Old Dominion University Research Foundation

DEPARTMENT OF PSYCHOLOGY
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

FUNCTIONAL RELATIONSHIPS AMONG MONITORING PERFORMANCE: SUBJECTIVE REPORT OF THOUGHT PROCESS AND COMPROMISING STATES OF AWARENESS

By

Dr. Frederick Freeman, Principal Investigator

Summary of Research (Final Report)
For the period ended September 30, 1995

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

Under
Research Grant NCC1-176
Dr. Alan T. Pope, Technical Monitor
FDCD-Human/Auto Integration Branch

September 1995

DEPARTMENT OF PSYCHOLOGY
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

FUNCTIONAL RELATIONSHIPS AMONG MONITORING PERFORMANCE: SUBJECTIVE REPORT OF THOUGHT PROCESS AND COMPROMISING STATES OF AWARENESS

By

Dr. Frederick Freeman, Principal Investigator

Summary of Research (Final Report)
For the period ended September 30, 1995

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

Under
Research Grant NCC1-176
Dr. Alan T. Pope, Technical Monitor
FDCD-Human/Auto Integration Branch

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508

September 1995

Abstract

A biocybernetic system for use in adaptive automation was evaluated using EEG indices based on the beta, alpha, and theta bandwidths. Subjects performed a compensatory tracking task while their EEG was recorded and one of three engagement indices was derived: $\beta/(\alpha+\theta)$, β/α, or $1/\alpha$. The task was switched between manual and automatic modes as a function of the subjects' level of engagement and whether they were under a positive or negative feedback condition. It was hypothesized that negative feedback would produce more switches between manual and automatic modes, and that the $\beta/(\alpha+\theta)$ index would produce the strongest effect. The results confirmed these hypotheses. There were no systematic changes in these effects over three 16-minute trials. Tracking performance was found to be better under negative feedback. An analysis of the different EEG bands under positive and negative feedback in manual and automatic modes found more beta power in the positive feedback/manual condition and less in the positive feedback/automatic condition. The opposite effect was observed for alpha and theta power. The implications of biocybernetic systems for adaptive automation are discussed.

Descriptors: Biocybernetic system, Alertness indices, EEG feedback

Recently, Pope, Bogart, and Bartolome (in press) reported on a biocybernetic system that controlled the level of task automation using the degree of operator involvement, as measured by different indices of arousal. It was argued that the types of automated systems, which are increasingly appearing in today's workplace, typically require passive monitoring and promote decreased situational awareness. Consequently, the operator is less capable of reacting to sudden changes in system functioning which require active cognitive processing (Wickens, 1992). Adaptive automation (i.e. the ability of systems to change their level of functioning in response to situational demands) has been a growing interest of researchers in the area of human performance (cf. Morrison, Gluckman, & Deaton, 1991; Rouse 1988). Numerous proposals have been made concerning how task allocation might be conducted in automated systems. One type of proposal involves behavioral measures such as monitoring the operator's workload (Hancock, Chignell, & Lowenthal, 1985; Riley, 1985; Rouse, 1977) or vigilance performance (Carriero, 1977). Other investigators have suggested incorporating the use of physiological measures such as ERPs into adaptive systems (Parasuraman, 1990; Wickens, 1990). The research of Pope, et al. addressed this question through the use of EEG measures in a biocybernetic system. In order to develop such technology, however, a better understanding is needed of the basic functioning of biocybernetic systems. Although the concept of a biocybernetic system has been discussed (Gomer, 1981), very little research has been reported on how such a system might function.

In the biocybernetic system described by Pope, et al., the subject's electroencephalogram (EEG) was recorded and an index was derived that reflected the level of engagement or arousal of the operator. EEG has often been used in mental workload and vigilance paradigms to assess arousal levels (Gale, 1987; Gale & Edwards, 1983). The bandwidths typically employed include alpha, beta, and theta waves. Beatty and colleagues (Beatty, Greenberg, Diebler, & O'Hanlon, 1974; O'Hanlon & Beatty, 1979; O'Hanlon, Royal, & Beatty, 1977), for example, using biofeedback techniques, found that increases or decreases in attention could be produced by suppressing or increasing theta waves, although the magnitude of these effects is very small (Alluisi, Coates, & Morgan, 1977). Siervaag, Kramer, deJong, and Mecklinger (1988) observed decreases in theta with increases in task difficulty. Increases in mental workload have also been shown to be correlated with alpha activity (Ray & Cole, 1985; Veigel & Sterman, 1993) while increases in arousal level are often associated with increases in beta activity (cf. Davidson, 1988).

Lubar and associates (Lubar, 1991; Lubar, Swartwood, Swartwood, & O'Donnell, 1995) in their research on Attention Deficit/Hyperactivity Disorder, have argued that low levels of attention are associated with decreased beta and increased theta activity. He and his associates have used a ratio of beta to theta waves in treating ADHD patients. Pope, et al., studied different candidate indices, based on the work of Lubar and other EEG researchers (e.g. Offenloch & Zahner, 1990; Streitberg, Rohmel, Herrmann, & Kubicki, 1987) in evaluating their biocybernetic system. In their system, both negative and positive feedback were evaluated using three indices: $\beta/(\alpha+\theta)$, β/α, and $1/\alpha$. Under negative feedback, increases in arousal, operationally defined by a specific ratio index, caused a tracking task to become automated, while decreases switched the task mode to manual, requiring the subject to "engage" in or control the tracking task. Thus, depending on the parameters of the system, the subject's arousal level index was not allowed to move very far in either direction before the task mode changed, which in turn affected the index of arousal. Under positive feedback increases in the arousal index caused the task to switch to (or remain) in a manual condition while decreases caused the task to switch to (or remain) in the automated state. As Pope, et al. predicted, negative feedback produced more oscillations between manual and automated conditions, while positive feedback produced episodes of manual and automatic control that were longer and of more variable length. This effect was strongest for the $\beta/(\alpha+\theta)$ index.

