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Quantitative EEG Patterns of Differential In-flight Workload

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ABSTRACT

Four test pilots were instrumented for in-flight EEG recordings using a custom portable recording system. Each flew six, two minute tracking tasks in the Calspan NT-33 experimental trainer at Edwards AFB. With the canopy blacked out, pilots used a HUD display to chase a simulated aircraft through a random flight course. Three configurations of flight controls altered the flight characteristics to achieve low, moderate, and high workload, as determined by normative Cooper-Harper ratings. The test protocol was administered by a command pilot in the back seat. Corresponding EEG and tracking data were compared off-line.

Tracking performance was measured as deviation from the target aircraft and combined with control difficulty to achieve an estimate of "cognitive workload". Trended patterns of parietal EEG activity at 8-12 Hz were sorted according to this classification. In all cases high workload produced a significantly greater suppression of 8-12 Hz activity than low workload. Further, a clear differentiation of EEG trend patterns was obtained in 80% of the cases. High workload produced a sustained suppression of 8-12 Hz activity, while moderate workload resulted in an initial suppression followed by a gradual increment. Low workload was associated with a modulated pattern, lacking any periods of marked or sustained suppression.

These findings suggest that the quantitative analysis of appropriate EEG measures may provide an objective and reliable in-flight index of cognitive effort that could facilitate workload assessment.

INTRODUCTION

The referential electroencephalographic (EEG) signal, obtained from one active EEG electrode referenced to an indifferent site, such as the earlobe, reflects the summated electrical activity from pools of neurons around the active site. This summation depends upon the collective behavior of individual cortical neurons which, in turn, reflects the presence or absence of input to these neurons (Anderson and Anderssen, 1968). In the non-engaged, eyes closed state metabolic and circuit influences at a major cortical input source, the thalamus, cause some of its elements to discharge synchronously, and to send gated volleys to related areas of cortex (Steriade and Llinas, 1988). These gated excitatory volleys from thalamus give rise to rhythmic cortical field potentials that produce a dominant 8-12 Hz pattern in the corresponding EEG.

When the eyes are opened this pattern is attenuated, or "blocked" (Berger, 1930). This is presumed to result from the

fact that many cells become active and cease their gated discharge. However, not all cells are activated, and a sufficient number remain in the gated state so as to produce residual activity in the dominant frequency band of the EEG. With further cognitive challenge additional cells are activated but primarily in brain sites related to that challenge. Thus, differentially localized further attenuation of 8-12 Hz activity has been documented (Serman et al, 1992). Localized decreases in this activity were found to be related specifically to signal processing and were not a simple consequence of increased movement.

The discovery of this meaningful relationships between the EEG and cognitive effort was facilitated by the application of quantitative frequency analysis methods. The use of the Fast Fourier Transform to achieve quantitative spectral estimates of frequency density simultaneously at many cortical recording sites has provided a sensitive and efficient EEG tool for this application. The combination of a potentially reliable EEG metric for cognitive effort, and the capacity for an efficient quantitative assessment of this metric, suggested to us that an objective, physiological measurement of "cognitive workload" could now be achieved. We report here on a preliminary assessment of this measurement within the context of an in-flight air-to-air tracking task in the Calspan NT-33 experimental training aircraft. This study sought to advance the search for an objective, biological index of workload.

METHODS

Four 90 minute designated test flights were carried out in the Calspan NT-33 aircraft at the Test Pilot School, Edwards Air Force Base, California. This specially configured two-seat trainer aircraft provides for systematic modification of both aircraft handling characteristics and HUD avionics displays. Four volunteer test pilots were specially instrumented for EEG recording during these flights.

A portable EEG recording system for in-flight applications has been under development in our laboratory for the past five years. This system consists of a fire-resistant cloth helmet liner containing 12 pre-positioned EEG recording sites marked by velcro-sealed ports. Gold-plated recording electrodes are hard-wired to adjacent custom-designed, miniature pre-amplifier units. Inputs from linked earlobe references are connected to the output of these preamplifier units to provide for referential (monopolar) EEG recordings. The custom preamplifier units, developed in collaboration with the Teledyne Corporation, provide very high input impedance (10 megaohms), a high-pass filter, and an instrumentation amplifier. These units remove all DC variations of the input signal and significantly attenuate low frequency artifact. They also provide amplification at the signal source and a high common-mode rejection ratio.

