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STEADY-STATE EVOKED POTENTIALS POSSIBILITIES FOR MENTAL-STATE ESTIMATION

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ABSTRACT

The use of the human steady-state evoked potential (SSEP) as a possible measure of mental-state estimation is explored. A method for evoking a visual response to a sum-of-ten sine waves is presented. This approach provides simultaneous multiple frequency measurements of the human EEG to the evoking stimulus in terms of describing functions (gain and phase) and remnant spectra. Ways in which these quantities vary with the addition of performance tasks (manual tracking, grammatical reasoning, and decision making) are presented. Models of the describing function measures can be formulated using systems engineering technology. Relationships between model parameters and performance scores during manual tracking are discussed. Problems of unresponsiveness and lack of repeatability of subject responses are addressed in terms of a need for loop closure of the SSEP. A technique to achieve loop closure using a lock-in amplifier approach is presented. Results of a study designed to test the effectiveness of using feedback to consciously connect humans to their evoked response are presented. Findings indicate that conscious control of EEG is possible. Implications of these results in terms of secondary tasks for mental-state estimation and brain actuated control are addressed.

INTRODUCTION

By using appropriate signal averaging techniques, it is possible to detect a response in the human electroencephalograph (EEG) to evoking stimuli. When the stimulus is sinusoidally modulated the result is called a steady state evoked potential (SSEP). Research in this area (Spekreijse, 1966; Regan, 1972; Wilson and O'Donnell, 1980) suggests that the SSEP may be a useful indicator for mental-state estimation.

Using a light stimulus modulated by a sum of sine waves, a steady state evoked potential can be elicited that contains responses at all of the component frequencies of the driving stimulus. A technique has been developed to drive the stimulus with a 10 frequency sum of sines. This technique has been refined and the analysis has been upgraded to a level of sophistication that allows detailed analysis to be applied to the discrete Fourier transforms of the SSEP and the evoking stimulus. This analysis simultaneously produces describing function measures and background EEG spectra (Junker et. al., 1987). The describing function provides gain and phase information as a function of stimulus frequency, measures which are systems engineering based. The background EEG spectrum, referred to as the remnant in this report, provides information about the average power adjacent to, but not including the power at, stimulus frequencies. Thus, this remnant represents an average measure of EEG activity excluding the linear response to the evoking stimulus.

This analysis has been applied to SSEPs in taskloading and non-taskloading conditions. The tasks used were manual tracking, grammatical reasoning and decision making.

METHODOLOGY

The experimental apparatus used to obtain SSEP measures is illustrated in Figure 1. The apparatus consists of a stimulus presentation device which simultaneously delivered the evoking stimulus (flickering light) and a video task display. This presentation was achieved by combining the two images via a half-silvered mirror at 45 degrees to each image. The evoking stimulus was produced by two fluorescent light tubes behind a diffusing screen which distributed the light over the entire visual field. The intensity of the light was measured by a photocell placed at the subject's viewing point. The tasks were displayed on the video monitor. The average intensity of the evoking light was sufficiently low that a subject could comfortably discern the video task display within the same visual field.

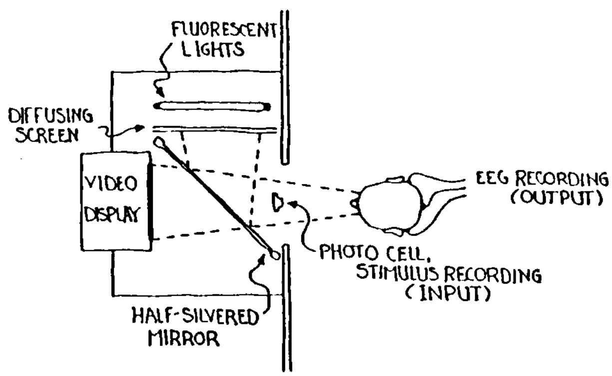


Figure 1. Experimental apparatus.

Subjects were seated in a darkened chamber facing the test apparatus. For the task conditions subjects were instructed to concentrate on the tasks. At the end of each 90 second trial, the subject's performance score appeared on the screen. For the non-task condition, called lights only, subjects were instructed to "relax and fixate on the center of the screen". Sessions were limited to 20 trials.

The EEG was recorded with silver/silver cloride electrodes at Oz with the right mastoid as reference and left mastoid as ground for the manual tracking. The grammatical reasoning and modeling results are reported here. For the investigation of decision making effects and loop-closure, gold cup electrodes were used with O1 as signal, P3 as reference and right ear as ground. Sum-of-sines generation and data collection were accomplished on a PDP 11/60 computer. The two channels of data (photocell and EEG) were filtered, digitized and stored for analysis. The collected data were discrete Fourier transformed, ensemble averaged, describing functions and remnant were computed, and the results were then plotted. Estimates of mean values for the gain and phase computations across trials were computed. For an indication of mean variability, standard errors were computed. The describing function gain (amplitude ratios of the EEG to photocell) indicates evoked response sensitivity at the component frequencies. The phase values relate to neurophysiological dynamics and transmission latency between photocell and EEG measurement.

Three tasks, requiring various levels of visual, mental, and motor processing, were used to elicit diverse cognitive states with the intention of evoking different visual-cortical responses. The three tasks were similar in that the input came from the video display and the output from subjects was produced by manual operation of a control stick or push-buttons.

The manual tracking task involved control of a first order instability driven by pseudo-random noise. Visually this involved minimizing a displayed error by keeping a cursor superimposed upon a moving dot. This task required continuous manual control and little or no conscious decision making once the task had been learned (Zacharias and Levison, 1979).

A grammatical reasoning task was used which imposed variable processing demands on mental resources used for the manipulation of grammatical information (Shingledecker et. al., 1983). Stimulus items were two sentences of varying syntactic structure accompanied by a set of three symbols. The sentences had to be analyzed to determine whether they correctly described the ordering of the characters in the symbol set.

The decision making task involved the problem of allocating attention among multiple tasks in a supervisory control system (Pattipati et. al., 1979). Subjects observed the video display on which multiple concomitant tasks were represented by moving rectangular bars. The bars appeared at the left edge of the screen and moved at different velocities to the right, disappearing upon reaching the right edge. At any given time there were, at most, five tasks displayed with a maximum of one on each line. The subjects could process a task by depressing the appropriate push-button. Once a button had been pushed, the computer remained dedicated to that task until task completion or the task ran off the screen. By processing a task successfully, the subject was credited with the corresponding reward, and the completed task was eliminated from the display. Two levels of difficulty were used. In the "easy" condition it was possible to successfully allocate attention among the multiple tasks. In the "hard" condition the time required exceeded the time available and it was not possible to complete all allocations successfully.

The sum-of-sines stimulus was composed of 10 harmonically non-related multiples of the fundamental frequency of 0.0244 Hz. In addition, none of these component frequencies contained a sum or difference of any of the other component frequencies. This restriction on the sine wave frequency selection was implemented to avoid first order nonlinear interactions. The component frequencies ranged from approximately 6.25 to 21.74 Hz, with intermediate frequencies at 7.73, 9.49, 11.49, 13.25, 14.74, 16.49, 18.25, and 20.23 Hz. For every data collecting trial, starting phase values for each of the 10 component sine waves were randomized, ensuring that the time sequence of flickering light presentation was random from trial to trial. By utilizing randomized starting phase values with the summing of the 10 sinusoids a peak depth of modulation of 13 % per sinusoid was possible. Results for two levels of depth of modulation (6.5% and 13%) and two levels of average luminance, (40 foot-Lamberts, (ftL), and 80 ftL) are presented. For a detailed discussion of the rationale for designing sum-of-sines inputs the reader is referred to Junker et. al., 1987.

STIMULUS EFFECTS

Investigation into the effects of stimulus parameter characteristics is perhaps best summarized in Figures 2 and 3. For the subjects tested, the evoked response frequencies of greatest sensitivity were between 9.49 Hz and 18.25 Hz. Two areas of obvious sensitivity were the alpha band and beta band. For the lowest level of modulation and intensity, and thus stimulus power, a strong response was evoked at 9.49 Hz and a not so strong (but obvious) response occurred at 16.49

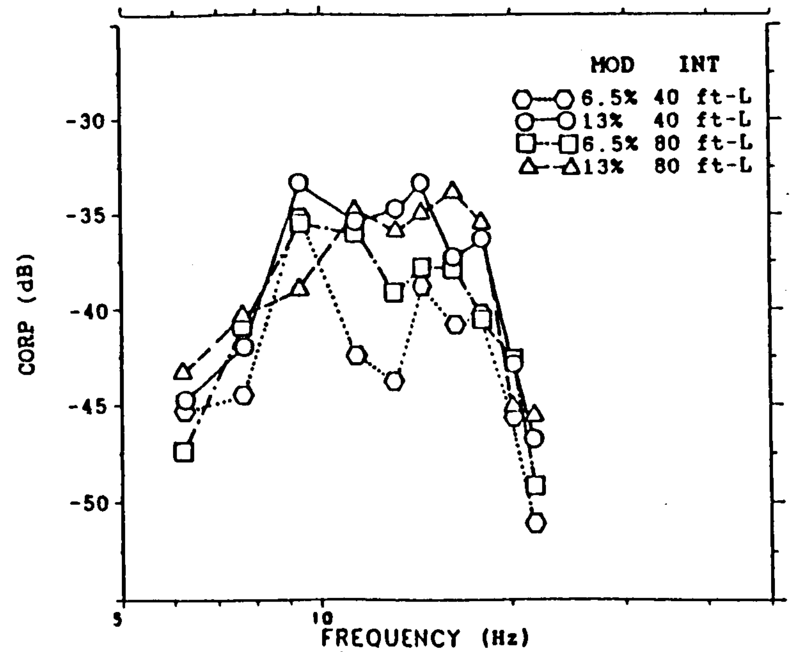


Figure 2. Effects of stimulus parameters; MODulation, and INTensity, on SSEP correlated power (power at evoking stimulus frequencies).