The purpose of the present study was to replicate and extend the results reported by Pope, et al. First, it should be noted that the Pope, et al. study included only six subjects. Thus, a larger sample size was used in the current study. Second, the only data reported by Pope, et al. were the number of runs under positive and negative feedback conditions. To better understand how the system is functioning it is important to examine exactly how the indices and the different EEG bands are being affected. Third, subjects were only examined after one run through the system. It is possible that different amounts of experience with the system may alter its functioning. Finally, in order for a biocybernetic system to have any practical value, it is essential to evaluate its effect on performance. Each of these problems was addressed in the present study.

METHOD

Subjects

Thirty-six subjects, 18 - 40 years of age, were used in the present study. All subjects were either undergraduate or graduate students and were given either extra credit for their class or $10.00 for participating in the experiment. All subject were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971).

Apparatus

EEG was recorded using an Electro-cap International lycra sensor cap. The cap consists of 22 recessed Ag/AgCl electrodes arranged according to the International 10-20 system (Jasper, 1958). EEG was recorded using a BIOPAC EEG100A differential amplifier module consisting of four channel, high gain, differential input, bio-potential amplifiers. The system has an input impedance of 2M(ω) differential and 1000M(ω) common mode, a maximum input voltage of -10V to +10V, and a CMRR of 10dB minimum. The frequency response was 1 to 100 Hz. The noise voltage (filter off) was 2 uV (pk-pk).

The gain was set at x5000 to allow an input signal range of 4000uV (pk-pk). The EEG100A was connected to a Macintosh Quadra on which a LabVIEW Virtual Instrument (VI) calculated total EEG power in three bands: 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 through serial port connections to the task computer. The task was presented on a WIN 386 SX computer with a NEC MultiSync 2A color monitor. An Analog Edge joystick, set at 60% of its maximum gain, was used for the compensatory tracking task.

Engagement Indices

Three engagement indices were employed: $\beta/(\alpha+\theta)$, β/α, and $1/\alpha$. EEG was recorded from the four sites found to be most effective in the Pope, et al. study : Cz, Pz, P3, and P4. The combined alpha, beta, and theta power from these four sites were used to derive each index. The index was first determined over a 40 second baseline period. It was then updated every two seconds. The slope of the changes in the index was derived and used to determine the manual/automatic task mode in the two feedback conditions (see below).

Task

Subjects performed the compensatory tracking task of the Multiple-Attribute Task (MAT) Battery (Comstock & Arnegard, 1992). The MAT Battery consists of four separate task areas or windows, comprising monitoring, tracking, communication, and resource management tasks. Each of these tasks is designed to be analogous to a task that crew members perform in flight management and each can be made either manual (subject controlled) or automated (the computer manages the task). In the current study, 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.

Feedback Conditions

Under the negative feedback condition, the task was switched to or remained in manual mode when the index was decreasing (negative slope) and switched to or remained in automatic mode when the index was increasing (positive slope). Under the positive feedback condition, the task was switched to or remained in manual mode when the index was increasing and switched to or remained in automatic mode when the index was decreasing.

Procedure

Upon entering the experimental suite, subjects were explained the nature of the experiment and asked to sign an informed consent form. The electrode cap and reference electrode were then attached. The left mastoid area was used as the reference. The impedance levels at the four recording sites (Cz, Pz, P3, and P4) and mastoid area were reduced below 5 kOhms.

Following the electrode attachment, subjects were seated in front of the monitor on which the MAT Battery was displayed. The nature of the tracking task was explained to them and they were allowed to practice for five minutes. All subjects used their right hand for the tracking task. Following the five-minute practice, the 40-second baseline recording was taken and the task was started.

Twelve subjects were randomly assigned to each of the three indices. Half of the subjects in each group began tracking under positive feedback and half under negative feedback. Half of each of these groups began with the manual task mode and half with the automatic. Subjects were run for 16 minutes of alternating four-minute blocks of positive and negative feedback. At the end of the 16 minutes subjects were given a five-minute rest. Three identical trials of 16 minutes were run with a five-minute intertrial interval. Due to technical problems, the performance data were only available for the last 18 subjects (six subjects for each index) run.

Dependent Measures

The primary dependent measure was the number of task allocations between automatic and manual modes. Subject performance was assessed by the RMS error on the tracking task. In addition, power analyses were performed on the alpha, beta, and theta bandwidths.

RESULTS

Task Allocations

A 3 (Index) by 3 (Trial) by 2 (Type of Feedback) mixed design ANOVA was used to analyze the number of task allocations (or switches) between manual and automatic task modes. A significant effect was found for Index, F (2, 33) = 9.98, p< .01 and for the Index by Feedback interaction, F (2, 33) = 3.60, p< .05. There were no other significant effects. As seen in Figure 1, the pattern of switches remained relatively constant across all three trials. For the $\beta/(\alpha+\theta)$ index the number of switches was consistently greater across trials for negative feedback compared to positive feedback. For the other two indices the number of switches was inconsistent, although there was a tendency for more switches to occur under positive feedback.

Performance

A 3 (Index) by 3 (Trial) by 2 (Feedback) mixed design ANOVA was used to analyze the RMS error for tracking performance. It is important to note, that only data from the episodes under manual control were available for analysis. The only significant effect was for Feedback, F (1, 15) = 25.02, p< .01, with subjects showing better tracking performance under negative (Mean = 11.07) than under positive (Mean = 12.03) feedback.

