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Biocybernetic system evaluates indices of operator engagement in automated task

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Abstract

A biocybernetic system has been developed as a method to evaluate automated flight deck concepts for compatibility with human capabilities. A biocybernetic loop is formed by adjusting the mode of operation of a task set (e.g., manual/automated mix) based on electroencephalographic (EEG) signals reflecting an operator's engagement in the task set. A critical issue for the loop operation is the selection of features of the EEG to provide an index of engagement upon which to base decisions to adjust task mode. Subjects were run in the closed-loop feedback configuration under four candidate and three experimental control definitions of an engagement index. The temporal patterning of system mode switching was observed for both positive and negative feedback of the index. The indices were judged on the basis of their relative strength in exhibiting expected feedback control system phenomena (stable operation under negative feedback and unstable operation under positive feedback). Of the candidate indices evaluated in this study, an index constructed according to the formula, beta power / (alpha power + theta power), reflected task engagement best.

Keywords: Closed-loop feedback; EEG; EMG; Manual/Automated system; Attentional capability

1. Introduction

As automated systems become more capable, human operators spend less time actively controlling such systems and more time passively monitoring system function-

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ing. This type of task demand challenges human capabilities for maintaining sustained attention and engagement in the supervision of an automated system. Mental engagement in an automated operation may not be sufficient to promote the timely and accurate updating of an operator's mental model of system function, i.e., to ensure situation cognizance. Situation cognizance refers to the intellectual grasp of the situation that is supported by this mental model updating. In designing for effective integration of human and system, it is important to provide ready access to useful information so that situation cognizance supports informed action. It is also important to design for human involvement in system function to promote effective situation cognizance; i.e., to promote consistent mental engagement in the supervisory task. Mental engagement in automated environments may be enhanced by judicious allocation of task responsibility between the human and the automated system.

A closed-loop method has been developed to evaluate a human/automation interface design based on its capacity to promote mental engagement. The method was developed to determine optimal human (manual) / system (automated) task allocation 'mixes,' based upon a criterion of mental engagement derived from brain electrical activity, the electroencephalogram (EEG). In the method, a biocybernetic loop is formed by adjusting the mode of operation of a task set (e.g., level of automation) based on the brain activity criterion (EEG-based index of engagement) reflecting an operator's engagement in the task set (Fig. 1). An optimal mode of operation of the task set is observed when the behavior of the closed-loop feedback system attains a stable oscillation, reflecting stable engagement, and is defined by the mode(s) that maintain stable operation. The subject performs a set of tasks presented on a desktop computer display (as shown in Fig. 1) while EEG is monitored.

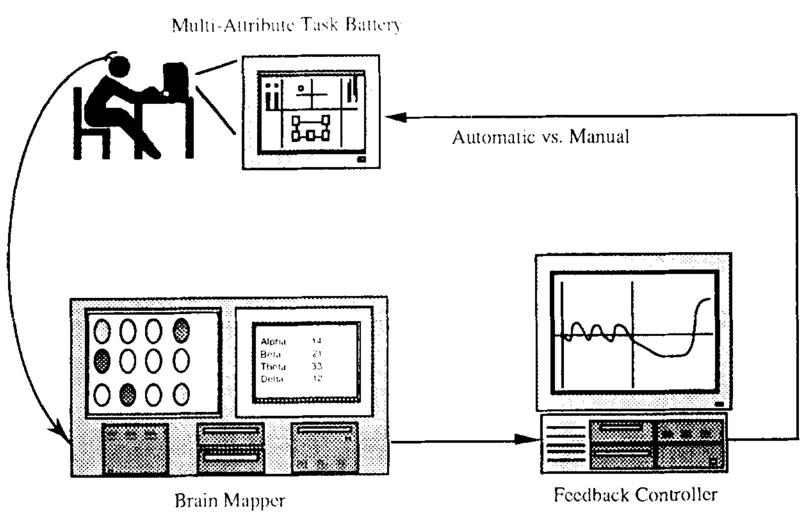

Fig. 1. Operation of EEG-controlled task mode loop.