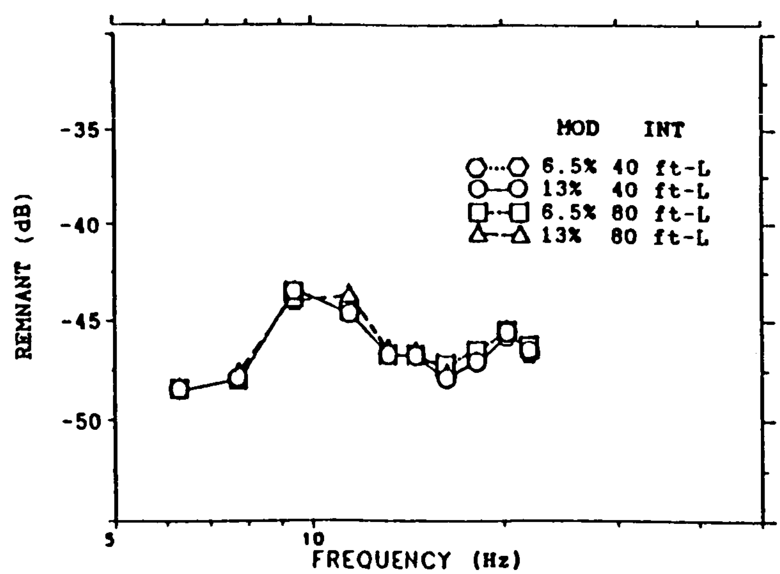


Figure 3. Effects of stimulus parameters; MODulation, and INTensity, on background EEG or remnant.

Hz. Increasing the depth of modulation to 13%, with the intensity unchanged (40 ftL), resulted in the largest evoked response and a flattening in the correlated EEG power spectrum (11.49 Hz to 14.74 Hz). At 13% modulation, increasing the intensity further (to 80 ftL) succeeded only in producing a slightly noticeable increase in the evoked response at 16.49 Hz. This high level of intensity and modulation actually resulted in the smallest evoked response at 9.49 Hz. These results indicate that the evoked response is a function of frequency as well as stimulus strength. These findings correspond to others reported in the literature (Regan 1972). It was also observed that saturation across frequencies was unequal, the alpha region being the most sensitive.

As can be seen in Figure 3, the remnant responses were only mildly affected by the different stimulus parameter values. In addition it can be observed that the alpha peaking in the remnant curves corresponded to the alpha sensitivity in the evoked responses of Figure 2. The results also indicated that differences in evoked responses between subjects were significant, and that they must be considered for a more complete picture of visual-cortical functioning.

From our results, it can be concluded that the lower level of intensity and higher level of modulation provide the better stimulus parameter values. In designing a stimulus, it would be best to choose values which cause minimal distraction of the tasks being investigated. An intensity level of 40 ftL was adequate for the experimental paradigm investigated for this report.

The investigation of stimulus parameters points to future research possibilities. Tailoring the stimulus spectrum to each individual as a function of their evoked response sensitivity may produce optimal SSEP responses.

TASK EFFECTS

Different effects upon the visual-cortical response were observed for the three tasks investigated. Manual tracking had the least effect for most subjects, and grammatical reasoning and decision making had the greatest effect.

Comparisons between lights only (LO), manual tracking (MT), and grammatical reasoning (GR) for 4 of the subjects tested are given in Figure 4. Results indicate that the more mental processing required, the greater the alpha band decrease and the greater the beta band increase. Of course this is somewhat specific to each subject tested. Subjects 02 and 05 could be classified as alpha responders due to their large alpha band remnant peaks (Figure 4a). For these subjects, with task loading, a decreasing remnant alpha

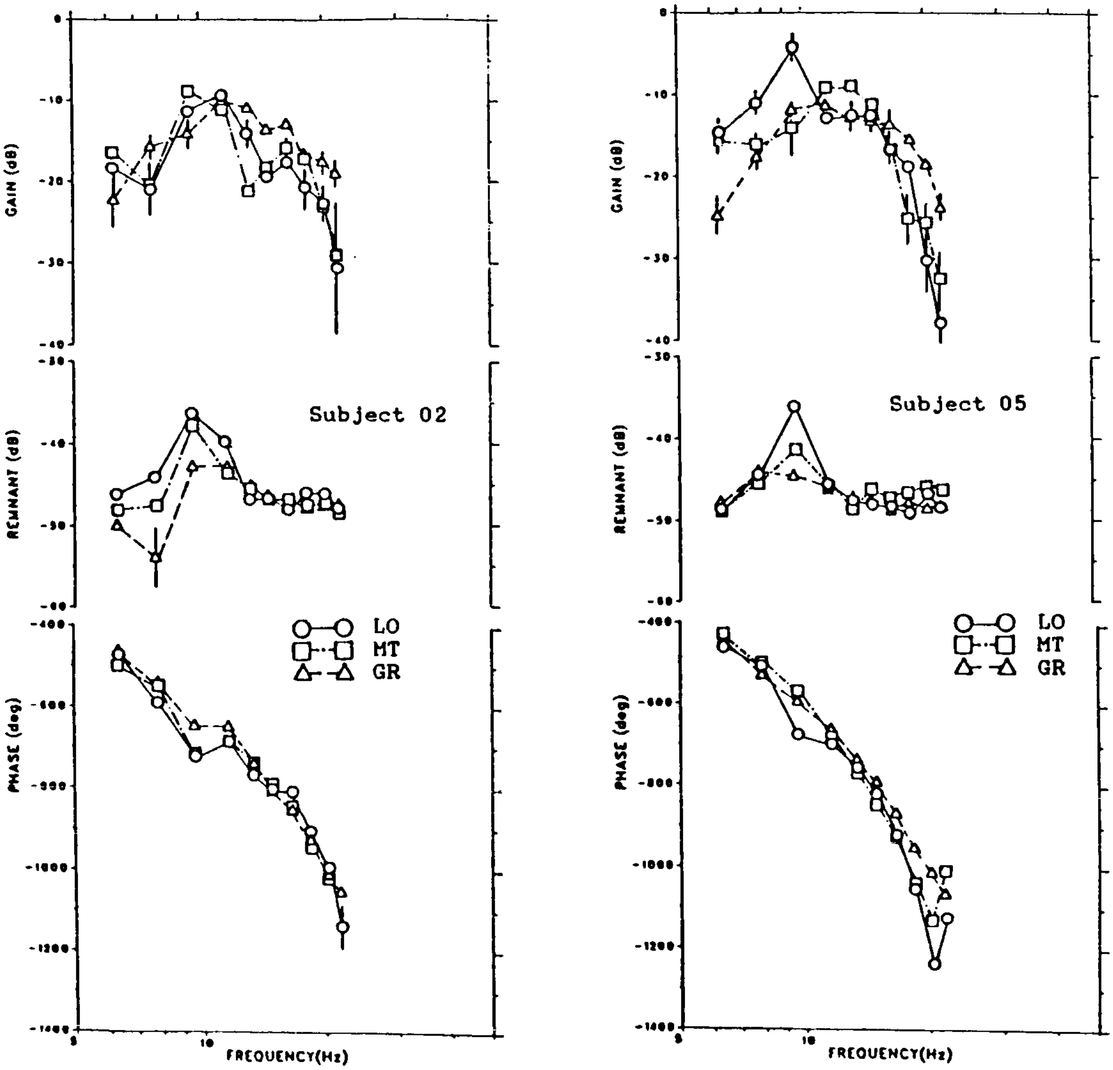


Figure 4a. SSEP describing functions (gain and phase) and remnant across three conditions; Lights Only (LO), Manual Tracking (MT), and Grammatical Reasoning (GR).

response corresponding to the degree of mental processing required can be seen. Subjects 10 and 15, non-alpha responders, do not exhibit such responses (Figure 4b).