The preamplifier outputs are led through a light-weight coaxial cable to a second stage filter/amplification unit. This

unit uses a six layer printed circuit board to accomplish analog signal conditioning, including filtering and second stage amplification. It is carried, together with a DC battery power supply unit, time-code generator, audio communications patch, and microrecorder in the pockets of a modified standard flight vest. The second-stage amplifier provides isolation and variable gain for matching output level to recorder input level requirements. Downstream from the isolation amplifier are two switch-capacitor filter banks (3rd order high-pass and 5th order low-pass) which narrow the EEG bandwidth to a range of 4-16 Hz, and provide anti-aliasing and noise rejection for the recorded signal. An audio patch connection between the aircraft intercom system and one channel of the microrecorder provides a continuous record of vocal transactions during the flight. The microrecorder provides for up to three hours of continuous recording of EEG and audio communications data.

Six sequential tracking tests were performed by each pilot. A blue helmet visor together with an orange canopy cover created blackout conditions restricting control to the HUD instrumentation. Each test required continuous tracking performance over a period of 1.5 to 2 minutes. These were marked on the data tapes by verbal protocol and by a special audio tone coded for the start and finish of each test. A continuous video record of the HUD display was recorded throughout the flight.

Unpredicted, random movements of the HUD target aircraft were matched by the pilot flying the T-33 aircraft into corresponding orientations. Accuracy was measured as sampled deviation from target throughout the test. Three configurations of flight controls altered the flight characteristics of the aircraft to achieve low, moderate, and high workload, as determined by previously registered normative Cooper-Harper ratings. The test protocol was administered by a command Calspan pilot in the back seat.

Space and technical considerations for this test limited EEG recording to four channels, including F3, T4, P3, and P4, placed according to the International 10/20 System. These sites were selected on the basis of previous findings. EEG recording was continuous during each test flight. Additionally, two minute reference periods of eyes closed and eyes open were obtained prior to and during each flight. Data were subsequently downloaded to laboratory computers off-line, and subjected to digital transform and Fast Fourier Analysis. Log transformed spectral magnitude values in the 8-12 Hz frequency band were generated for sequential two-second epochs and tabulated for the baseline conditions and for each tracking test segment. EEG data were plotted graphically for each tracking test for magnitude, trend, and pattern analysis. Statistical comparisons used the Analysis of Variance Test.

RESULTS

As in previous studies, EEG spectral values in the 8-12 Hz frequency band were found to be highest during the eyes closed

condition and to decrease significantly with eyes open. A further attenuated and/or differential modulation was seen during the tracking tests. Tracking test EEG data from some recording sites was fragmented due to a preamplifier design problem that has since been corrected.

The tracking tests were scored for three categories of "cognitive workload", according to a scale which combined both flight characteristics and actual performance. Thus, both good handling and good performance was rated as low cognitive workload, while bad handling and bad performance was rated as high on this scale. Intermediate performance in an aircraft with medium handling was rated as moderate cognitive workload. However, poor performance in a medium handling aircraft was rated as high, instead. All other combinations were scored as moderate cognitive workload. This classification scale is shown together with performance ranking, aircraft handling characteristics, and Cooper-Harper scores for each pilot and all tracking tests in Table 1. Tracking tests were ordered according to performance rank in this table.

Table 1. Comparisons of pilot performance, aircraft handling, Cooper-Harper, and Cognitive Workload Scale in four subjects participating in the NT-33 Tracking Study.

	Performance Rank	Handling Character	Cooper-Harper	Cognitive Workload Scale
Subject 1				
Test 6	1	Good	4	Low
Test 1	2	Med	4	Mod
Test 2	2	Bad	6	High
Test 4	2	Bad	6	High
Test 3	5	Good	4	Mod
Test 5	6	Med	6	High
Subject 2				
Test 6	1	Good	3	Low
Test 4	2	Bad	8	Mod
Test 3	3	Good	2	Low
Test 5	4	Med	6	Mod
Test 1	5	Bad	6	High
Test 2	5	Med	7	High
Subject 3				
Test 5	1	Good	3	Low
Test 2	2	Bad	6	Mod
Test 3	3	Med	3	Mod
Test 6	4	Good	5	Mod
Test 1	5	Med	8	High
Test 4	6	Bad	5	High
Subject 4				
Test 4	1	Good	2	Low
Test 1	1	Good	2	Low
Test 5	3	Med	5	Mod
Test 3	4	Med	5	Mod
Test 2	5	Bad	8	High
Test 6	6	Bad	8	High