EEG

To assess the effect of the biocybernetic system on EEG, a 3

(Index) by 3 (Trial) by 2 (Feedback) by 2 (Task Mode: manual or automatic) mixed design ANOVA was performed on the power of each of the alpha, beta, and theta bandwidths. For alpha power there was a significant effect for Task Mode $F(1, 34) = 12.04$, $p < .01$, and for the Feedback by Task Mode interaction, $F(1, 34) = 47.74$, $p < .01$. The interaction is shown in Figure 2. For positive feedback, relative alpha power was higher under the automatic task mode and lower under the manual task mode, regardless of index. This pattern was reversed for the negative feedback condition, though the differences between manual and automatic task modes were smaller than for positive feedback.

For theta power, there was a significant effect of Index, $F(2, 34) = 5.84$, $p < .01$, and Trial, $F(2, 64) = 3.68$, $p < .05$, and a significant Index by Trial interaction, $F(2, 64) = 5.47$, $p < .01$. The Index by Trial interaction is shown in Figure 3. Theta power was less for the β/α and the $1/\alpha$ indices and tended to increase across trials. For the $\beta/(\alpha+\theta)$ index, theta power was greater and did not change systematically across trials. There was also a significant Feedback by Task Mode interaction, $F(1, 34) = 83.57$, $p < .01$, and a significant Index by Feedback by Task Mode interaction, $F(2, 34) = 8.02$, $p < .01$. The three-way interaction is shown in Figure 4. As with alpha power, under positive feedback there was more theta for the automatic task mode and less for the manual task mode. The reverse was seen for negative feedback. However, unlike with alpha power, positive feedback resulted in less of a difference between manual and automatic task modes compared to negative feedback. Theta power was greater for the $\beta/(\alpha+\theta)$ index and the differential between task modes was not as great as that seen for relative alpha power.

For beta power, there was a significant effect of Task Mode, F (1, 34) = 5.21, $p < .05$, and for the Index by Task Mode interaction, F (2, 34) = 5.38, $p < .01$. For the β/α and $1/\alpha$ indices relative beta power tended to be higher for the automatic task modes while for the $\beta/(\alpha+\theta)$ index beta power was higher for the manual task mode (see Table 1). There was also a significant Index by Feedback by Task Mode interaction, F (2, 34) = 49.90, $p < .01$. As seen in Figure 5, for the $\beta/(\alpha+\theta)$ index the relationship between feedback and task mode was the reverse of that for alpha and theta. Beta power was greater for the positive feedback manual mode and negative feedback automatic mode and lower for the other two conditions. For the other two indices there does not appear to be any consistent relationship between feedback and task mode.

Finally, a factor analysis using the Varimax Rotation Method was performed on the EEG data, using the three bandwidths for each of the four sites to produce twelve variables. Three factors emerged: the first consisted of the alpha bandwidth across sites, the second, the theta bandwidth across sites, and the third, the beta bandwidth across sites. The variance explained by each factor was 29%, 28%, and 28% for the alpha, theta, and beta bandwidths, respectively.

DISCUSSION

The primary purpose of the present study was to extend the results reported by Pope, et al. As found in the Pope, et al. study, negative feedback produced more task allocations than positive feedback. This effect was found to be the strongest for the $\beta/(\alpha+\theta)$ index compared to the other two indices, which did not yield any consistent pattern. Furthermore, the effect for $\beta/(\alpha+\theta)$ index was maintained over the three 16-minute trials, indicating that practice or fatigue was not a factor in producing the effect. It is possible, however, that extended practice with the system, over hours or days, might yield different effects.

Regarding tracking, the negative feedback resulted in a small, but significant, enhancement of performance. This is an important finding, since the value of any biocybernetic system will ultimately be determined by how well the system operator is able to function. Even if task allocations are greater under negative feedback, as was predicted, there is little practical value of such systems if they do not result in better performance. While the effect seen in the present study was small, and there was no interaction with the type of index, it should be remembered that the investigation of the system is at a preliminary stage. Variables that might improve how the system functions (e.g. length of the window used to obtain an average index), discussed below, need to be manipulated and evaluated.

The results tend to support the use of the $\beta/(\alpha+\theta)$ index in the biocybernetic system used in the present study. That is, the

$\beta/(\alpha+\theta)$ index produced the greatest differential amount of task allocations between positive and negative feedback. Further, although there were no significant interactions for the performance data, the $\beta/(\alpha+\theta)$ and the β/α indices tended to result in better performance.

The use of index ratios rather than raw EEG was also validated, at least in part, by the results. The poorest index, in terms of differential amount of task allocations between positive and negative feedback was $1/\alpha$. This was the only index that relied solely on the power within one bandwidth. It is possible that the use of beta or theta power alone might have produced better results. However, the pattern of the relationship between feedback and task automation was the same for theta as it was for alpha. Thus, under positive feedback, alpha and theta were low under the manual mode and high under the automatic mode; for negative feedback the reverse was true. The pattern for beta was exactly the opposite. Thus, although neither theta nor beta were used alone to drive the system, their patterns suggest that the effects would be the same as those seen for the $1/\alpha$ index.

One anomaly of the interaction between feedback and task modes was the effect of negative feedback on the differential amount of power seen under the manual and automatic conditions for theta and beta. One would expect that negative feedback would not allow the index to increase too much under the manual mode or decrease too much under the automatic mode. Conversely, under positive feedback one would expect to find the highest values of the index and of beta under the manual mode and the lowest under automatic. Alpha and theta power would be expected to show the opposite patterns. While this relationship was found for alpha, it was not apparent for beta and theta power. The negative feedback, automatic mode produced as much of an increase in beta (and a decrease in theta) as positive feedback did under the manual mode. An ideally functioning system would be expected to produce a minimal amount of change under negative feedback for either task mode and a maximal change under positive feedback for both task modes.