The level of automation of the task set may be varied so that all, none, or a subset of the tasks require operator intervention, enabling a range of levels of system management demand to be imposed on the operator. These levels of task demand are assumed to elicit corresponding degrees of mental engagement. The task mix is adapted to the subject's degree of engagement in the task set by assigning an additional task to the subject when it is determined from the EEG-based index that task set engagement is waning over a time interval. Conversely, when the engagement index exhibits a sustained rise, indicating that the subject is capable of monitoring attentively, an additional task is automated, decreasing demand on the subject. In this way, the feedback system eventually achieves a steady-state condition in which neither sustained rises nor sustained declines in the engagement index are observed. The combination of automated and manual tasks, the task 'mix,' with which the subject is presented in this condition may be considered optimal by this particular criterion of mental engagement derived from brain electrical activity.

This adaptive process is essentially a feedback control process whereby stable task engagement, reflected in stable short cycle oscillation of the engagement index, is achieved by systematic adjustment of task demand for operator participation. EEG parameters have been used similarly as control variables in the critical administration of anaesthesia. In that application, closed-loop feedback control methods compare the set-point of the control variable, e.g., median EEG frequency, with the value actually measured to modify rate of drug delivery (Schwilden, et al., 1989).

A critical issue for the operation of this method is the selection of features of the EEG to provide an index of engagement upon which to base decisions to adjust task set mode. This report describes a method to evaluate the relative usefulness of candidate EEG indices for reflecting mental engagement in a task. Candidate engagement indices are gleaned from the EEG literature on attention and vigilance (Davidson, 1988; Lubar, 1991; Offenloch and Zahner, 1990; Streitberg, et al., 1987).

The problem of determining the relative usefulness of a task engagement index translates into one of determining the relative strengths of the functional relationships between the candidate indices and task operating mode (i.e., manual versus

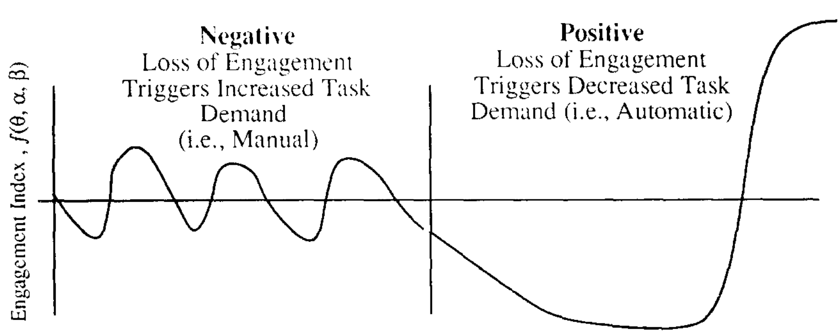

Fig. 2. Expected behavior of effective engagement index under negative and positive contingencies.

automatic) in the closed-loop configuration. Eberlin and Mulholland (1976) have demonstrated a procedure for determining these relationships in a different context — that of EEG alpha-blocking with light stimulation. They were able to demonstrate a functional relationship between light stimulation and EEG alpha production. This was accomplished by showing that the temporal patterning of alpha activity exhibited the expected behavior for a feedback control system under both positive and negative feedback conditions. This result was taken as evidence of a feedforward path (functional relationship) between light stimulation and alpha production (Mulholland, 1977). An adaptation of this procedure was employed for making similar determinations in the present studies.

2. Method

2.1. Subjects

Six volunteer subjects between the ages of 25 and 50 (mean age 35.5 years) participated to produce the first set of results (Fig. 3). These six subjects were run again to produce the second set of results (Fig. 4).

