis. The primary subprogram used was REGRESSION, with both stepwise and forced inclusion. Other subprograms used were CONDESCRIPTIVE, MANOVA, PARTIAL COVR, and SCATTERGRAM.

The cases were analyzed in three different ways: aggregated by individual, aggregated by run number, and individually. Individual cases provided the most data points, of course, but results had to be treated with caution. If a dummy variable for each subject were used, any between-group or demographic effects would be masked. Omitting such dummy variables, however, would lead to highly distorted levels of significance: each scored run would be treated as if it had been accomplished by a different individual.

Cases aggregated by individual provided the truest tests of between-group and demographic differences. Analysis was accomplished twice: once using an overall average score for each individual, and a second time using only runs 25-48, after most of the learning of the task had
already occurred.

Cases aggregated by run number could show no individual differences, but they did provide valuable insight into the nature of the learning curve. Using aggregate scores smoothed out much of the fluctuation found in individual learning curves.

The effect of learning had to be considered in the data analysis. E. B. Cochran described characteristics of learning for short cycle operations as follows:

A close relationship between unit output and unit cost, with the latter shrinking as the former expands in a rather "linear" fashion when plotted on log/log paper, and

An eventual leveling out of cost, as the operator reaches the limits of his capability and ability to find methods improvements (Cochran, 1968:19).

In these experiments, unit output was the number of runs completed and unit cost was the error score. The log/log relationship was accounted for by using natural logarithms of run number and error score as the relevant variables whenever the learning effect was considered. The leveling-out effect could have been accounted for, if necessary, by equating all run numbers beyond the point where all learning had occurred.

Data Presentation and Reporting

Text. The analysis of results is shown in Chapter IV. The chapter is divided into three sections: learning
curves, comparison of groups, and within-group and individual results.

Appendices. There are three appendices to this thesis. Appendix A is the questionnaire that was administered to all experimental subjects. Appendix B is a tabular presentation of experimental results, including information from each individual's questionnaire. Appendix C includes a scatter diagram of each individual's learning curve, as well as an aggregate learning curve and an aggregate learning curve adjusted for fatigue.
IV Results and Analysis

This chapter gives the analysis of experimental results, and shows some of the different approaches that were used in analyzing the data. The chapter is in three parts. First, scores are fit to learning curves and the log/log nature of the learning curve is demonstrated; second, results are compared across groups to identify effects of the experimental variables. Finally, within-group and individual results are examined. Individual experimental results are tabulated in Appendix B.

Significance, as used in this chapter, is the probability that the sample population will yield the computed (or higher) coefficient in the regression equation, given that the coefficient for the overall population is zero. A highly significant predictor variable would have a low numerical significance.

Learning Curves

Plots of score against run number for the first four subjects to complete 48 runs (subjects 1, 2, 4, and 5) showed irregular lines convex to the origin of the graph, suggesting an inverse or negative logarithmic relationship between score and run number. When semi-log paper was used, the plots (logarithm of score against run number)
still retained a definite convexity, but the use of log/log paper (plotting logarithm of score against logarithm of run number) produced patterns that seemed to be approximately linear. A later search of the literature on learning curves (Cochran, 1968, and others) confirmed the notion of a log/log relationship between performance and experience.

Because of the strong influence of the learning effect, most of the data analysis used the natural logarithm of the score, rather than the score itself, as the criterion variable. Linear regression with such a variable yields predictor variables that have multiplicative effects on predicted score. Since it was felt that some effects may have been additive rather than multiplicative, some analysis with averaged data for each subject used an average raw score as the criterion variable.

Scatter Diagrams. Scatter diagrams were run to produce a visual depiction of each subject's learning experience. Although individual learning patterns and amount of scatter varied a great deal, all curves seemed to generally fit the predicted logarithmic relationship. Percent of variance explained ($R^2$) varied among individuals from a low of 38.8 percent to a high of 94.2 percent, with mean $R^2$ equal to 76.9 percent. Scatter diagrams are in Appendix C.

When fluctuations were removed by averaging logarithm of score across all individuals for each run, the predictive power of the learning curve model improved dramatically.
R² for average logarithm of score was 97.9 percent. When regression analysis showed fatigue to have a significant effect (significance less than .001) on average performance, a fatigue adjustment was added to the averages. R² for the adjusted model increased to 98.5 percent, and the scatter diagram gave convincing support to the applicability of the log/log learning model.