Results from the decision making tasks on the SSEP are presented in Figure 5. During decision making as compared to the lights only condition, a consistent reduction in phase lag in the beta band was observed for all subjects tested (refer to Figure 5). As in the tracking and grammatical reasoning conditions, reductions in the alpha band and increases in the beta band with task loading could be observed. There were, however, no observable differences in

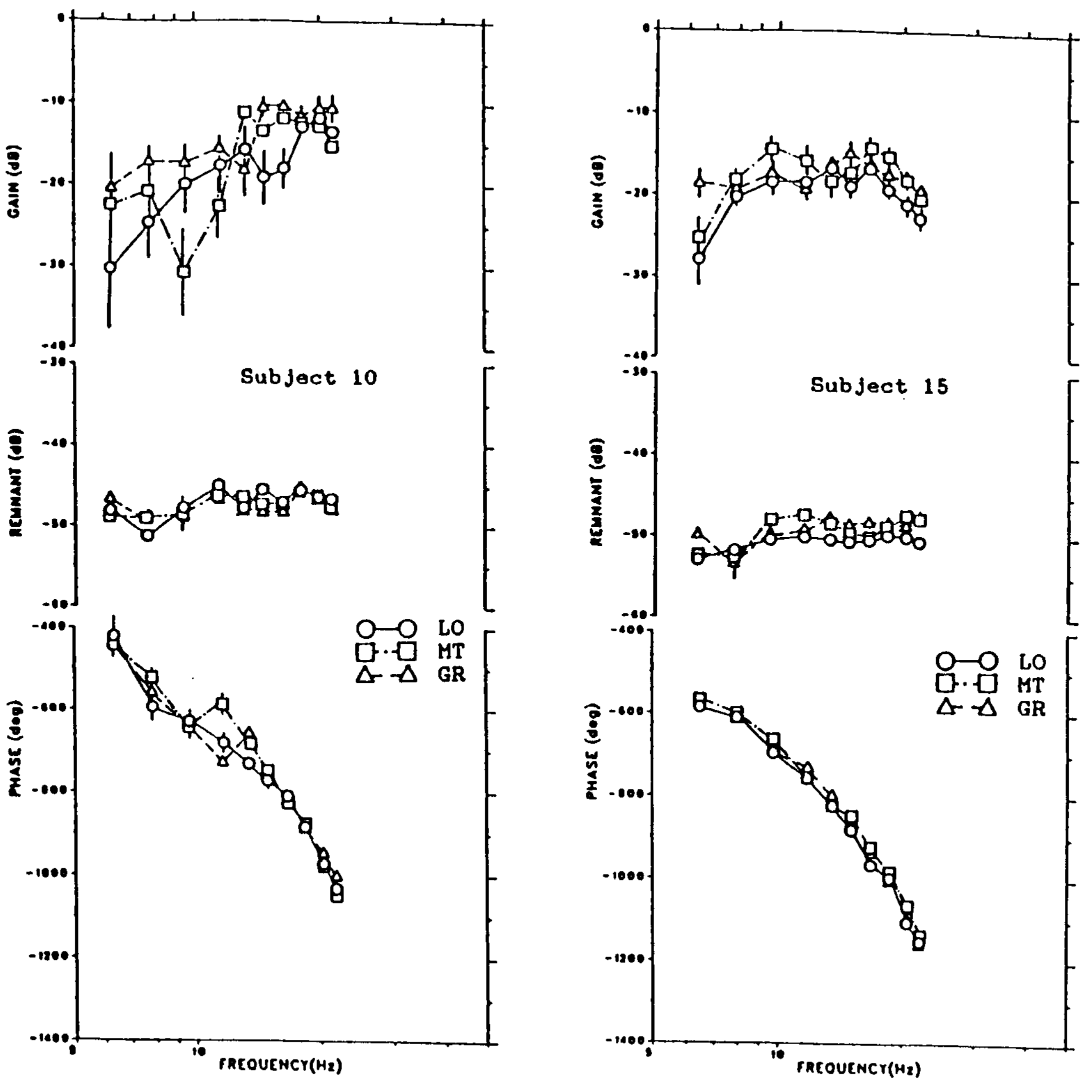


Figure 4b. SSEP describing functions (gain and phase) and remnant across three conditions.

the evoked responses across the two levels of decision making task difficulty. Subjects 13 and 77 could be classified as alpha responders based upon their remnant and gain responses in the alpha region (Figure 5a).

The changes across tasks were specific to each individual tested. The differences in subject responses suggest that it would be useful to group subjects into at least two groups: alpha responders, and non-alpha responders. Determination of how to group each subject could be based upon alpha band resonance or peak responses for remnant and gain. With task loading, subjects with alpha decreases in both the remnant and gain response could be classified as alpha responders. Non-alpha responders could be

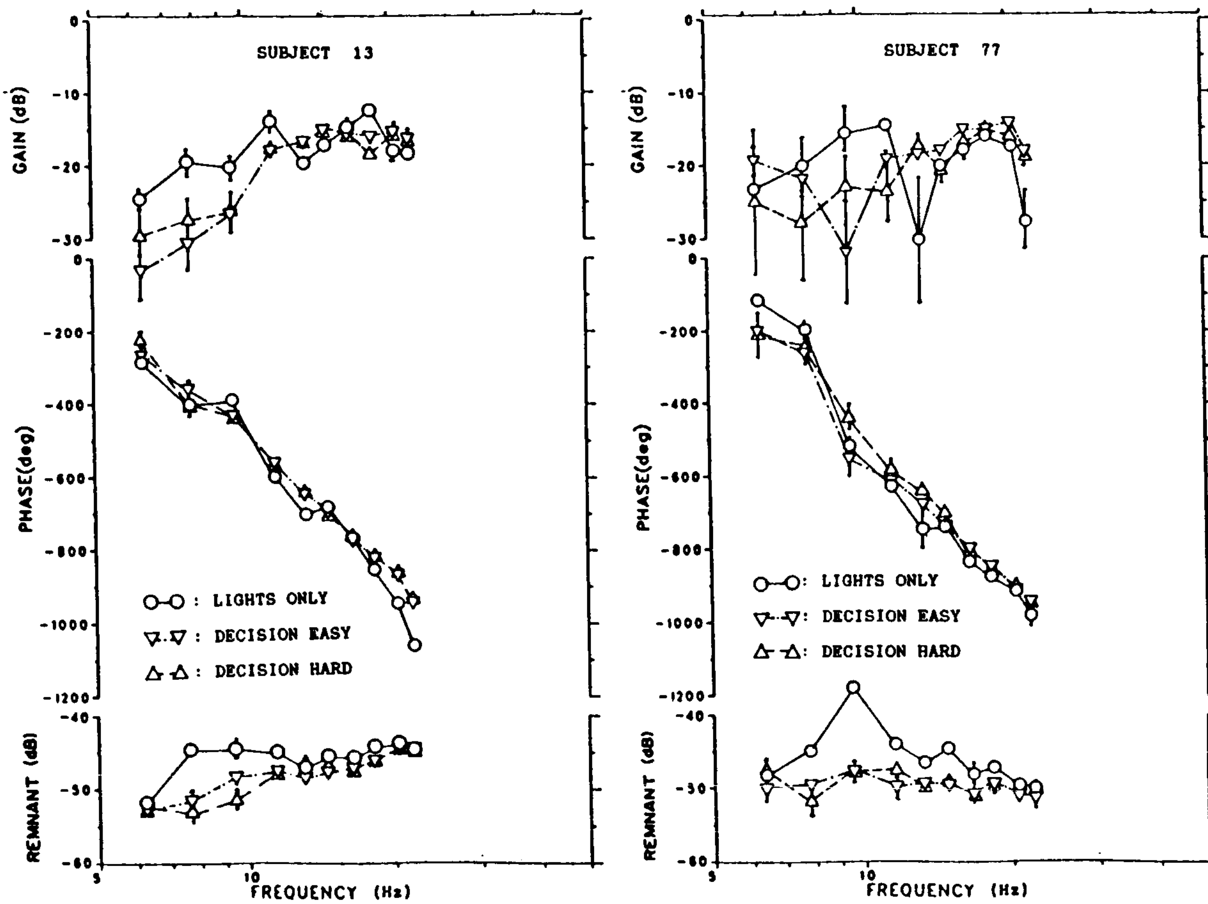


Figure 5a. SSEP describing functions and remnant for two levels of decision making task difficulty. Note large alpha response in lights only condition.

characterized primarily by a beta increase in gain and remnant with task loading.

Gain curve changes corresponded to remnant changes in the alpha band for subjects classified as alpha responders (Subjects 02, 05, 13, and 77). In the beta band (above 13 Hz) the gain curve activity appeared to be independent of the measured remnant for most subjects tested.