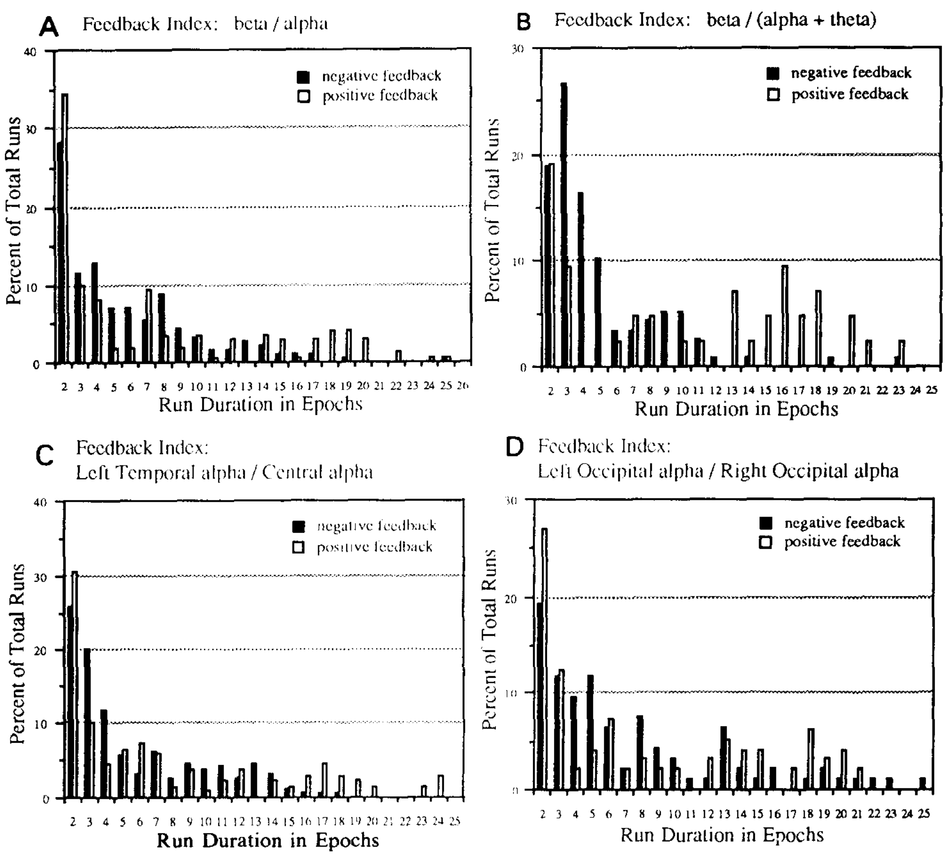

Fig. 3. Run duration distributions for four candidate indices.

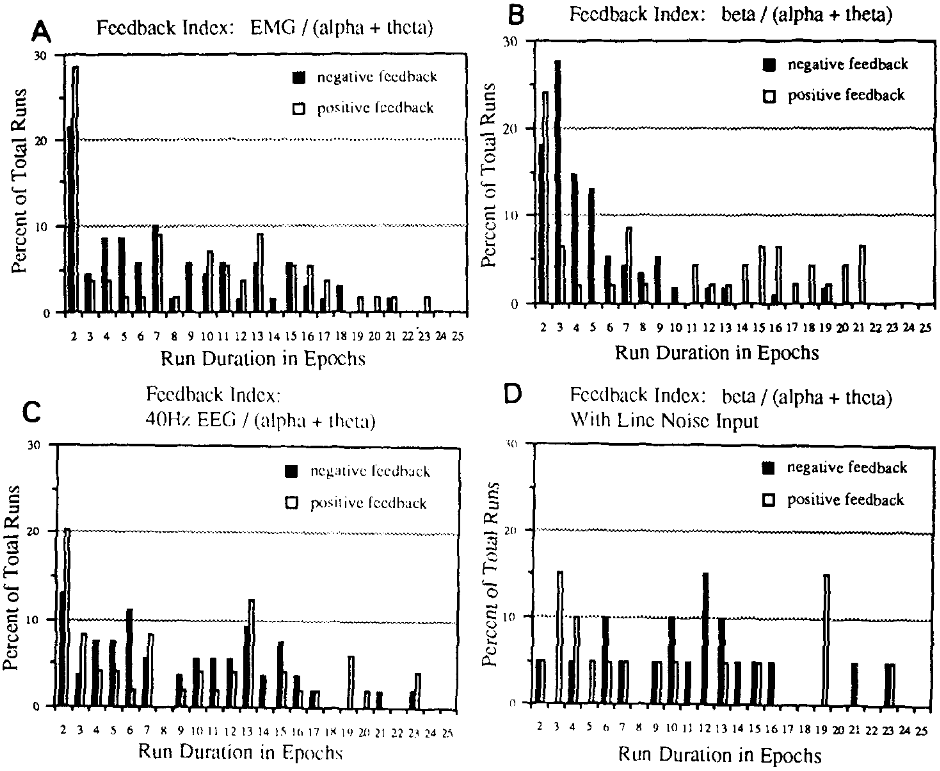

Fig. 4. Run duration distributions for experimental control conditions.