Available EEG data segments for each tracking test were

sorted into these three categories and evaluated for magnitude and trend characteristics in the 8-12 Hz frequency band. Data for frontal and parietal sites were combined for the evaluation of overall spectral magnitudes for the three categories of cognitive workload. Analysis of Variance followed by Planned Comparison t-tests showed that magnitude was significantly decreased with high cognitive workload (Fig. 1). Average magnitude, however, did not differentiate low from moderate cognitive workload.

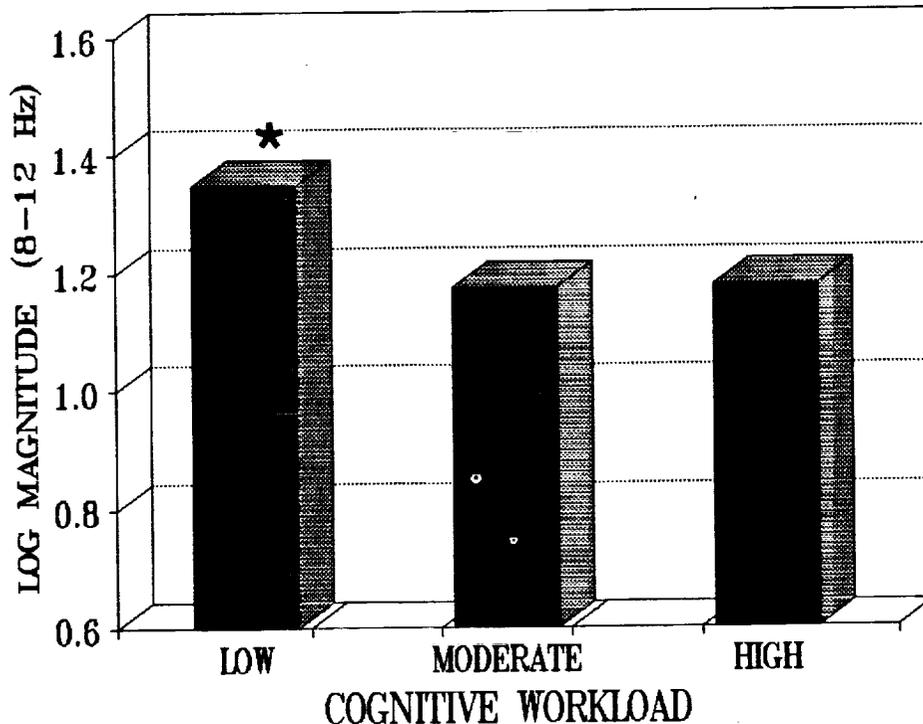


Figure 1. Comparison of mean EEG spectral magnitude values at frontal and parietal sites in the 8-12 Hz frequency band during in-flight tracking tests in four pilots across three categories of "cognitive workload". Activity in the 8-12 Hz band was significantly suppressed during high cognitive workload (* = $p < 0.10$).

Trend analysis of parietal EEG data (P4), on the other hand, differentiated 80% of all tracking tests according to this scale. High workload was associated with a pattern of sustained, low 8-12 Hz activity, often characterized by transient epochs of further suppression. Moderate workload showed a pattern of initially low 8-12 Hz activity followed by a gradual increment with occasional sharp decrements across the test period. Finally low workload resulted in a pattern of higher 8-12 Hz activity with distinctive modulation across the test period. A representative example of these patterns is shown in Figure 2.