**Leveling Off.** One other aspect of learning is a leveling-off point, beyond which performance does not improve. Bunching of data caused by the log/log model makes it difficult to identify such a point with much precision, and visual examination of a performance diagram may be the easiest way to locate the approximate leveling-off point. Examination of the adjusted group diagram suggests that leveling off did not occur before the 38th run, and may not have occurred after run number 48. Further analysis of those individuals who went beyond 48 runs revealed no significant additional learning, which suggests that virtually all learning had occurred by the 48th run.

**Interruption of Learning.** Because of a combination of final examinations, school vacation, and non-availability of the RATS, seven of the subjects had a five-week interruption between tracking sessions. Each of these subjects was given three minutes of refamiliarization time with the control stick before beginning his first session after the interruption. Examination of scores before and after the
TABLE I
Overall Regression on Ln(Score)

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>R²</th>
<th>R² CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln(Run)</td>
<td>-.537</td>
<td>.000</td>
<td>.393</td>
<td>.393</td>
</tr>
<tr>
<td>Expert</td>
<td>-.826</td>
<td>.000</td>
<td>.529</td>
<td>.136</td>
</tr>
<tr>
<td>Left-handed</td>
<td>.292</td>
<td>.000</td>
<td>.536</td>
<td>.007</td>
</tr>
<tr>
<td>EMG</td>
<td>.747E-2</td>
<td>.000</td>
<td>.539</td>
<td>.002</td>
</tr>
<tr>
<td>EMG²</td>
<td>-.168E-4</td>
<td>.000</td>
<td>.547</td>
<td>.009</td>
</tr>
<tr>
<td>Training</td>
<td>.258</td>
<td>.000</td>
<td>.560</td>
<td>.013</td>
</tr>
<tr>
<td>Biofeedback</td>
<td>.343</td>
<td>.000</td>
<td>.562</td>
<td>.002</td>
</tr>
<tr>
<td>Fatigue</td>
<td>----</td>
<td>.323</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Age</td>
<td>----</td>
<td>.535</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>Pilot</td>
<td>----</td>
<td>.656</td>
<td>----</td>
<td>----</td>
</tr>
</tbody>
</table>

interruption revealed no significant shifts in learning curves due to the interruptions.

Comparison of Groups

Initial Analysis. Initial linear regression analysis was performed using each run as a separate case and including EMG and EMG² as predictor variables. Although computed significances were unrealistic, the analysis served as a baseline to indicate trends in the data.
There were ten variables considered for inclusion in the regression equation, and seven entered the equation with F-statistics greater than 3.0 (see Table 1). Variables having a positive effect on logarithm of score were left-handedness, EMG, biofeedback, and training. "Biofeedback" refers to the group receiving active biofeedback while tracking; while "training" refers to the group receiving biofeedback training only. Variables with a negative effect were logarithm of run number (learning), tracking expert identifier, and $\text{EMG}^2$. The variables not entering the equation were age, pilot identifier, and fatigue. "Fatigue" was defined for purposes of analysis to be the number of runs since the last rest break.

All three of the omitted variables would seem intuitively to be good predictors. Some explanation of why they were not may help increase understanding of the regression model.

One might expect increased age to have a detrimental effect on performance, but no such effect was observed. Two factors help account for this. First, the sample size of twenty was relatively small. The smaller the sample, the easier it is for a group's performance to not correlate highly with that of the overall population. Second, the age spread of the sample population was small; the youngest subject was 18 years old and the second-youngest was 22, while the oldest was 36 and the second-oldest was 34.
Pilots might be expected to have lower error scores because of better hand-eye coordination and more experience with tasks somewhat similar to the one being measured. Again, two factors help explain why this was not so. First, control stick inputs were, in a sense, opposite to initial pilot expectations; forward pressure drove the target up, and backward pressure drove the target down. Second, and perhaps most important, is the difference between optimal scoring strategy and normal pilot techniques. One subject, a pilot, remarked, "Don't be afraid to overshoot; forget about bringing it back gently to mid-point. Piloting techniques don't work on this task."

Fatigue would be expected to have a detrimental effect on score. This effect did exist, but was masked in this regression model by the use of EMG and EMG^2 as predictor variables. In the stepwise entry of variables, fatigue had a significance level of .039 before EMG and EMG^2 entered the equation. Later analysis continued to use fatigue as a variable of interest.