One potential factor contributing to the anomaly just described is the use of changes in the slope of the index rather than absolute levels. Because the major purpose of the present study was to replicate and extend the results of Pope, et al., the same basic system parameters were employed. Future research employing comparable biocybernetic systems should involve manipulation of variables such as the absolute value of the index employed. Other system parameters which need to be systematically varied include the degree of change in the index that should drive the system, the length of the window on which the average index is based (the current study used 40 seconds), and how often the average should be updated.

In addition to system variables, a number of operator and EEG variables need to be examined. Hemispheric differences in arousal and alertness (cf. Heilman, 1995; Posner & Petersen, 1990) may strongly contribute to how well the system functions. Further, the recording sites used in the present study and by Pope, et al. were primarily over the parietal lobes. Other research (e.g. Lubar, et al., 1995) suggests that the frontal lobes may be important in the control of alertness and attention. It may also be of practical value to evaluate the maximum number of recording sites necessary to drive the system adequately.

Finally, task variables need to be investigated. In the current study subjects performed a simple compensatory tracking task, using their dominant (right) hand. Variables such as task difficulty and increases in mental workload might have important effects on how the system functions. In addition, the system would need to be evaluated for qualitatively different kinds of tasks. Tracking, as used here, represents a relatively simple, continuous performance task. Would the system function differently for more cognitive types of tasks? The potential usefulness of biocybernetic systems will require a great deal of basic research to answer these questions.

References

Alluisi, E.A., Coates, G.D., & Morgan, B.B. (1977). Effects of temporal stressors on vigilance and information processing. In R.R. Mackie (Ed.), Vigilance: Theory, operational performance, and physiological correlates (pp. 361-421). NY: Plenum.

Beatty, J., Greenberg, A., Diebler, W.P., & O'Hanlon J.F. (1974). Operant control of occipital theta rhythm affects performance in a radar monitoring task. Science, 183, 871-873.

Carriero, N. (1977). Physiological correlates of performance in a long duration repetitive visual task. In R.R. Mackie, (Ed.), Vigilance: Theory, operational performance and physiological correlates (pp. 307-330) New York: Plenum Press.

Comstock, J.R. & Arnegard, R.J. (1992). The multi-attribute task battery for human operator workload and strategic behavior research. National Aeronautics and Space Administration Technical Memorandum No. 104174.

Davidson, R.J. (1988). EEG measures of cerebral asymmetry: Conceptual and methodological issues. International Journal of Neuroscience, 39, 71-89.

Gale, A. (1987). The electroencephalogram. In A. Gale and B. Christie (Eds.), Psychophysiology and the electronic workplace. London: John Wiley & Sons.

Gale, A. & Edwards, J. (1983). EEG and human behavior. In A. Gale and J. Edwards (Eds.), Physiological correlates of human behavior (Vol. 2). London: John Wiley & Sons.

Gomer, F. (1981). Physiological monitoring and the concept of adaptive systems. In J. Moral, & K.F. Kraiss, (Eds.), Manned systems design (pp. 257-263). New York: Plenum Press.

Hancock, P.A., Chignell, M.H., & Lowenthal, A. (1985). An adaptive human-machine system. Proceedings of the IEEE Conference on Systems, Man, and Cybernetics. 15, 627-629.

Heilman, K.M. (1995). Attentional asymmetries. In R.J. Davidson & K. Hugdahl (Eds.) Brain Asymmetry (pp. 217-234). Cambridge: The MIT Press.

Jasper, H.H. (1958). Report on the committee on methods of clinical examination in electroencephalography. Electroencephalography and Clinical Neurophysiology, 10, 370-375.

Lubar, J.F. (1991). Discourse on the development of EEG diagnostics and biofeedback treatment for attention-deficit/hyperactivity disorders. Biofeedback and Self-Regulation, 15, 201-225.

Lubar, J.F., Swartwood, M.O., Swartwood, J.N., & O'Donnell, P.H. (1995). Evaluation of the effectiveness of EEG neurofeedback training for ADHD in a clinical setting as measured by changes in T.O.V.A. scores, behavioral ratings, and WISC-R performance. Biofeedback and Self-Regulation, 20, 83-99.

Morrison, J.G., Gluckman, J.P., & Deaton, J.E. (1991). Program plan for the adaptive function allocation for intelligent cockpits (AFAIC) program. (Final Report No. NADC-91028-60). Warminster, PA: Naval Air Development Center.

Offenloch, K. & Zahner, G. (1990) Computer aided physiological assessment of the functional state of pilots during simulated flight. NATO Advisory Group for Aerospace Research and Development-Conference Prodeedings-490, 1-9.

O'Hanlon, J.F. & Beatty, J. (1979). Concurrence of electroencephalographic and performance changes during a simulated radar watch and some implications for the arousal theory of vigilance. In R.R. Mackie (Ed.), Vigilance: Theory, operational performance, and physiological correlates (pp. 189-201). NY: Plenum.

O'Hanlon, J.F., Royal, J.W., & Beatty, J. (1977). EEG theta regulation and radar vigilance performance of professional radar operators and air traffic controllers under laboratory and controlled field conditions. In J. Beatty & H. Legewie (Eds.), Biofeedback and Behavior (pp. 147-165). NY: Plenum.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia, 9, 97-114.

Parasuraman, R. (1990). Event-related brain potentials and human factors research. In J.W. Rohrbaugh, R. Parasuraman, & R. Johnson, jr., (Eds.) Event-Related brain potentials: Basic issues and applications (pp. 279-300) New York: Oxford University Press.

Posner, M.I. & Petersen, S.E. (1990). The attention system of the human brain. Annual Review of Neuroscience, 13, 25-42.