MODELING

Describing function data were modeled using a second order linear model form. Results of the model match (Figure 6) indicated that a good match could be achieved for some

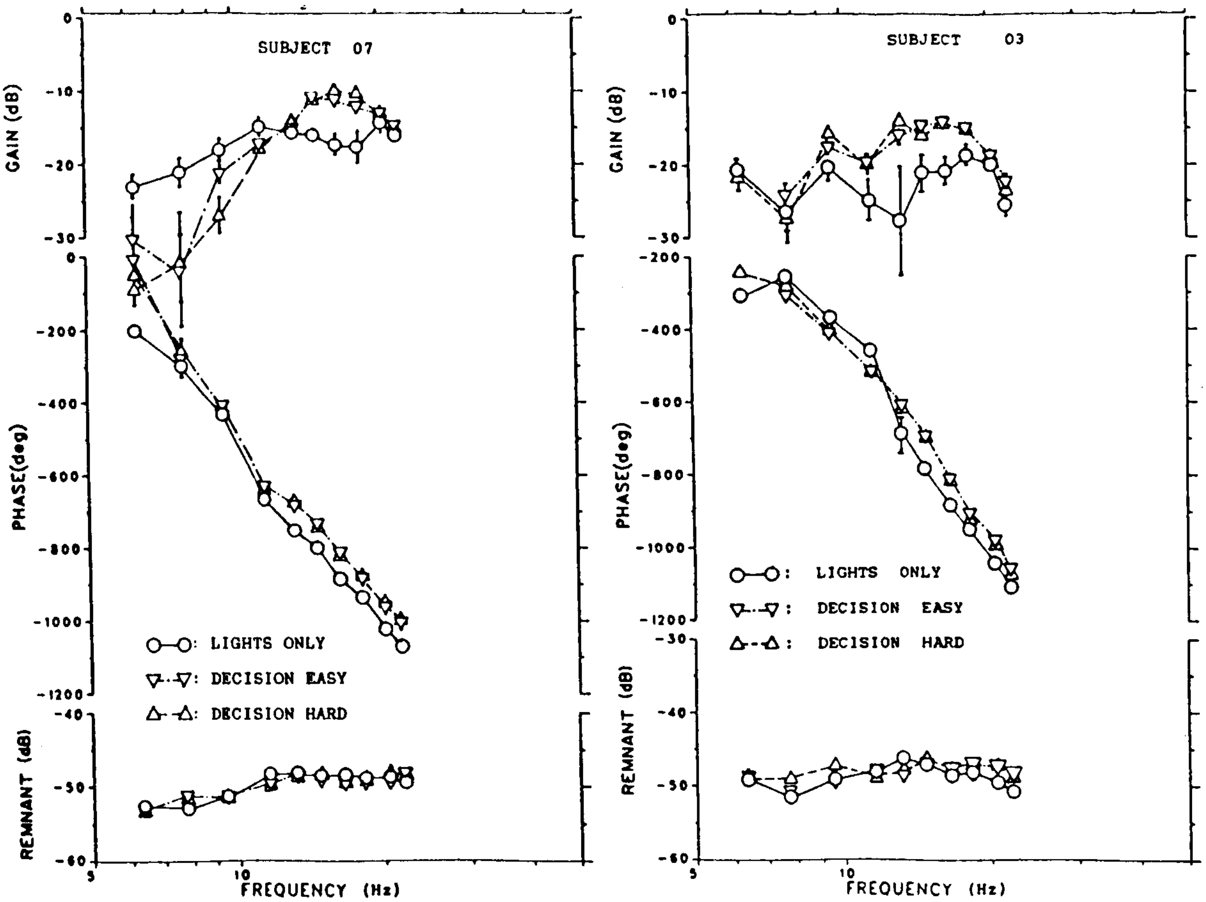


Figure 5b. SSEP describing functions and remnant, two levels of decision making. Note the absence of alpha changes in remnant from lights only to decision making.

subjects and not others. Due to individual differences in the evoked responses, it will be necessary to tailor the form of the model used to each subject. Perhaps by grouping subjects into two groups (alpha and non-alpha responders), two general model forms would be sufficient to compress the visual-cortical response data into a more parsimonious format.

A simple gain-delay model was useful as an aid in phase unwrapping. It was also used to parameterize the SSEP describing functions in terms of gain and delay. These values were compared to performance scores for the manual tracking task (refer to Table 1). Subject 10 achieved the best performance as indicated by the lowest error score, and Subject 15 achieved the worst as indicated by the largest

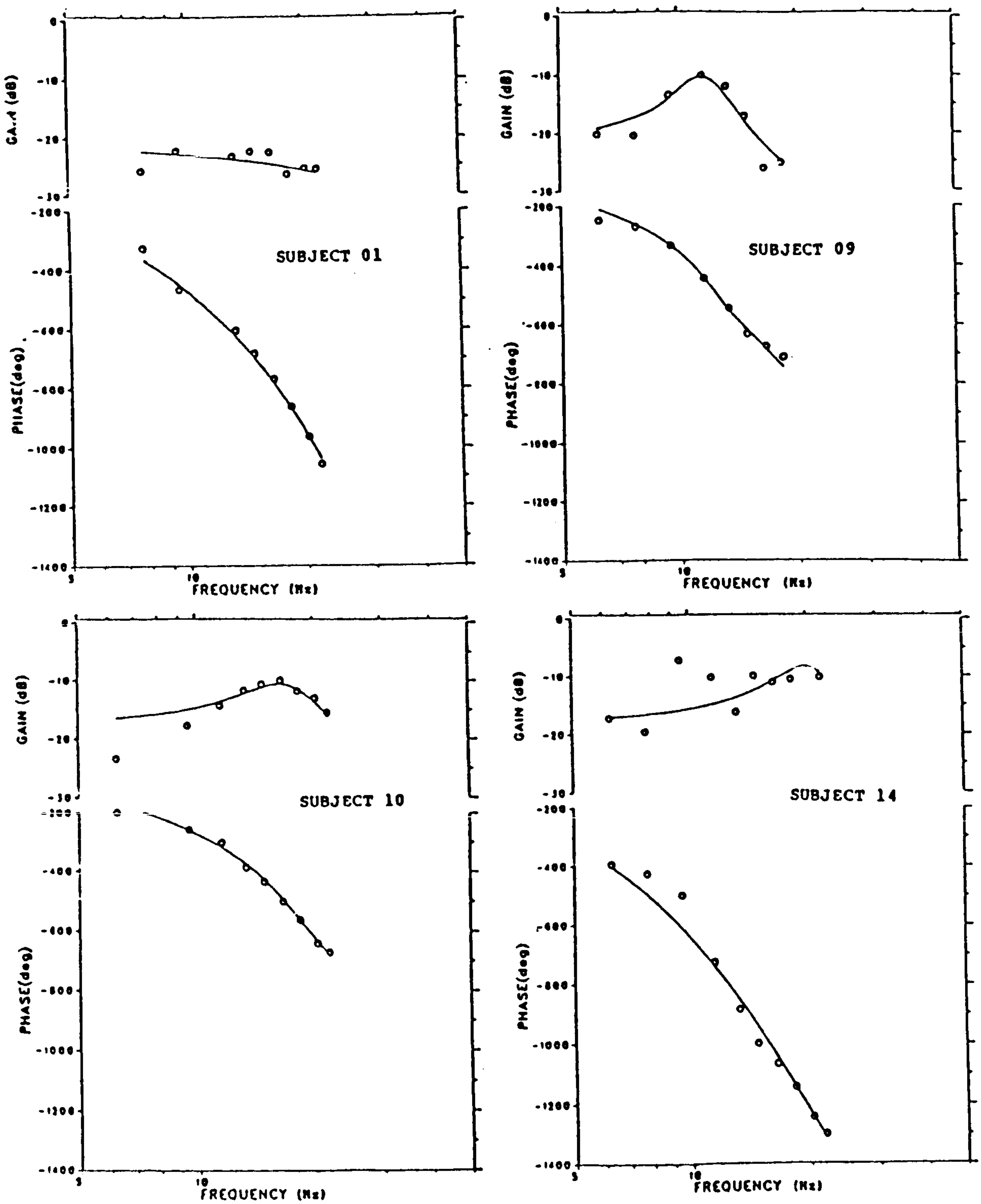


Figure 6. SSEP response, lights only condition. Circles represent phase-adjusted experimental values, lines are model predictions.

TABLE 1 Manual tracking performance scores and SSEP describing function model results (gain and delay values).

SUBJ #	RMS ERROR MEAN	SD	MODEL GAIN	DELAY
02	1.78	0.40	.151	.169
05	2.20	0.52	.240	.124
10	1.32	0.20	.222	.109
15	2.43	0.51	.135	.126

error score. It is interesting to note that Subject 10 also had the lowest modeled SSEP delay and Subject 15 had the lowest modeled SSEP gain. These results suggest the possibility that task performance may correlate with visual-cortical response frequency measures. Thus model parameterization may provide predictive information regarding a subject's ability to perform a particular task.

LOOP-CLOSURE OF THE VISUAL-CORTICAL RESPONSE

The results of our research effort indicate that describing functions can be obtained and that they are sensitive to changes in task loading. It was also found that the results are unique to each individual within the general classifications of alpha and non-alpha responders. Further, it was found that the results are sensitive to attention, especially in the alpha band.

These results are promising, however there is one difficulty with this and perhaps other evoked physiological measures that needs to be addressed. The visual-cortical response is an open loop measure. Unlike manual control, where an optimal behavior for best performance exists, the subject is not provided with an environment directing a certain response.