Of the variables that entered the regression equation, three can be explained without much further discussion. The first is learning, which was examined in the previous section. Second is the tracking expert identifier, which separates subjects 8 and 11 from the rest of the sample population because of their extensive simulator experience. Although they accomplished half their runs with biofeedback
and half without, failure to separate them would bias the results against the control group. The third variable is left-handedness. Since control was exercised with the right hand only subject 3 was left-handed, his scores should not be directly compared with those of the rest of the sample population.

EMG and EMG^2 will be treated together in the discussion. The squared term was included in the analysis to investigate a possible curvilinear relationship between tension and performance; specifically, it had been hypothesized that there was an optimal tension level from which deviation in either direction would degrade performance. The regression model showed both the linear and squared terms to be highly significant (significance .00), but with opposite signs from those hypothesized; the linear term was positive and the squared term negative, producing a maximum positive effect on predicted score at an EMG level of 22.2 microvolts. Fewer than two percent of the runs had EMG levels that high, and increasing tension was generally associated with higher error scores.

One difficulty in using EMG as a predictor variable is that EMG readings were part of the experimental results rather than being previously defined inputs. There is some conceptual difficulty in using EMG readings to predict error scores; higher tension may cause higher scores, but it is also possible that higher scores (that is, target
TABLE II

Regression on Average Ln(Score)

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>$R^2$</th>
<th>$R^2$ CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofeedback</td>
<td>.177</td>
<td>.642</td>
<td>.016</td>
<td>.016</td>
</tr>
<tr>
<td>Pilot</td>
<td>-.102</td>
<td>.742</td>
<td>.018</td>
<td>.003</td>
</tr>
<tr>
<td>Age</td>
<td>.858E-2</td>
<td>.790</td>
<td>.025</td>
<td>.007</td>
</tr>
<tr>
<td>Left-handed</td>
<td>.118</td>
<td>.858</td>
<td>.027</td>
<td>.002</td>
</tr>
<tr>
<td>Training</td>
<td>.883E-1</td>
<td>.814</td>
<td>.032</td>
<td>.005</td>
</tr>
</tbody>
</table>

displacements from center) cause higher tension. The possible feedback effects of tension and target displacement cannot be easily accounted for in the simple linear regression model.

The last two variables in the equation were the group differentiators for the biofeedback group and the biofeedback training group. The final regression equation showed both groups to have a highly significant (significance .000) derogatory effect on score, but significance levels are highly overstated. Each subject produced 48 or more cases for this model, but each case is treated statistically as if it came from a different subject. Even in this distorted model, biofeedback training did not show a significant effect (significance was .115) until after EMG entered the equation.
TABLE III

Regression on Average Ln(Score), Last Half

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>$R^2$</th>
<th>$R^2$ CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofeedback</td>
<td>.270</td>
<td>.474</td>
<td>.074</td>
<td>.074</td>
</tr>
<tr>
<td>Pilot</td>
<td>-.623E-1</td>
<td>.838</td>
<td>.077</td>
<td>.003</td>
</tr>
<tr>
<td>Age</td>
<td>-.633E-2</td>
<td>.842</td>
<td>.081</td>
<td>.004</td>
</tr>
<tr>
<td>Left-handed</td>
<td>.331E-1</td>
<td>.959</td>
<td>.081</td>
<td>.000</td>
</tr>
<tr>
<td>Training</td>
<td>.653E-1</td>
<td>.860</td>
<td>.083</td>
<td>.002</td>
</tr>
</tbody>
</table>

Overall $F$-Value = 0.218
Significance = .948

Aggregation by Subject. Additional regression analyses were performed with one case per subject. Subjects 8 and 11 were not included, as they could not be identified with a specific experimental group. Only the first 48 runs for each subject were considered. Regression analyses were run using three different aspects of performance as criterion variables: average logarithm of score, average logarithm of score for the last 24 runs (after most learning had occurred), and average raw score for the last 24 runs. Tables 2 through 4 show the results of these regression analyses.