2.2. Apparatus

During data collection, an experimental subject interacted with the compensatory tracking task of the Multiple-Attribute Task (MAT) Battery (Comstock & Arnegard, 1992) presented on a desktop computer display while the subject's brain electrical activity was monitored. The MAT Battery primary display is composed of four separate task areas or windows, comprising the monitoring, tracking, communication and resource-management tasks. Each of these tasks in the MAT set is designed to be analogous to a task that crew-members perform in flight management and each can be made either manual (subject must manage task) or automated (computer manages task). In the version of the MAT developed for these studies, the monitoring, communication and resource-management tasks remained in automatic mode, and the compensatory tracking task was performed by the subject when in manual mode and only monitored by the subject when in automatic mode.

The EEG was recorded at electrode sites Cz, T5, P3, Pz, P4, O1 and O2 as defined by the International 10-20 system (Jasper, 1958). Each scalp site was referred to an average of left and right earlobes. The EEG was amplified by a Cadwell Spectrum-32 topographical brain-mapping system with filter cutoff settings of 1.6 Hz and 55 Hz, digitized at 200 Hz and recorded on optical disk for subsequent analysis. Digitized input channels were converted back to analog, then routed to an EEG interface with a LabVIEW Virtual Instrument (VI). The VI calculated total EEG power in three bands (theta, alpha, and beta) for each of the selected electrode sites. The EEG frequency bands were defined as: alpha (8–13 Hz), beta (13–22 Hz), and theta (4–8 Hz). The VI also performed the engagement-index calculations and commanded the MAT task-mode changes.

2.3. Procedure

Subjects were run using the modified version of the MAT Battery described under the section 2.2. The tracking task was switched between manual and automatic mode contingent upon the behavior of an EEG index. The specific mode of the tracking task was determined by the programmed feedback contingency (positive or negative) as well as the behavior of the index. When in manual mode, this task requires a subject to keep a moving symbol within a central rectangle using a joystick. When automated, the computer constrains movement of the symbol in both axes to within a central rectangle. The task display contained either the message 'Auto' or the message 'Manual' corresponding to the current mode of the tracking task. Prior to data collection, each subject was trained on the manual tracking task for 15 min and was shown the automated tracking condition.

Six subjects were run in the closed-loop feedback configuration (Fig. 1) under four candidate definitions of an engagement index: (combined beta power) / (combined alpha power), (combined beta power) / (combined alpha power + combined theta power), (sum of alpha power at sites T5 and P3) / (sum of alpha power at sites Cz and Pz), and alpha power at O1 / alpha power at O2. The 'combined' powers are sums of powers at Cz, Pz, P3, and P4. The first three definitions were derived from the EEG literature on attention and vigilance (Davidson, 1988; Lubar, 1991; Offenloch and Zahner, 1990; Streitberg et al., 1987). The fourth candidate index was arbitrarily defined and not expected to be related to engagement. Under each of these conditions the temporal patterning of the index was observed for both positive and negative feedback of the index (Fig. 3). Under negative feedback, task mode was switched to (or maintained at) manual when the index was decreasing (negative slope), and under positive feedback, task mode was switched to (or maintained at) automatic when the index was decreasing (Fig. 2). During the 16 min that each subject was performing the task under each candidate index, the task was presented for four continuous blocks of 4 min each, alternating positive and negative feedback blocks. When questioned immediately after their participation in the experiment, subjects responded that the shifts in task mode seemed random. No condition combination (e.g., manual mode and negative contingency) was operative for a continuous interval of more than a few seconds, reducing the likelihood that any appreciable further learning of the compensatory tracking task took place.

3. Results and discussion

If there was a functional relationship between an index and task mode (and consequently, task demand), the index would exhibit stable short-cycle oscillation under negative feedback (left half of Fig. 2) and longer and more variable periods of oscillation under positive feedback (right half of Fig. 2). The strength of the relationship would be reflected in the degree of contrast between the behavior of the index under the two feedback contingencies. The lack of a relationship would be reflected in there being no difference between the behavior of the index under the two feedback contingencies.

The candidate indices were judged on the basis of their relative strength in producing expected feedback control system phenomena (stable operation under negative feedback and unstable operation under positive feedback). That is, a better index choice would cause the index to oscillate more regularly and stably under negative feedback than an inferior choice would, and a better index would increase the degree of contrast between the behavior of the index under the two feedback contingencies. This report's analysis is conducted on histograms (Figs. 3 and 4) of the switching behavior of the closed-loop system, which is directly controlled by the behavior of the index as discussed above.