In the lights-only condition, subjects were told to "look at the lights". No feedback relative to how well they were responding was provided. Even with this lack of feedback or loop closure, the evoked response was somewhat repeatable. This is demonstrated in Figure 7 for two subjects that were tested over a 3 year span. It is interesting to note that task loading often increased the evoked response and reduced response variability. However, subjects were often unaware of their state of attention, resulting in a weak or unevoked response.

Based upon what was learned from manual control experiments (Levison, 1983; Levison and Junker, 1978; Levison et. al., 1971), it was concluded that the solution to

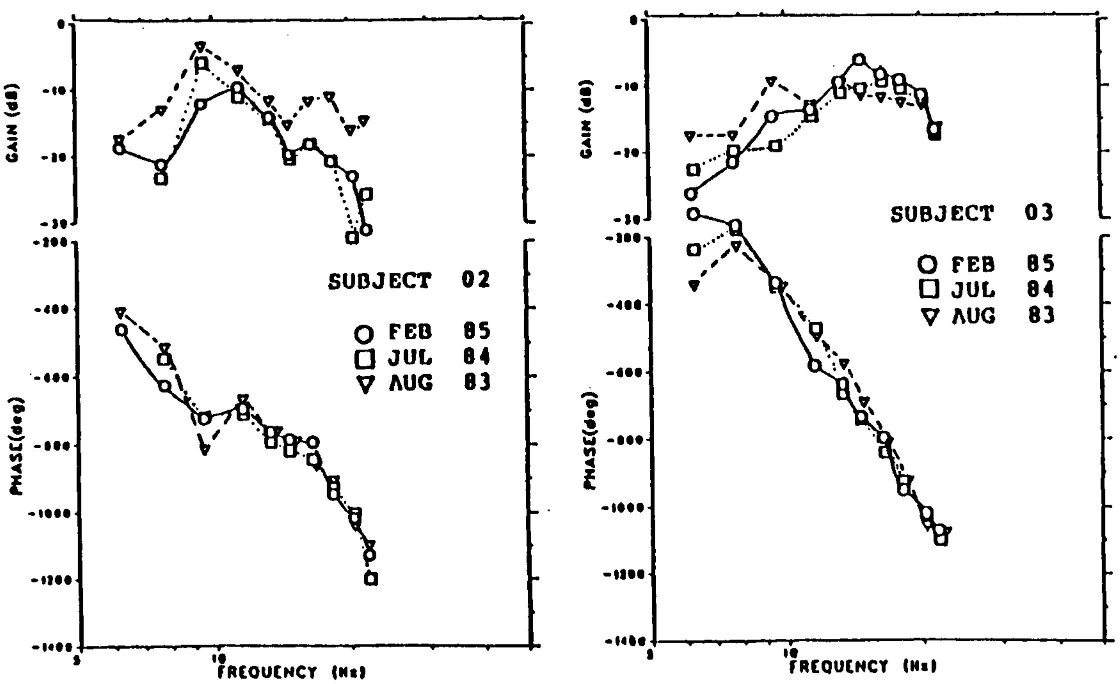


Figure 7. Repeatability of the SSEP as illustrated by describing function gain and phase values for 2 subjects over a 3 year span.

improvement of the visual-cortical response measure is to develop a closed-loop visual-cortical response paradigm. This requires providing an appropriate feedback signal to the subject.

From the evoked response data it was observed that evoked potentials could exhibit frequency responses as narrow as the measurement bandwidth of the experimental system being used, for example 0.0244 Hz (Junker et. al. 1987). Thus we concluded that frequency specificity of the feedback signal should be of concern.

If a feedback loop is to be effective it must also contain minimal transport delays. EEG biofeedback trainers at the Menninger Foundation (Biofeedback Center, Topeka, Kansas, personal communication) indicated that a biofeedback signal should not be delayed more than 4 cycles for it to be a useful signal from which subjects could learn to "control" their EEG.

From the above discussion, it was concluded that for the feedback signal to be effective it must be both timely and frequency specific. Useful feedback information about a 10 Hz response, for example, might require no more than a 0.4 second delay. To achieve this small delay and simultaneous frequency specificity is not an easy task. For the work reported above, a frequency specificity of 0.0244 Hz was achieved, but only by analyzing 40.96 seconds of data at a time. Thus we concluded that frequency resolution and timeliness could not be achieved by our available digital apparatus. Instead, an analog active-filter approach was pursued.

The approach involved using a tunable bandpass filter in combination with a Lock-in Amplifier System (LAS). A diagram for this system is presented in Figure 8. The LAS consists of two quadrature phase sensitive detectors, the outputs of which are lowpass filtered and converted to polar form to yield continuous gain and phase signals at the lock-in frequency. The lock-in frequency is determined by a clock which generates a square wave, a quadrature square wave, and a sine wave. The square waves drive amplifiers A and B. The sine wave is used to drive the light stimulus. A narrow bandpass filter (tuned to the clock frequency) is used to improve the signal to noise ratio of the signal analyzed by the LAS. The responsiveness and frequency specificity of the LAS depends upon the cutoff frequency of the lowpass filters.

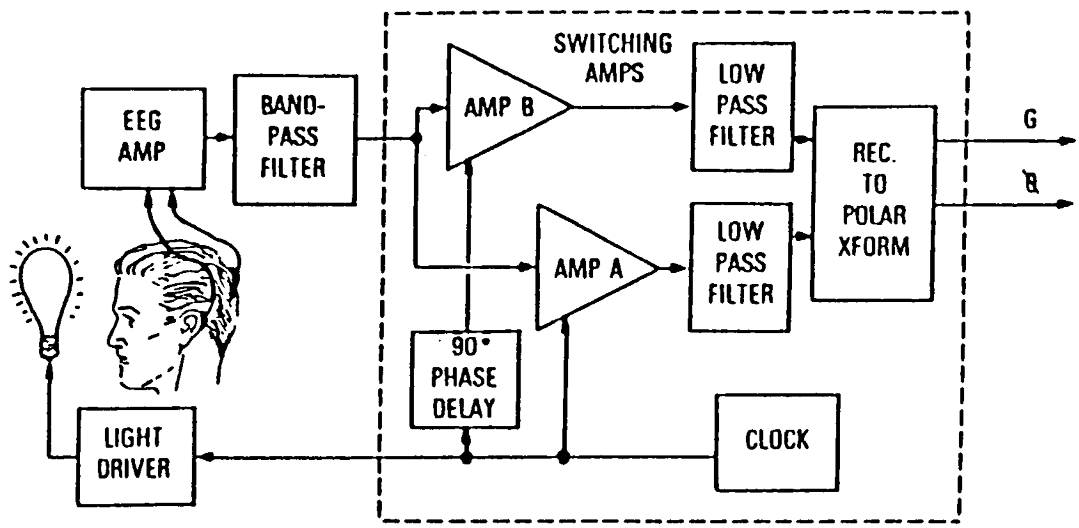


Figure 8. Lock-in amplifier system.

The LAS provides a continuous measure of gain and phase suggesting that it could be used in conjunction with steady-state stimulation to explore the time varying nature of task loading. A possible approach would be to stimulate with the SOS stimulus and continuously record the LAS output at one of the 10 SOS frequencies. Correlations between the continuous measure and the time varying nature of the task could be investigated. In the case of the decision making task this might be the times of appearance of new targets and times before or at the moment of button pushing.

The above is still an open loop measure. To close the loop using our approach, it was necessary to provide feedback to subjects of their EEG production at one or more evoking frequencies. The experimental setup we used to accomplish this is illustrated in Figure 9. Feedback of EEG production was provided to subjects through two modes: a light bar display, and an amplitude modulated tone. The qualifications for tone selection were that it be harmonically related to the evoking stimulus frequency and also subject verified as 'pleasing'. As the subject's EEG amplitude increased at the target frequency, as indicated by the LAS gain signal, more light bars became lit and the tone volume increased.

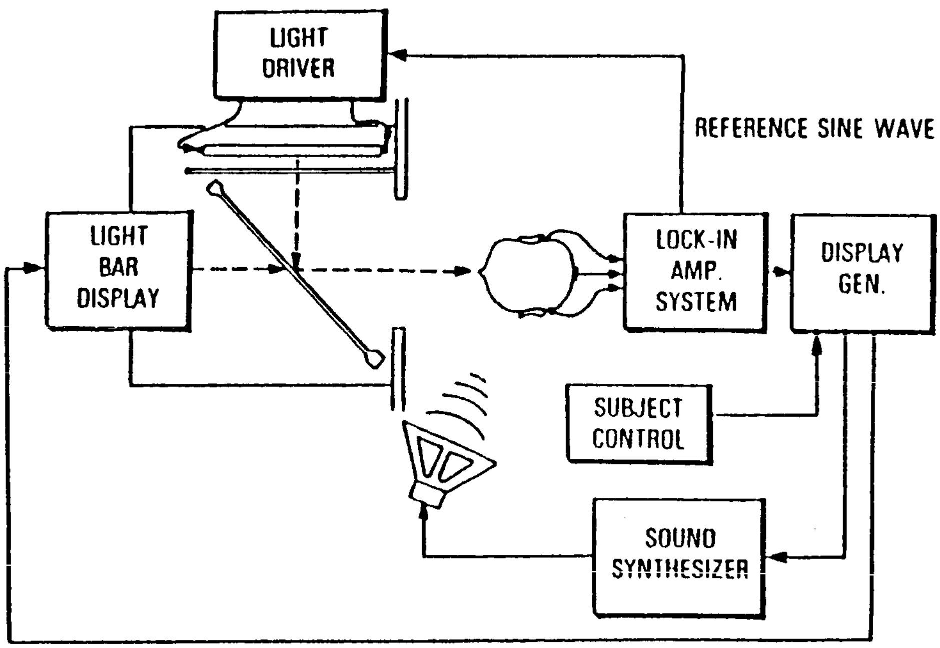


Figure 9. Experimental setup for feedback training.