Predictor variables for all three regressions were age, pilot identifier, left-handedness, biofeedback, and training. None of the variables had any significant predictive power (significance less than .200) in any of the
A 48-run learning curve was used for each subject, and the slope (coefficient of logarithm of run number) and Y-intercept (estimated logarithm of score for the first run) became variables in the ensuing regression analysis. Slope times minus one, or rate of learning, became the new criterion variable; Y-intercept, biofeedback, and training were the predictor variables (Table 5). The regression equation showed biofeedback training (significance .585) to have no significant effect on rate of learning, while biofeedback (significance .035) and
TABLE V
Regression on Rate of Learning

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>$R^2$</th>
<th>$R^2$ CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofeedback</td>
<td>-.161</td>
<td>.035</td>
<td>.390</td>
<td>.390</td>
</tr>
<tr>
<td>Y-Intercept</td>
<td>.112</td>
<td>.037</td>
<td>.561</td>
<td>.171</td>
</tr>
<tr>
<td>Training</td>
<td>-.374E-1</td>
<td>.585</td>
<td>.571</td>
<td>.010</td>
</tr>
</tbody>
</table>

Overall F-Value = 6.20  Significance = .007

Y-intercept (significance .037) did have significant effects. Rate of learning was positively correlated with Y-intercept and negatively correlated with the presence of biofeedback. The Y-intercept effect is intuitively appealing; the better the initial performance, the less that remains to be learned. The biofeedback effect may be explained by viewing the biofeedback audio signal as a distraction from the primary tracking task; since tracking receives only divided attention, it is learned more slowly.

The last analysis performed with one case per subject was a regression analysis using EMG as the criterion variable (Table 6). Comparison of groups showed both the biofeedback and biofeedback training groups to have significantly lower readings than the control group (significance less than .010). This was to be expected, since the control group received no specific instructions to relax. In addition there was a slight, but not statistically
### TABLE VI

Regression on EMG

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>R²</th>
<th>R² CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofeedback</td>
<td>-72.1</td>
<td>.002</td>
<td>.192</td>
<td>.192</td>
</tr>
<tr>
<td>Training</td>
<td>-61.3</td>
<td>.008</td>
<td>.500</td>
<td>.308</td>
</tr>
<tr>
<td>Biofeedback (compared with training)</td>
<td>-10.8</td>
<td>.569</td>
<td>.192</td>
<td>.192</td>
</tr>
<tr>
<td>Control Group</td>
<td>61.3</td>
<td>.008</td>
<td>.500</td>
<td>.308</td>
</tr>
</tbody>
</table>

significant, difference between the biofeedback and training groups (significance .569). So it appears active biofeedback aided in relaxation, but was counterproductive in learning the tracking task.

**Within-Group and Individual Results**

**Within-Group Results.** This section deals with those subjects who performed tracking runs both with and without active biofeedback, and who could thus serve as their own control group. A big advantage in this method of analysis, especially with small groups, is that all demographic and individual differences are neutralized. A disadvantage that is not directly measurable is that the subjects may unknowingly vary their performances, subconsciously trying
TABLE VII
Regression on Ln(Score) with Internal Control

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>COEFFICIENT</th>
<th>SIGNIFICANCE</th>
<th>R^2</th>
<th>R^2 CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individuals</td>
<td>----</td>
<td>----</td>
<td>.588</td>
<td>.588</td>
</tr>
<tr>
<td>Ln(Run)</td>
<td>-.313</td>
<td>.000</td>
<td>.798</td>
<td>.210</td>
</tr>
<tr>
<td>Biofeedback</td>
<td>.454E-1</td>
<td>.155</td>
<td>.798</td>
<td>.001</td>
</tr>
<tr>
<td>Fatigue</td>
<td>-.519E-2</td>
<td>.728</td>
<td>.799</td>
<td>.001</td>
</tr>
<tr>
<td>EMG^2</td>
<td>-.117E-4</td>
<td>.001</td>
<td>.799</td>
<td>.000</td>
</tr>
<tr>
<td>EMG</td>
<td>.727E-2</td>
<td>.001</td>
<td>.810</td>
<td>.011</td>
</tr>
</tbody>
</table>

Overall F-Value = 93.5, Significance = 0

to help the experimenter. In addition, certain comparisons are not possible, such as between those who have and have not received biofeedback training.

Subjects 3, 4, 7, 8, and 11 all participated in tracking runs with and without biofeedback. For subjects 3, 4, and 7, the first 48 runs were not used in this analysis. After allowing for learning and for individual differences, the effects of biofeedback and EMG on logarithm of score were analyzed, both separately and together (Table 7). Neither variable had any significant predictive power (significance less than .200) in the regression equation.