Pope, A., Bogart, E., & Bartolome, D. (in press). Biocybernetic system evaluates indices of operator engagement. Biological Psychology.

Ray, W. & Cole, H. (1985). EEG alpha activity during cognitive processin: Influence of attentional factors. International Journal of Psychophysiology, 3, 43-48.

Riley, V. (1985). Monitoring the monitor: Some possible effects of embedding human models in highly automated manned systems. Proceedings of the IEEE Conference on Systems, Man, and Cybernetics, 15, 6-9.

Rouse, W.B. (1977). Human-computer interaction in multitask situations. IEEE Transactions Systems, Man, and Cybernetics, SMC-7, 384-392.

Rouse, W.B. (1988). Adaptive aiding for human/computer control. Human Factors, 30, 431-443.

Siervaag, E., Kramer, A., deJong, R., & Mecklinger, A. (1988). A psychophysiological analysis of multi-task processing demands. Psychophysiology, 25, 482.

Streitberg, B., Rohmel, J., Herrmann, W.M., & Kubicki, S. (1987). COMSTAT Rule for vigilance classification based on spontaneous EEG activity. Neuropsychobiology, 17, 105-117.

Veigel, B. & Sterman, M. B. (1993). Topographic EEG correlates of good and poor performance in a signal recognition task. Proceedings of human factors and ergonomics Society 37th annual meeting (in press).

Wickens, C.D. (1990). Applications of event-related potential research to problems in human factors. In J.W. Rohrbaugh, R. Parasuraman, & R. Johnson, jr., (Eds.) Event-Related brain potentials: Basic issues and applications (pp. 301-309) New York: Oxford University Press.

Wickens, C.D. (1992). Engineering psychology and human performance, 2nd Ed. New York: Harper Collins.

Table 1. Index by Task Mode Means for Relative Beta Power.

		Manual Task Mode	Automatic Task Mode
I	$\beta/(\alpha+\theta)$	.035	.034
N			
D	β/α	.035	.037
E			
X	$1/\alpha$	.038	.040

Figure Captions

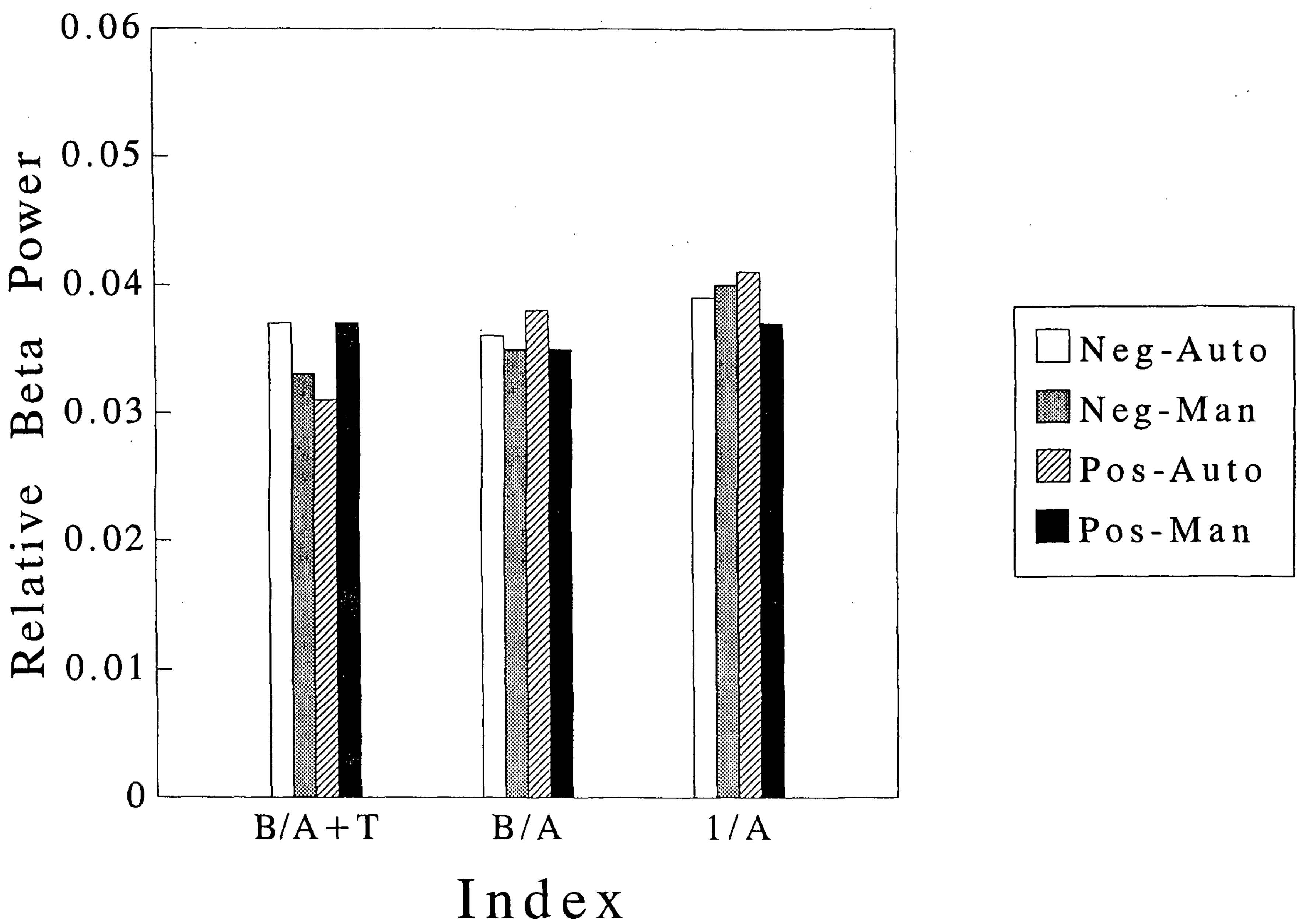
Figure 1: Number of switches between manual and automatic modes as a function of index and trials.