For feedback training it was decided to use frequencies that would hopefully reside within relatively quiet areas of the EEG spectrum for the initial investigation. Therefore two frequencies were chosen, one below the alpha band and one between the alpha band and beta band. In addition the two frequencies were selected from the 10 sinewaves used in the SOS stimulus so that describing function data would be available for subsequent comparisons. Therefore frequencies of 7.73 Hz and 13.25 Hz were used.

To evaluate the effectiveness of feedback, two conditions were investigated. The first condition consisted of using the experimental setup as illustrated in Figure 9. One group of subjects trained under this condition. For the second condition, true EEG feedback was replaced by false feedback from an analog random noise generator. This output was injected into the bandpass filter of the experimental setup instead of the subject's EEG (refer to Figure 8). A second set of subjects was used for this false feedback condition. The subjects, although aware of the possibility of getting either real or false feedback, were not informed until the experiment's conclusion as to which type of feedback they had received. After receiving 6 sessions of false feedback these subjects received true feedback for 4 sessions.

The four subjects used for the decision making task investigation (Figure 5) were used in this experiment. Subjects were randomly assigned to the two experimental groups with the constraint that the two alpha producers (Subjects 13 and 77) would not be in the same group. This resulted in Subjects 13 and 07 being assigned to the true feedback group and Subjects 77 and 03 to the false feedback group.

To provide comparable results between subjects for each frequency under investigation, the EEG response was adjusted to approximately the same level for each subject at the start of each session. A variable gain control of the EEG signal prior to the bandpass filter (refer to Figure 8) was used to achieve EEG gain adjustment. The result of this adjustment was determined by monitoring the subject's EEG spectrum with an HP Fourier analyzer at the output of the variable gain control.

For each experimental session, subjects trained at both frequencies. The first half of the session consisted of training at one frequency and the next half at the second frequency. The task of the subject was to either increase the feedback signal or decrease the feedback signal over a 100 second trial. An experimental session consisted of two blocks of eight 100 sec periods for each frequency or a total of 4 blocks per session. Within each block of 8 trials, subjects were instructed to "raise the light bar" (increase the feedback signal) for 4 trials, and "lower the light bar" (decrease the signal) for 4 trials. The order of presentation of the two frequencies as well as the order of raising and lowering was randomized.

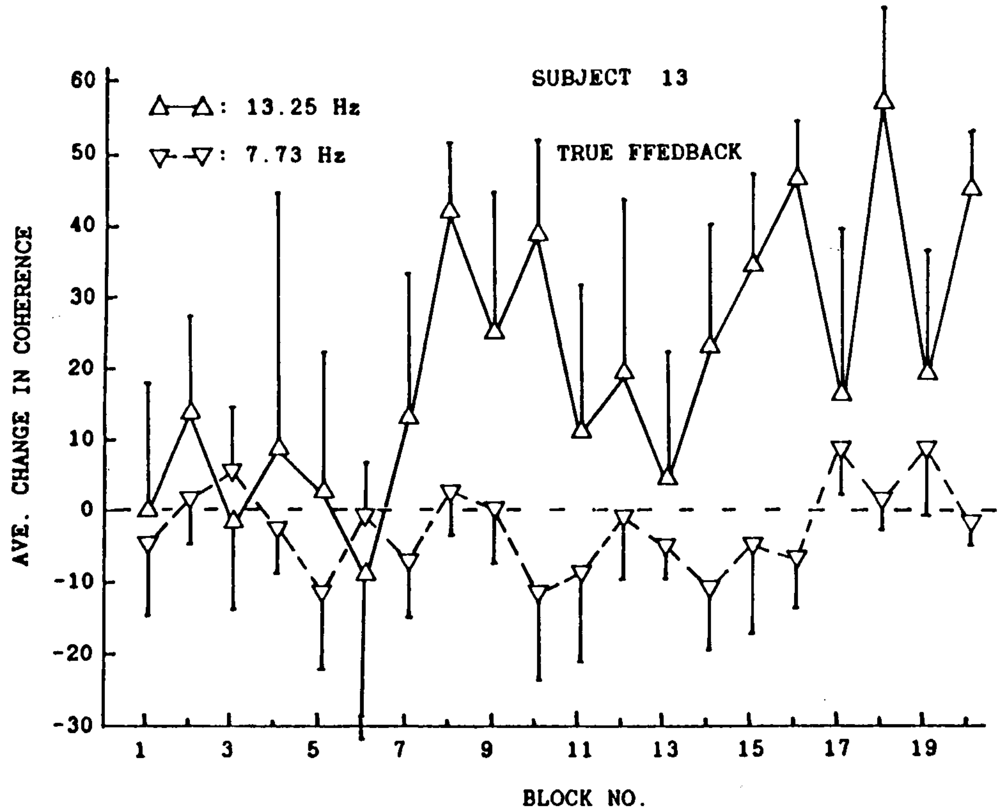
One mode of EEG control is the ability, at a given frequency, to hold one's amplitude above or maintain it below a hypothetical threshold. The fifth light bar on a 16 light bar display was chosen as a threshold. Performance scoring was a measure of how many seconds, out of a 100 second trial, the subject's amplitude went above this fifth bar level. The second performance measure was the coherence between subject EEG and the evoking light stimulus. For each block of eight trials, the average difference for each performance measure between increasing and suppressing the EEG signal was computed. This resulted in average performance scores and standard deviations for both increasing and suppressing EEG signals for each block. The results of this analysis are presented in Figures 10 and 11. Plotted in each graph are the average values and the largest standard deviation (either from increasing or suppressing) per block. A value above the dashed line in each graph indicates for that block the average of the 4 'increasing' values was greater than the average of the 4 'suppressing' values. Values below the dashed line indicate that the opposite trend occurred.

DISCUSSION OF FEEDBACK TRAINING RESULTS

Before beginning discussion of the feedback training results it is informative to refer to the Subjects' describing functions and remnant spectra of Figure 5. Looking first at Subject 13's responses, a weak response at the lower frequency (7.73 Hz) as indicated by the large standard error bars for the three conditions tested can be observed. The response at 13.25 Hz, compared to the alpha response at 11.49 Hz for the lights only condition, was low but increased with task loading. Subject 77's responses at both frequencies were low and weak as indicated by the mean values and the large standard error bars. Subject 07 exhibited large variability in the evoked response at 7.73 Hz. Subject 03's response at 13.25 Hz for the lights only condition was weak.

The coherence results for Subject 13 at 7.73 Hz (Figure 10a) indicate that no net change in coherence occurred due to feedback training. Over the 20 blocks, the average value in coherence was only slightly greater when suppressing than when increasing. At 13.25 Hz, however, by the seventh block a consistent increase in coherence between the increasing and suppressing trials can be observed. The lack of change in coherence at 7.73 Hz may relate to the weak response obtained in the Subject's describing functions of Figure 5a. Subject 07 exhibited similar trends in both the average change in coherence and in the describing functions of Figure 5b.

Data for the subjects receiving false feedback for 6 sessions (12 blocks) and then true feedback for 4 sessions are shown in the second two graphs of Figure 10. Subject 77 exhibited greater average coherence during the increasing trials for 13.25 Hz, even during the false feedback conditions. Due to the large variation in the data however this trend was not very consistent. Subject 03 exhibited greater coherence during the increase trials as compared to the suppress trials at 7.73 Hz, but not at 13.25 Hz. This corresponds to the gain sensitivity observed for Subject 03 in Figure 5b.