A run duration is defined as the number of 2-s epochs that the MAT tracking task remained in one mode, either manual or automatic. Figs. 3a-3d show the summary distributions of the run durations for the positive and negative feedback conditions for the six subjects, with the indices defined as shown. A strong functional relationship between a candidate index and task operating mode (i.e., manual versus automatic) would be reflected in stable operation under negative feedback and unstable operation under positive feedback. In such a case, the negative feedback distribution would appear positively skewed and peaked (stable short-cycle oscillation of the engagement index and, as a programmed consequence, of the task mode), and the positive-feedback distribution would appear relatively flat (longer and more variable periods of alternation). A Kolmogorov-Smirnov two-sample test was used to test the significance of the differences between the positive and negative distributions.

A significant difference was found between the positive and negative-feedback conditions for the first three of the candidate indices (Fig. 3). Subjects exhibited longer and more variable periods in the positive-feedback condition than in the negative-feedback condition. The greatest significant difference ($p < 0.001$) was found between the positive and negative-feedback conditions for the beta / (alpha + theta) index. Therefore, on the basis of strength in producing expected feedback control system phenomena (stable operation under negative feedback and unstable operation under positive feedback), the beta / (alpha + theta) index reflects task engagement best. The distribution differences obtained for the group were also apparent for each subject in the group.

To examine the effects of electromyographic (EMG) activity on the behavior of the closed-loop system, EMG power in the frequency band 42–100 Hz was explicitly substituted for beta power in one index definition. The behavior of the closed-loop system under this combined EMG-EEG index definition is shown in the distributions in Fig. 4a for this second experiment with the same six subjects. The difference between the positive and negative distributions for this index definition is significant ($p < 0.05$), but with the positive feedback case exhibiting stable feedback-control behavior (short cycle oscillation of the engagement index). The effect of EMG band power in the numerator of the index appears to be opposite to the effect of beta power in the numerator. The summary distributions for the beta / (alpha + theta) index are shown in Fig. 4b and the difference between them is again significant ($p < 0.0001$) in the expected direction for feedback control (stable, short-cycle operation under negative feedback and unstable operation under positive feedback).

Shown in Fig. 4c are summary distributions for the six subjects, obtained with an index definition substituting 38–42 Hz band power for the previous beta power definition. The differences between the positive and negative distributions for this condition is significant ($p < 0.005$), but with the positive-feedback case exhibiting stable feedback-control behavior. The effect of 38–42 Hz band power in the numerator of the index, like the effect of EMG band power there, appears to be opposite to the effect of beta power in the numerator. There are no significant differences ($p > 0.1$) between the results obtained with the 38–42 Hz band power definition and the EMG-EEG index definition shown in Fig. 4a. Fig. 4d shows the distributions obtained when the loop is broken and system noise alone drives the task mode changes. The difference between the positive and negative distributions for this condition is not significant ($p > 0.5$).

Therefore, closed-loop systems employing the three selected EEG indices exhibit expected feedback-control behavior, whereas systems employing the experimental control indices do not. These results are taken as evidence of feedforward paths (functional relationships) between changes in the selected EEG parameters and task mode changes, with the strength of the relationships indicated by the degree to which the indices exhibit feedback-control behavior. The effect of 38–42 Hz or EMG band power in the numerator of the index appears to be opposite to the effect of beta power in the numerator. This implies that the effect of EMG artifact in the EEG beta band is to reduce the extent to which the closed-loop system employing the beta / (alpha + theta) index exhibits expected feedback-control behavior.

The closed-loop method enables an index of engagement to be identified which is maximally sensitive to changes in task demand. Using this methodology, hypotheses about which features of brain signals best modify an automated system to suit human attentional capability can be efficiently tested.

The ultimate objective of this effort is the development of new methodologies to assess the extent to which automated flight-deck systems maintain pilot engagement. The closed-loop process employing a full task set, described at the beginning of this report, is designed to determine optimal human/system task allocation 'mixes,' based upon a brain activity criterion of mental engagement. This closed-loop method is intended to provide a dynamic, interactive method of adjusting a system design to optimize the operator's engagement.

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