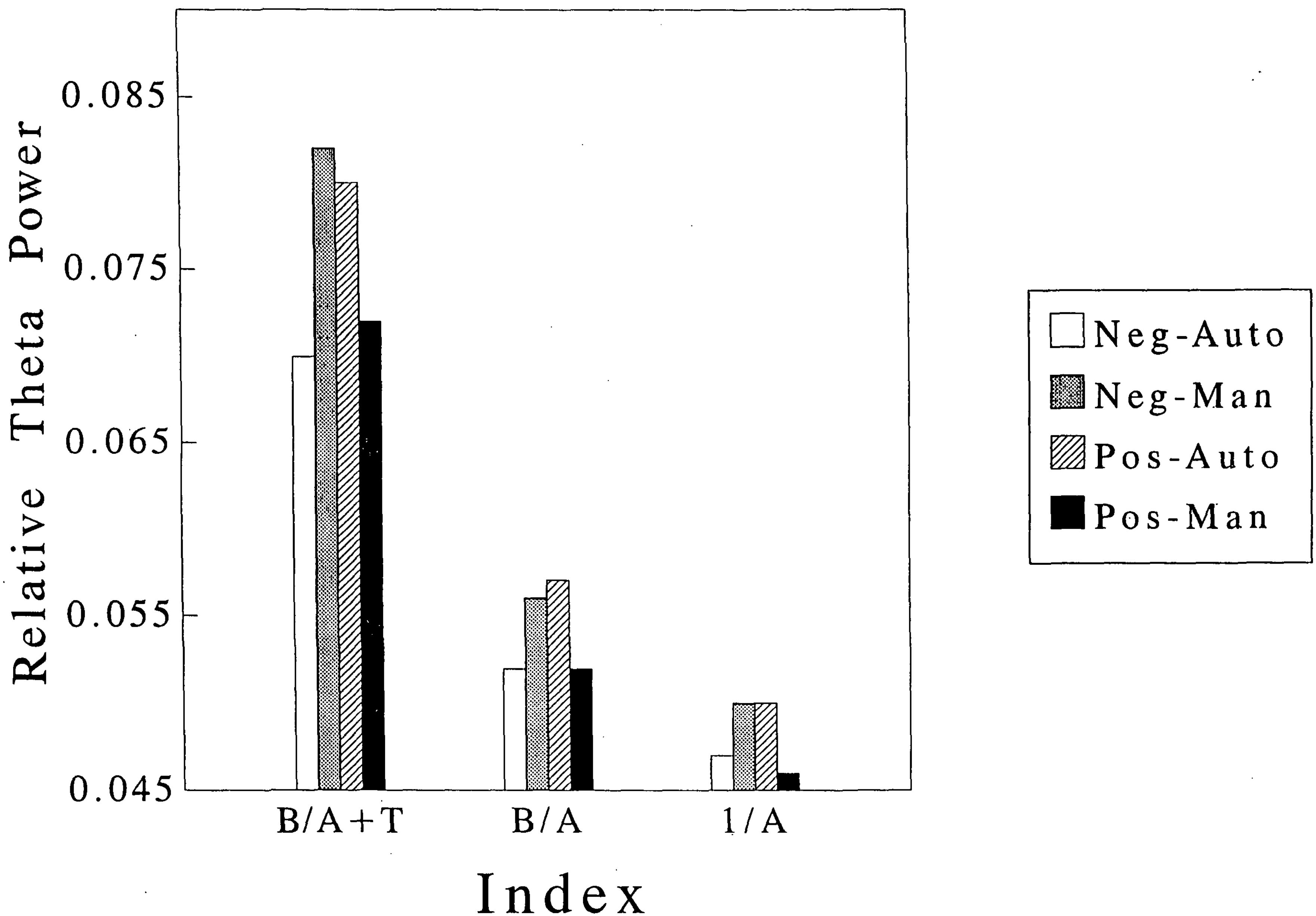
Figure 2: Relative alpha power as a functio of the three indices under positive and negative feedback.