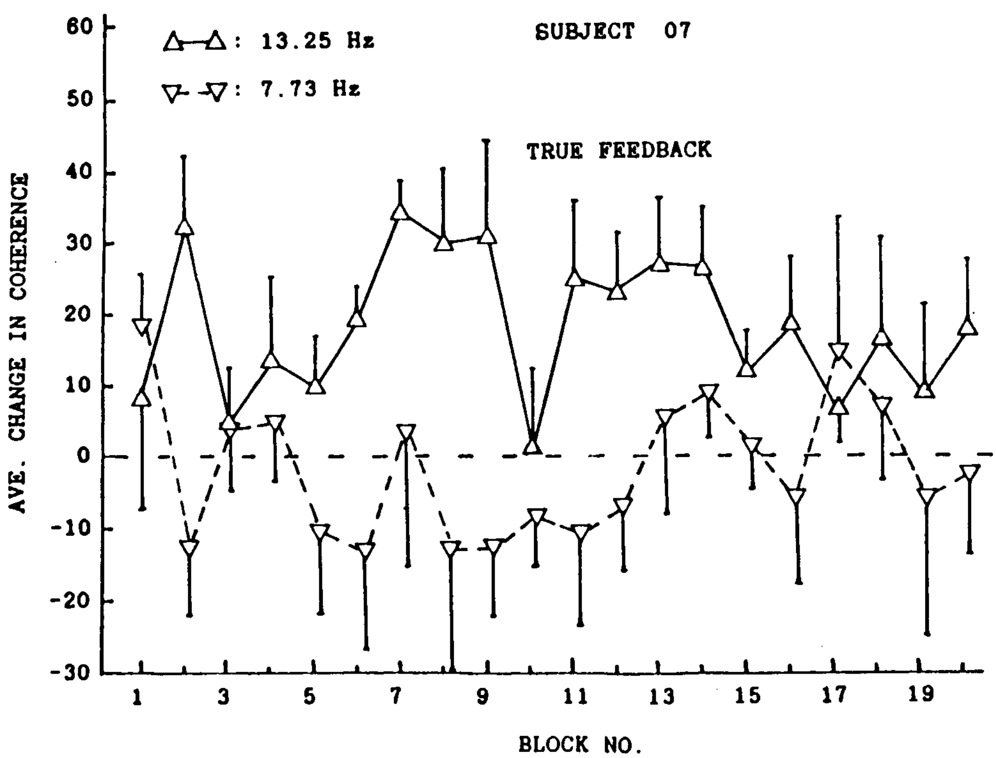


Figure 10a. Average change in coherence for subjects with true feedback, standard deviation bars included.

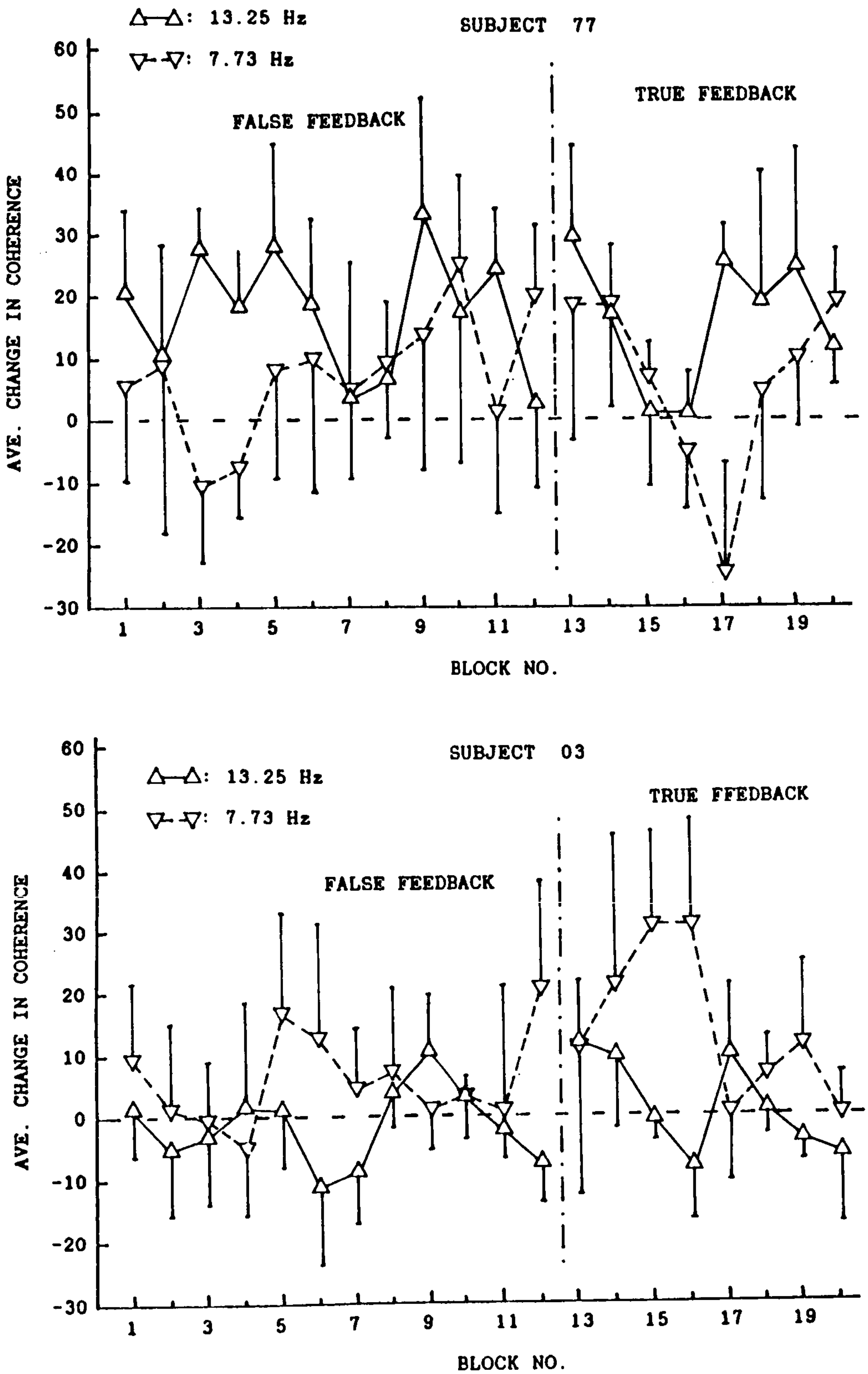


Figure 10b. Average change in coherence for subjects who received false feedback for the first 12 blocks.