Individual Results. A regression analysis was performed on logarithm of score with each run as a separate case, but using dummy variables to account for individual
TABLE VIII
Overall Regression on Ln(Score), Allowing for Individual Differences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Significance</th>
<th>$R^2$</th>
<th>$R^2$ CHANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ln(\text{Run})$</td>
<td>-.545</td>
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Fatigue entered the regression equation with a significance of .006, but after EMG (significance .000) and $EMG^2$ (significance .001) entered the equation, the significance of fatigue became .122. The effect of EMG and $EMG^2$ was to make predicted score a monotonically increasing function of EMG throughout the range of observed EMG values.

Separate regression equations were computed for each of the twenty subjects. Criterion variable was logarithm of score, and predictor variables were logarithm of run number (learning), fatigue, EMG, and $EMG^2$. Some similarities among subjects were apparent, but the differences that existed showed that not all individuals react the same way to the same experimental variables.
Learning was a highly significant predictor (significance .000) for all subjects. It was felt originally that the two tracking experts might not show any significant learning, but this task was different enough for them that substantial learning did occur.

Fatigue was a significant predictor variable (significance less than .050) for six of the twenty subjects. For one of the six, though, fatigue significantly improved (significance .013) performance instead of degrading it. Perhaps for him, "recent reinforcement of learning" would be a more accurate term than "fatigue".

EMG was a significant predictor variable (significance less than .050) for five of the twenty subjects, accompanied by EMG for two of the five. For two of the subjects, predicted scores rose with EMG throughout its range, and two others had predicted scores rising with EMG through most of its range. Only subject 17 showed a predominantly negative relationship between EMG and predicted score.

It should be noted that neither fatigue nor EMG was a significant predictor variable for a majority of the subjects, although both were significant in aggregate analysis.
Summary, Conclusions, and Recommendations

Summary

Methods. Experiments consisted of three minutes of target tracking with a force control stick, with each three-minute run scored based on mean squared error. Forehead muscle tension (EMG) readings were taken three times (each 60 seconds) during each tracking run.

There were 20 male subjects, and each tracked for a minimum of 48 runs. The subjects were divided into three groups; the control group received no biofeedback training, the first experimental group received biofeedback training and an active audio biofeedback signal while tracking, and the second experimental group received biofeedback training only. The two experimental groups were told to try to relax while minimizing tracking scores; the control group was told only to try to minimize tracking scores.

Results. The first significant result that was observed was learning. Although individual scores fluctuated a great deal, average performance across all subjects showed an almost steady improvement with experience. The applicability of a log/log improvement model to these experiments was demonstrated, as the log/log relationship between score and run number produced an $R^2$ of 98 percent.
The main result of analyses using a single representative measure of performance for each subject was that the sample population showed no significant differences between groups and no significant differences caused by demographic factors such as age.

The one area that did produce a significant group difference was rate of learning, or slope of the learning curve. The presence of active biofeedback had a significant detrimental effect on rate of learning, a result that was opposite to the hypothesis being tested.

When each run was considered and individual differences were accounted for, fatigue was shown to be a significant factor in predicting performance. EMG was also a significant predictor, and the addition of EMG to the regression equation caused the removal of fatigue as a significant predictor. This suggests that perhaps fatigue is incorporated into generalized muscle tension.

When separate equations were computed for each subject, individual results varied considerably. Fatigue significantly degraded performance for five subjects, but significantly improved performance for one subject. Similarly, increased tension was significantly associated with degraded performance for four subjects, but was significantly associated with improved performance for one other subject.
Conclusions

In general, biofeedback and biofeedback training did not significantly affect performance in the direction hypothesized. One possible explanation for this is that there were two counteracting effects working simultaneously. First, the biofeedback training and audio signals caused a reduction in tension, which in turn caused an improvement in performance. At the same time, the conscious attempt to relax and the presence of the audio signals were distractions that prevented the subjects' full concentration on the tracking task, thereby degrading performance.

The presumption that biofeedback relaxation training causes a reduction in tension was not directly tested in these experiments, as the control group received no training or instructions concerning relaxation. The difference in tension between the active biofeedback and the biofeedback training groups was not significant for this sample population, although more extensive sampling might show that such a difference does exist.

For the overall population, there was a significant relationship among fatigue, tension, and performance. Regression results suggest that fatigue may not affect performance directly; instead, fatigue causes higher tension, which in turn leads to degraded performance.

The last conclusion is that people are different, which seems to be a basic requirement for understanding
human performance. One cannot expect different individuals to react the same way to the same situation, and the realization of that fact must be incorporated in any analysis of experimental results.