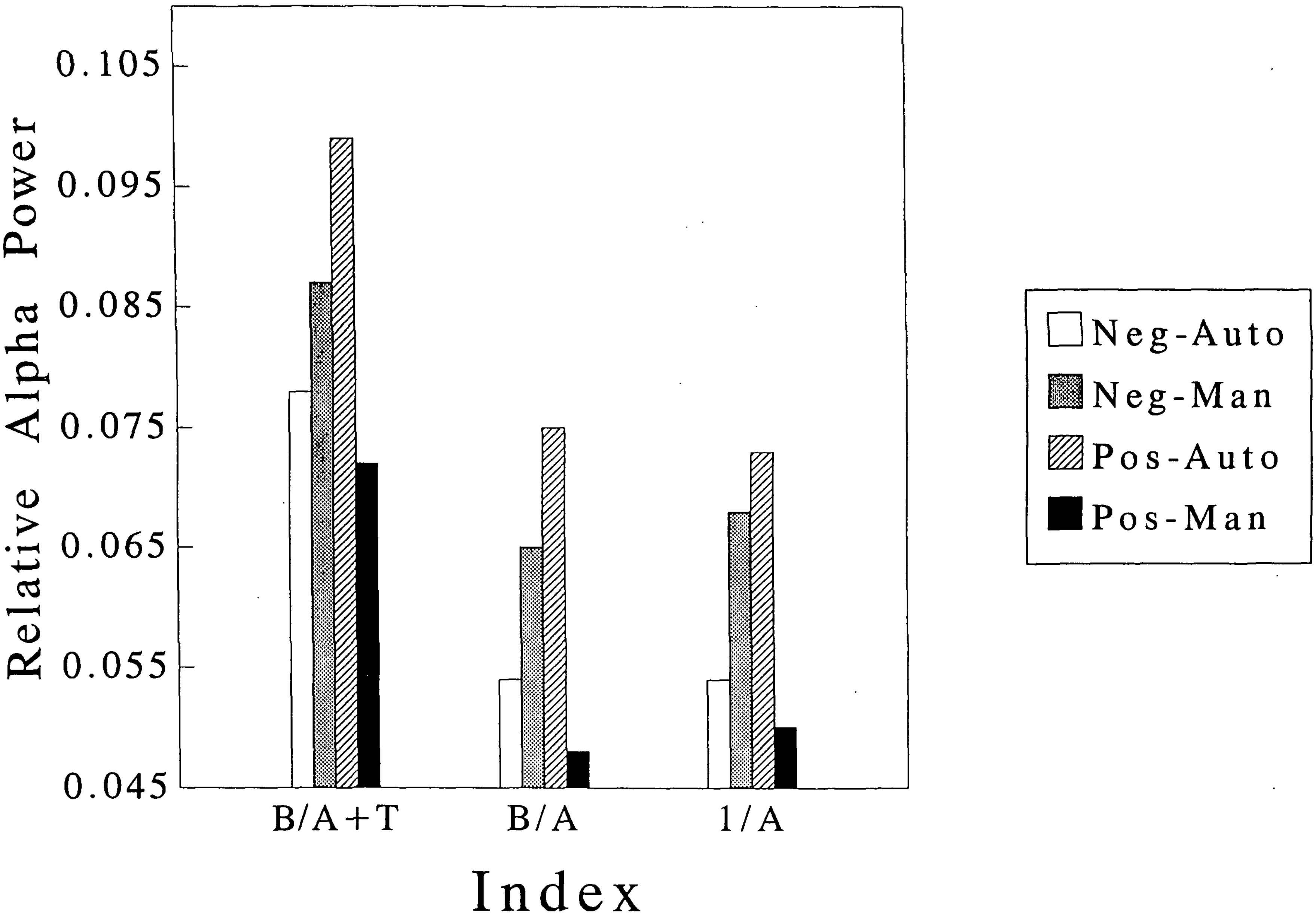
Figure 3: Relative theta power as a function of index and trials.

Figure 4: Relative theta power as a function of the three indices under positive and negative feedback.

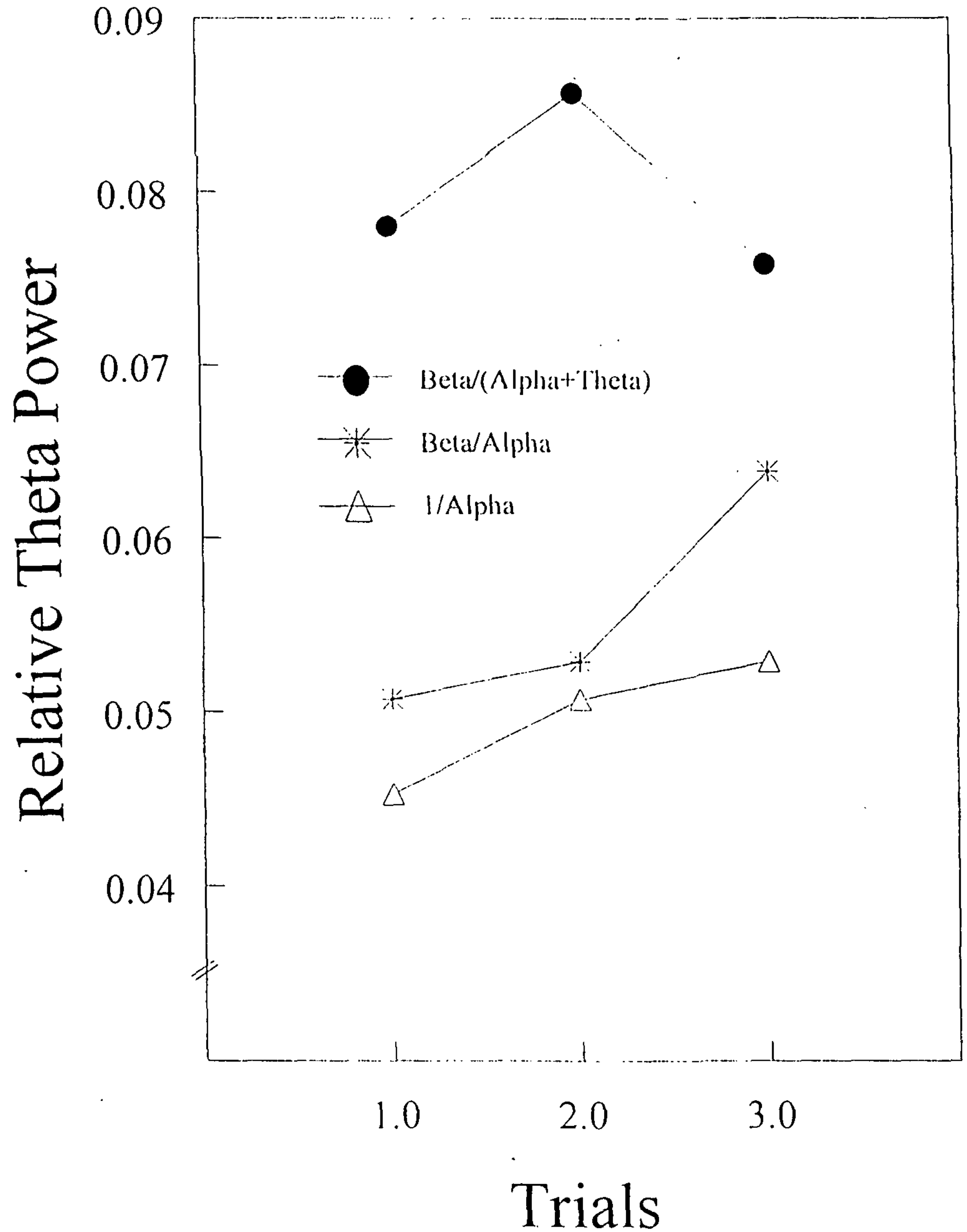
Figure 5: Relative beta power as a function of the three indices under positive and negative feedback.