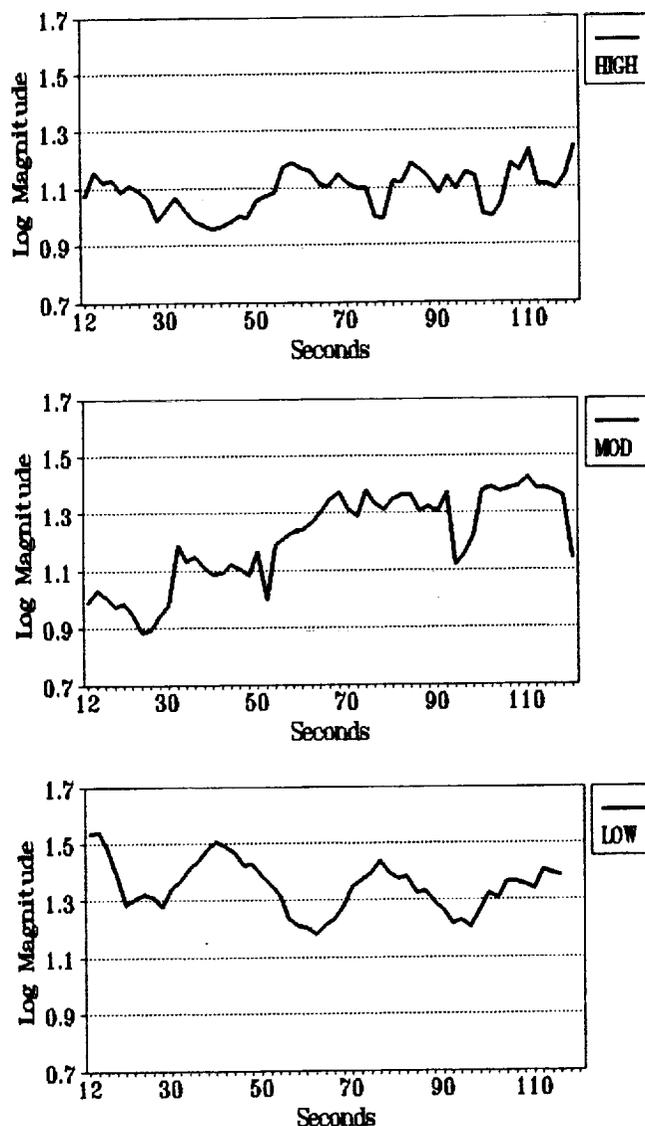


Figure 2. Representative EEG spectral magnitude trends for 8-12 Hz activity at three cognitive workload levels for tracking tasks in the NT-33 aircraft. Data were smoothed by 20 second moving average and are all from right mid-parietal recording site (P4) in the same pilot. Note magnitude and pattern differences.

DISCUSSION

Collectively, these findings agree with concepts derived from earlier laboratory and in-flight studies (Sterman, et, al, 1988, 1992), and suggest that selected EEG measures may successfully distinguish cognitive workload, at least when a combination of system configuration and performance outcome are the basis for validation. EEG spectral magnitude trends associated with this scale also provided for a meaningful resolution of events during each test. These patterns appeared

to reflect attentional modulation related to target movements and to changes in the pace of target activity. Thus, for low workload situations, increases in parietal 8-12 Hz activity accompanied successful target acquisition and/or reductions in the pace of target movements. With moderate workload, tracking was difficult initially but adaptation to handling characteristics eventually developed, leading to a graded increment in 8-12 Hz activity. Occasional, abrupt reversals were most likely due to transient increases in effort. In the case of high workload such an adjustment was minimal, since the pilot was rarely "caught up", and 8-12 Hz activity remained suppressed. Even at this level of effort additional load was accompanied by further, transient attenuations.

It is important to point out that very few EEG sites were available for analysis in this test. Laboratory simulator studies have shown that dynamic medial-lateral shifts in spectral magnitude occur in certain areas with escalating task saturation (Serman, et al, 1992), aspects of the EEG which could not be examined with the restricted data acquired here. Despite this limitation, we were able to demonstrate that EEG data could be successfully acquired during demanding tactical flight. Most importantly, however, a combination of magnitude level, trend characteristics, and trend modulation provided a consistent EEG discrimination of workload as defined here. Computer algorithms for pattern analysis are currently being developed to extract this information from the EEG directly in order to provide an integrated metric. Clearly, the limited data obtained here have justified the effort, and will help to guide future studies.

Finally, our approach to the definition of workload may be controversial. Using a concept of cognitive workload, based on both system and human performance, we were able to demonstrate consistent physiological correlates which could lend a needed objective aspect to the somewhat diffuse concept of workload. The sample of subjective ratings reviewed here underscores the shortcomings of existing definitions.

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