Recommendations

Unless other research demonstrates advantageous effects of biofeedback on performance, biofeedback systems should not be included as part of new aircraft design.

It would not appear to be productive to continue these experiments without changes in experimental methodology. Some of the methodology changes that might prove fruitful are as follows:

(1) Raise the EMG threshold for the active biofeedback group so that no audio tone is heard when the subject is relaxed. The audio signal would not be a constant distraction; it would come on only to warn of increased tension.

(2) Include some kind of performance pretest before introducing an experimental variable. This would help account for pre-existing individual differences without the necessity for a large sample population.

(3) Give the control group a relaxation training session without biofeedback, and include relaxation as one of their performance objectives. The biofeedback would then be the only experimental variable, and its effects might be isolated more clearly.

(4) Allow each individual to be his or her own control after learning has occurred, sometimes receiving biofeedback and sometimes not. This would eliminate all the problems of individual differences, (differential reactions, fatigue, etc.), though it might introduce other biases.
BIBLIOGRAPHY


APPENDIX A

QUESTIONNAIRE
Personal Data Information for Tracking Biofeedback Experiments

The following personal information questions are for use by the scientists running the biofeedback tracking experiments in which you are taking part. Be assured that this information will not be divulged to anyone except the project scientists.

Your decision as to whether to supply this information is strictly voluntary. However, without this data we will be unable to properly evaluate your biofeedback EMG and tracking scores. Therefore, we earnestly solicit your help in providing accurate responses to these questions.

Thank you for taking the time to help us in this effort. We sincerely appreciate your interest in our work and your decision to be a volunteer. If you would like a copy of the report resulting from these experiments, please supply your address below:
1. What is your age (in years)? ____________

2. What is your sex?
   a. Male   b. Female

3. How much do you weigh (in pounds)? ____________

4. How tall are you? ____________

5. What is your highest level of education now?
   a. Non-high school graduate
   b. High school graduate (include GED or equivalency)
   c. Some college
   d. College graduate (BA, BS, or equivalent)
   e. Graduate study but no graduate degree.
   f. Master's degree
   g. Doctor's degree (PhD, MD, LLB, EdD, etc.)

6. What is your marital status?
   a. Married   c. Divorced, not remarried
   b. Single, never married   d. Legally separated
   e. Widow/Widower

7. Which of the following best describes you?
   a. Right-handed   b. Left-handed   c. Ambidextrous

8. Would you consider yourself unusually susceptible to motion sickness? (For example, do you get "car sick" easily, or get motion sick on carnival rides?)
   a. Yes   b. No

9. Do you have a history of double vision, eye surgery, best corrected vision less than 20/20, abnormal depth perception, or decreased visual field?
   a. Yes   b. No

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10. Have you ever had any of the following diseases? (Circle yes answers)
   a. Diabetes
   b. Multiple Sclerosis, seizure disorder, other chronic neurological disease, or an abnormal brain wave test.
   c. Head injury resulting in disturbance of consciousness.
   d. Fainting spells or low blood pressure.
   e. Psychiatric disorder.
   f. Any heart disorder, abnormal electrocardiogram, or decrease in exercise tolerance.
   g. Alcoholism
   h. Blood in your stools or ulcerative colitis
   i. Blood in your urine or kidney disease.
   j. Chronic liver or lung disease.
   k. High blood pressure.
   l. Inner ear problems.

11. Are you currently taking any drugs or medication? (Other than vitamins or birth control pills.)
   a. Yes   b. No

12. Have you taken any drugs or medication (legal or otherwise) in the past two months? (Other than vitamins, birth control pills, or over-the-counter pain relievers.)
   a. Yes   b. No
   If yes, please describe briefly:

13. Do you have full use and range of motion of all extremities and spine?
   a. Yes   b. No

14. Do you have, or have you had, any other medical condition(s) of which you feel the investigator should be aware?
   a. Yes   b. No
If answered yes to question 14, please describe briefly:

15. What is your flying status?
   a. Rated pilot
   b. Not a rated pilot, but holding a private pilot's license.
   c. Some piloting experience, but not a pilot.
   d. No piloting experience.