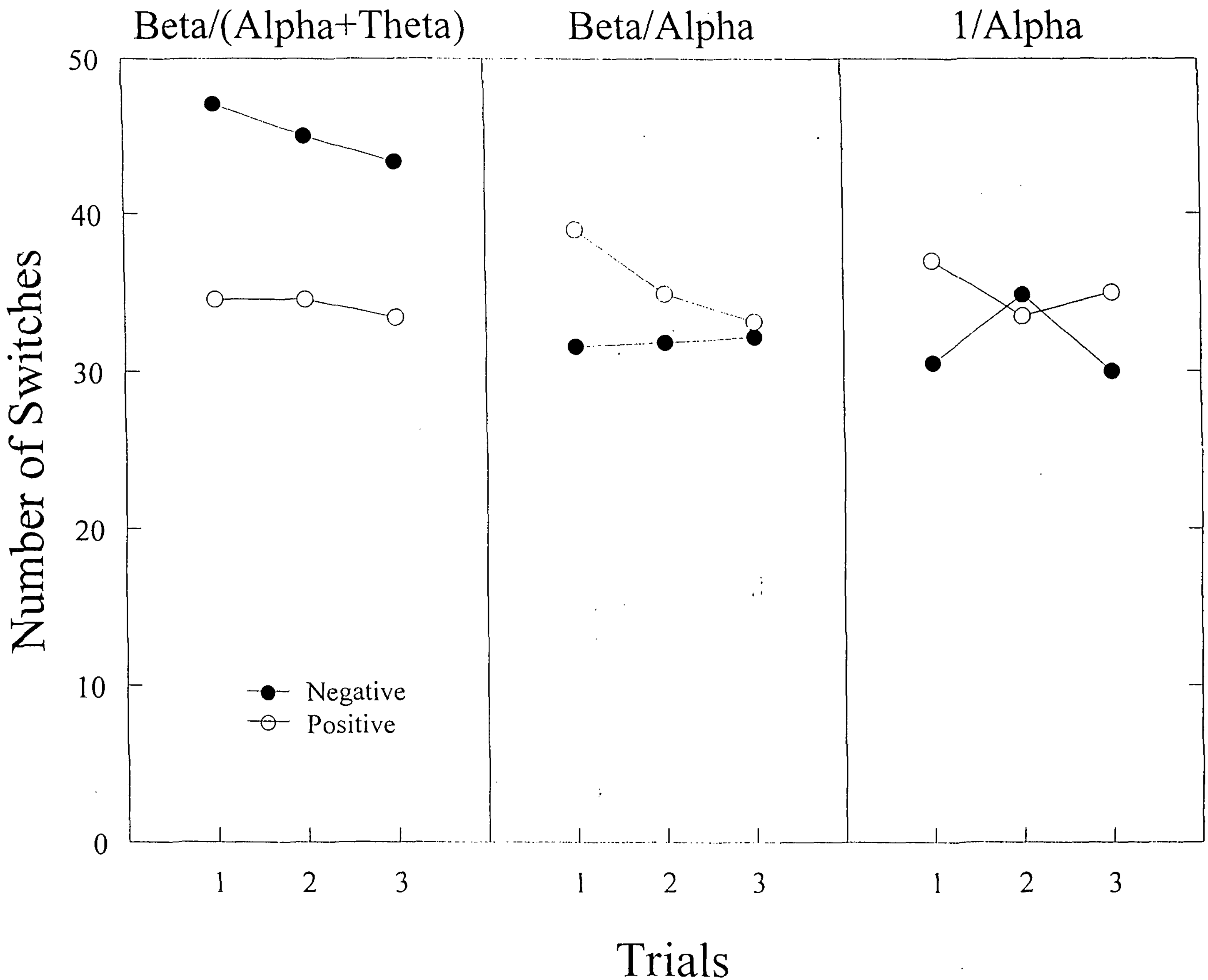

0.06
0.05
0.04
0.03
0.02
0.01
0
Relative Beta Power
B/A+T
B/A
1/A
Index
Neg-Auto
Neg-Man
Pos-Auto
Pos-Man


0.085
0.075
0.065
0.055
0.045
Relative Theta Power
B/A+T
B/A
1/A
Index
Neg-Auto
Neg-Man
Pos-Auto
Pos-Man



Relative Alpha Power
0.105
0.095
0.085
0.075
0.065
0.055
0.045
B/A+T
B/A
1/A
Index
Neg-Auto
Neg-Man
Pos-Auto
Pos-Man


0.09
0.08
0.07
0.06
0.05
0.04
Relative Theta Power
Beta/(Alpha+Theta)
Beta/Alpha
1/Alpha
1.0
2.0
3.0
Trials



Beta/(Alpha+Theta)
Beta/Alpha
1/Alpha
Number of Switches
50
40
30
20
10
0
Negative
Positive
1
2
3
Trials