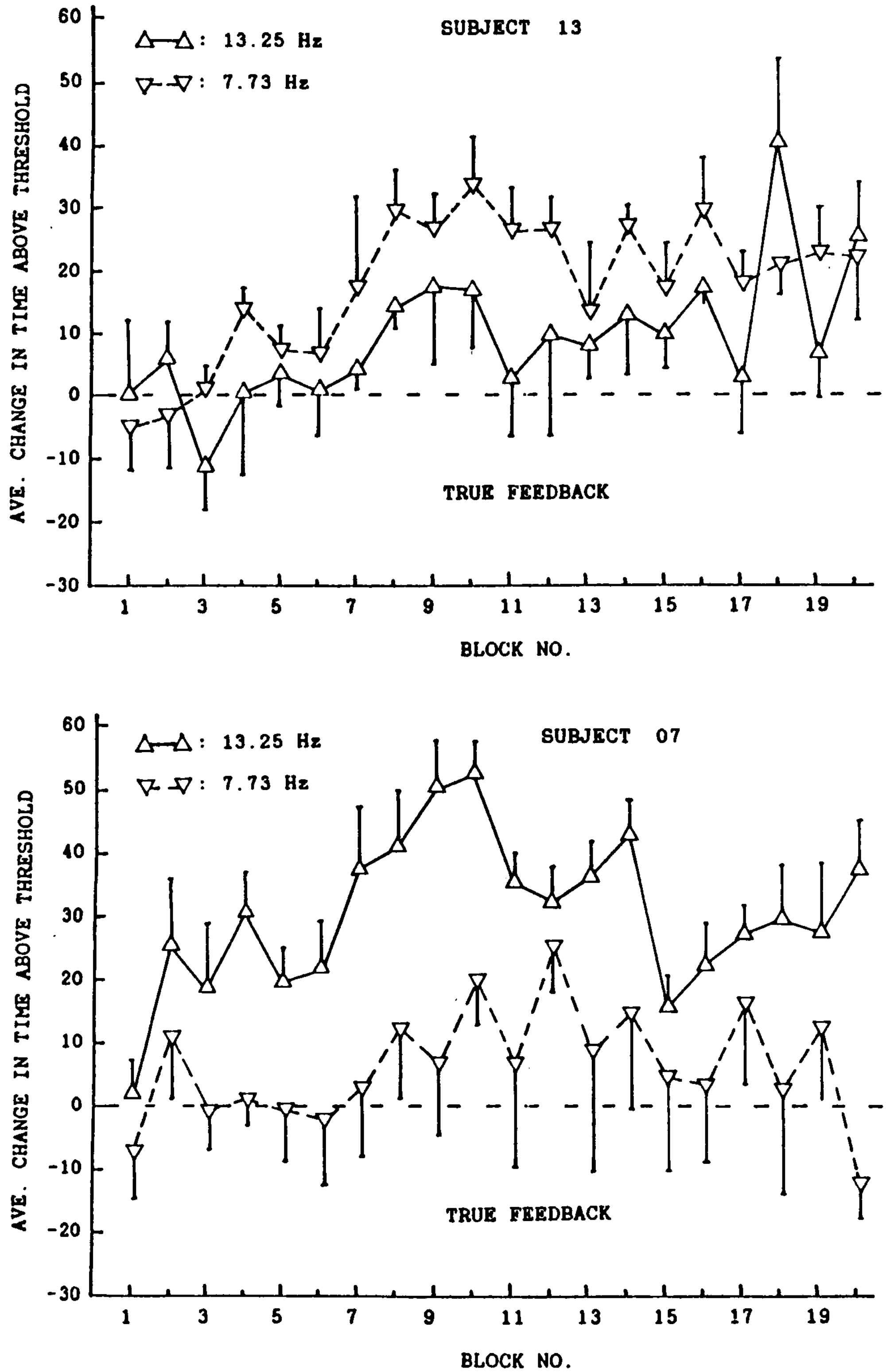
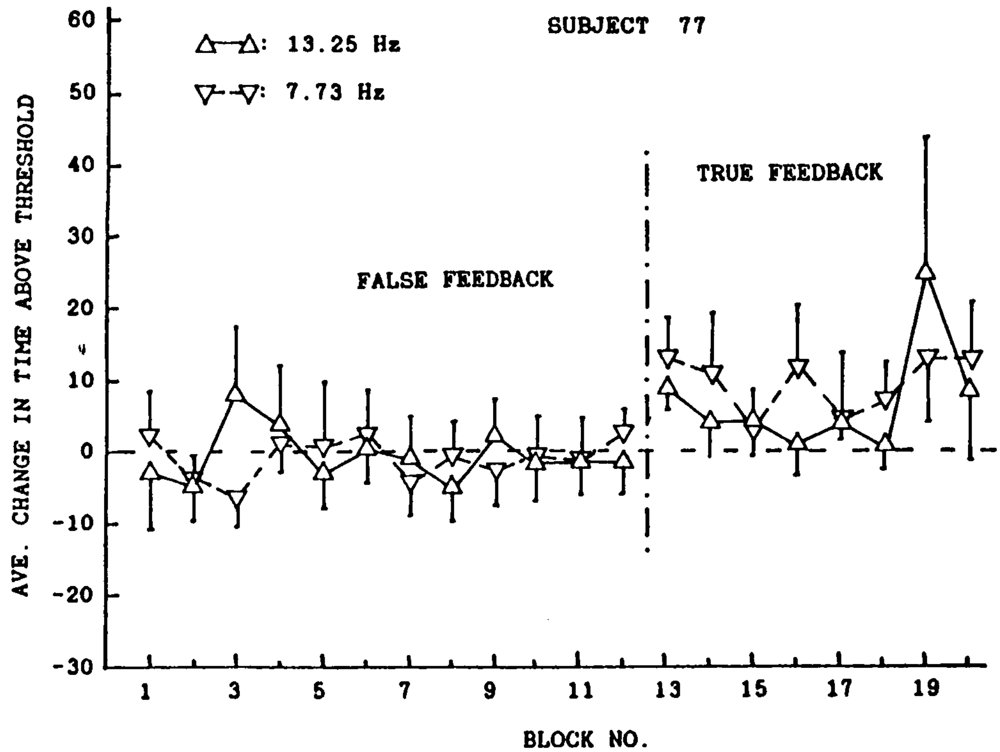


Figure 11a. Average change in time above threshold for subjects who received true feedback. Positive values indicate longer time above threshold for increasing trials than for suppressing trials.



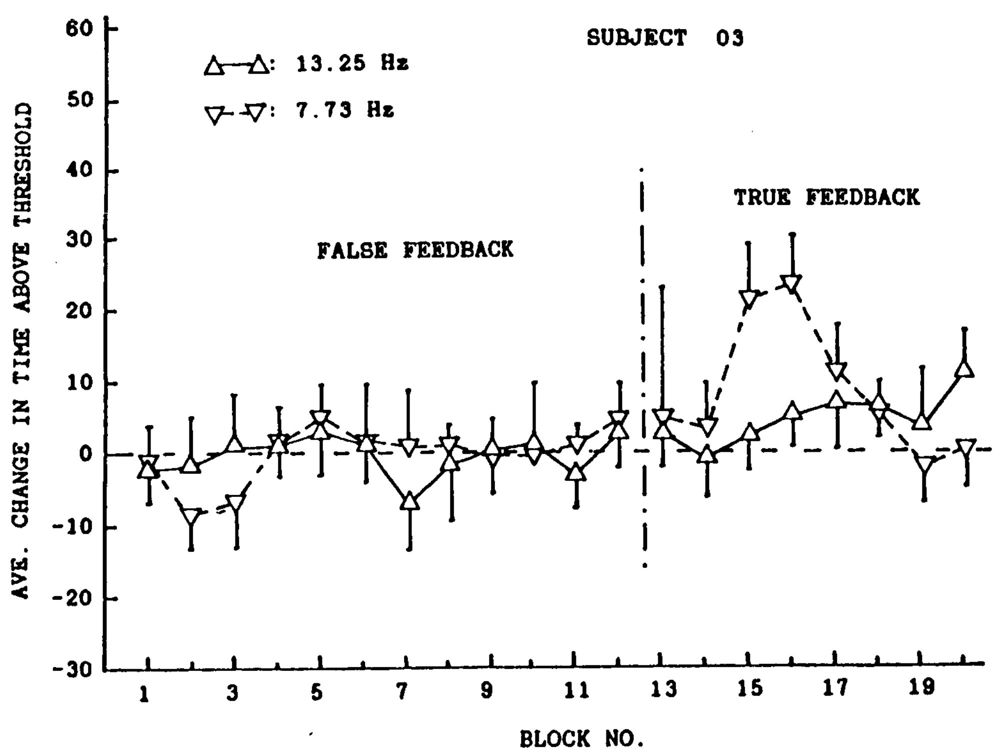


Figure 11b. Average change in time above threshold scores for subjects receiving false feedback for 12 blocks, and then true feedback for 8 blocks.

For the true feedback group, consistent positive trends in coherence were exhibited by subjects only after 7 blocks. Since the false feedback group only had 8 blocks of true feedback training, it is not unexpected that no conclusive trends in coherence were observed.

In contrast to the coherence results previously discussed for Subject 13, this Subject's positive average change in time above threshold (Figure 11a) was consistently higher for 7.73 Hz than for 13.25 Hz. Note that it took at least 4 sessions (8th block) before consistent control began to occur. Blocks 18 and 20 indicate that a big step in learning at 13.25 Hz had occurred. Subject 07 exhibited strong consistent control at 13.25 Hz and marginal control at 7.73 Hz.

For the second group, during the false feedback trials, as to be expected the average time above threshold was approximately zero as it was a result of noise. The plots for Subjects 77 and 03 during false feedback are actually plots of what they saw and heard in terms of feedback cues. When given true feedback both subjects began to exhibit positive average times above threshold indicating EEG control. With further sessions improvements similar to those observed for Subjects 13 and 07 might be expected.

CONCLUDING REMARKS

From the results of Figure 11, it can be concluded that conscious control of EEG at specific frequencies corresponding to evoking stimuli can be achieved. Further, this conscious control can affect the coherence of the response. This has interesting implications relative to the question of the appropriateness of using the SSEP for mental-state estimation. The subject's ability to manipulate their EEG levels is continually and unpredictably active and without the harnessing effects of feedback it may alter SSEPs in an unforeseeable manner. Thus open loop measures may be fraught with uncontrollable changes. A possible solution would be to employ the feedback paradigm reported here during performance so that subjects could be kept continuously aware of their mental state.

As configured in Figure 8, the LAS may be too slow in responding or not sufficiently frequency specific to provide the most effective feedback signal. For large amplitude or large phase variations in the EEG at the reference frequency this will be true. For small perturbations, once a feedback loop has been achieved, LAS response time may be acceptable.

Extending the lowpass filters' cutoff frequencies improves the LAS response time but increases the bandwidth. A possible improvement to the LAS may be the addition of a phase-locked loop. In a typical phase-locked loop system the reference frequency is made to follow the phase of the incoming signal for stability. Utilizing analog delay lines to shift the phase of the reference sine wave as it drives the light stimulus may achieve the desired effect. The approach would be to delay the sine wave one complete cycle and lead or lag an additional amount, determined by the phase signal of the LAS. The intention of this approach would be to provide a more effective evoking stimulus so that the visual-cortical system knows it is "looking at itself."

In closing, it has been shown that with appropriate loop closure humans can achieve narrow-band frequency control of their brain waves. This ability leads directly to control of brain actuated systems. Furthermore, two humans actuating the same control may be the foundation of brain-to-brain communication.

Considering the neurophysiology of the brain near the surface (Guyton, 1986), the cortex is rich in dendritic connections. This evokes the image of a sensitive radio receiver/transmitter. Perhaps in the future the equipment and technology discussed will not be needed to achieve brain actuated control and brain-to-brain communication. At this time, however, the technology presented can help to open the way, while providing insight into the workings of the human brain and a handle on mental-state estimation.

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