16. Do you have any previous target-tracking experience? (Air-to-air combat, gunship sensor operator, etc.)
   a. Yes    b. No
   If yes, please describe briefly:

17. Do you have any previous experience with biofeedback or the EMG (electromyogram)?
   a. Both biofeedback and EMG.
   b. Biofeedback, but not EMG.
   c. EMG, but not biofeedback.
   d. None
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**TABLE IX. EXPERIMENTAL RESULTS, SUBJECT 1**
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except as indicated (*)

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TABLE XXVIII. EXPERIMENTAL RESULTS, SUBJECT 20
APPENDIX C

LEARNING CURVE SCATTER DIAGRAMS
FIGURE 6. LEARNING CURVE, SUBJECT 1

NATURAL LOGARITHM OF RUN NUMBER

SUBJECT 01
Y Intercept = 8.863
Slope = -0.494
R Squared = 0.676
SUBJECT 02

Y Intercept = 8.807

Slope = -0.664

R Squared = 0.885

FIGURE 7. LEARNING CURVE, SUBJECT 2
FIGURE 8. LEARNING CURVE, SUBJECT 03

SUBJECT 03
Y Intercept = 8.279
Slope = -0.412
R Squared = 0.646
FIGURE 10. LEARNING CURVE, SUBJECT 5.

SUBJECT 05

Y Intercept = 9.684
Slope = -0.586
R Squared = 0.837
SUBJECT 06
Y Intercept = 7.211
Slope = -.269
R Squared = .511

FIGURE 11. LEARNING CURVE, SUBJECT 06
NATURAL LOGARITHM OF RUN NUMBER

SUBJECT 07
Y Intercept = 7.636
Slope = -0.502
R Squared = 0.822

FIGURE 12. LEARNING CURVE, SUBJECT 07
Figure 13. Learning Curve, Subject 08

Subject 08

Y Intercept = 7.585
Slope = -0.531
R Squared = 0.892
FIGURE 15. LEARNING CURVE, SUBJECT 10

Y Intercept = 7.606
Slope = -.266
R Squared = .388
Subject 11

Y Intercept = 6.492
Slope = -.231
R Squared = .570

Figure 16. Learning Curve, Subject 11
SUBJECT 12

Y Intercept = 8.534
Slope = -0.714
R Squared = 0.911

FIGURE 17. LEARNING CURVE, SUBJECT 12
SUBJECT 13

Y Intercept = 8.872
Slope = -0.754
R Squared = 0.911

FIGURE 18. LEARNING CURVE, SUBJECT 13
Figure 19. Learning Curve, Subject 14

Subject 14

Y Intercept = 2.684
Slope = -0.593
R Squared = 0.795
SUBJECT 15
Y Intercept = 8.950
Slope = -0.775
R Squared = 0.866

FIGURE 20. LEARNING CURVE, SUBJECT 15
 SUBJECT 17  
Y Intercept = 8.983  
Slope =  -0.508  
R Squared = 0.774

FIGURE 22. LEARNING CURVE, SUBJECT 17
SUBJECT 18

Y Intercept = 6.695
Slope = -0.734
R Squared = 0.942

FIGURE 23. LEARNING CURVE, SUBJECT 18
FIGURE 24. LEARNING CURVE, SUBJECT 19

SUBJECT 19
Y Intercept = 2.429
Slope = -0.539
R Squared = 0.503
SUBJECT 20

Y Intercept = 8.328

Slope = - .545

R Squared = .986
FIGURE 26. LEARNING CURVE, 20-SUBJECT AVERAGE

SUBJECT MEAN
Y Intercept = 8.377
Slope = -0.540
R Squared = 0.979
FIGURE 27. LEARNING CURVE, 20-SUBJECT AVERAGE ADJUSTED FOR FATIGUE

SUBJECT ADJ MEAN

Y Intercept = 8.340
Slope = -0.545

R Squared = 0.986
VITA

Mark Charles Kipperman was born on 29 June 1947 in Trenton, New Jersey. He graduated from high school in Coronado, California in 1964. He attended Harvey Mudd College, Southwestern College, and San Diego State University, receiving a Bachelor of Arts degree in mathematics from the latter in 1968. In 1969 he was commissioned in the USAF through the ROTC program at San Diego State. He served for two years as an electronics systems officer at La Junta, Colorado, before being assigned to Mather AFB, where he received his navigator wings in October 1972. Subsequent assignments were to Dover AFB as a C-5 navigator and air operations staff officer, and to Hurlburt Field as an AC-130H fire control officer. He entered the Air Force Institute of Technology in August 1978. He and his wife, the former Mary Brigid McAteer, have two daughters, Elizabeth and Sarah.

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