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Operant Control of Occipital Theta Rhythm Affects Performance in a Radar Monitoring Task

Abstract. *Detection efficiency of human observers deteriorates rapidly in monotonous monitoring tasks; this effect (the vigilance decrement) has been associated with increased theta band activity in the electroencephalogram. Suppression of theta activity by operant methods enhances monitoring efficiency, whereas theta augmentation further degrades task performance. These results demonstrate a lawful relationship between operantly regulated cortical activity and behavior in man.*

The detection efficiency of human observers deteriorates rapidly in a variety of monotonous monitoring tasks (*1*). This vigilance decrement is usually attributed to a decline of the level of central nervous system arousal. Thus, physiological signs of arousal might be expected to covary with detection efficiency; but, among the electroencephalographic (EEG) indicators, only the abundance of occipital activity in the theta frequency band (3 to 7 hertz) appears to be a reliable correlate of vigilance behavior (*2*). Since the relative abundance of activity in the various frequency bands of the EEG may be modified by operant conditioning techniques (*3*), we hypothesized that learned regulation of theta band activity would affect detection behavior in a prolonged monitoring task. Specifically, regulated suppression of theta activity should maintain more efficient performance, whereas regulated theta augmentation should result in a greater than normal decrement in performance of a monitoring task.

Nineteen experimentally naive undergraduate students were recruited through an advertisement in a university newspaper to serve as paid subjects. They were told nothing of the nature of the EEG patterns to be reinforced; the effects of expectation on subsequent performance were thereby minimized (*4*).

Monitoring performance was assessed by using a complex and realistic radar simulator. The subject's display was a cathode-ray tube 23 cm in diameter presenting the image of a conventional radar plan position indicator. The sweep line rotated at 10 rev/min, painting continuous video noise and occasional single targets. Targets (3 mm by 2 deg at a signal-to-noise ratio of 4 db) were presented at preselected times at random combinations of range and azimuth. Targets were repainted on successive sweeps until detected by the subject. The subject was required to both depress a microswitch indicating that a target was detected and to verbally identify the range and azimuth of the signal. The numbers of sweeps before detection constituted the basic behavioral data.

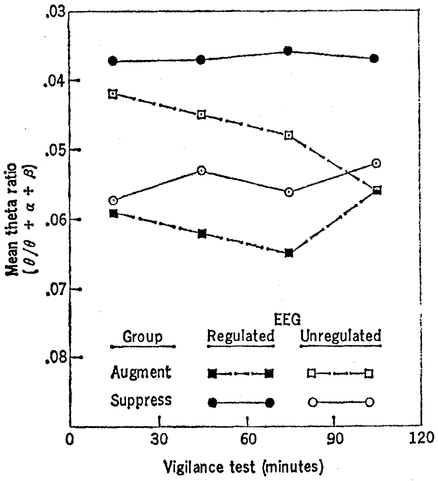

Fig. 1. Mean theta ratio as a function of time in the vigilance test for the theta augment group and the theta suppress group with regulated and unregulated EEG. The ordinate scale is inverted; θ, the number of waves in the theta frequency band (3 to 7 hertz); α, the number of waves in the alpha band (8 to 12 hertz); and β, the number of waves in the beta band (13 to 30 hertz).

In the initial session, each subject was trained to perform the monitoring task. After being shown sample targets, he performed a series of 5-minute training trials in which eight targets were presented at unpredictable intervals and locations on the display. In the first trial, knowledge of results was provided after every response of the subject. In subsequent trials this information was given only after the completion of the 5-minute period. Training continued until the subject performed in a stable and efficient manner for three consecutive trials. After a short rest period, the subject began his preliminary monitoring sequence: a 5-minute initial test with eight targets; a 120-minute vigilance test, with five targets in each successive 15-minute period; and a 5-minute final test of eight signals. The initial and final tests were employed to estimate detection efficiency under alerted conditions. The vigilance test constituted a continuous period of monitoring, in which the usual vigilance decrement was expected to occur. The preliminary sequence was included the first day to permit adaptation to any arousing aspects of the test environment and to familiarize the subject with the task he was later to perform under critical experimental conditions.

Subjects were assigned to one of two experimental groups. The theta suppress group was trained to reduce the probability of theta frequency activity in the EEG, while the theta augment group was trained under the opposite reinforcement contingency, which controlled for nonspecific effects of the training procedure. Since we were primarily interested in the predicted facilitatory effects of theta frequency suppression on performance, the theta suppress group was larger ($N = 12$) than the theta augment group ($N = 7$).

Each subject was trained in two separate 1-hour EEG conditioning sessions. The EEG was recorded from a bipolar configuration [O1 and P3 in the international ten-twenty system (*5*)] over the occipital and parietal cortex, referenced to the scalp over the ipsilateral mastoid bone. The response of the EEG system was essentially flat between 2 and 30 hertz (3 db lower at 0.6 and 40 hertz). The EEG was analyzed by digital computer (*6*) by the method of period analysis (*7*). For each second, the periods between positive-going zero crossings of the EEG were measured, and the theta ratio [ratio between the number of waves in the theta frequency band and the total number of waves (3 to 30 hertz)] was determined for that second.

The EEG conditioning sessions were composed of ten 210-second periods, of which periods 1, 4, 7, and 10 were baselines in which the subject received no reinforcement. In the remaining conditioning trials, the intensity of a quiet 400-hertz tone was augmented for 1 second if the value of the theta ratio in the preceding second had met or exceeded, in the appropriate direction, the criterion value (greater than criterion for the theta augment group, and less than criterion for the theta suppress group). The measurement and decision process was repeated in each second of the 210-second trial. The initial training criterion was based on the subject's baseline theta activity. During the trial, the criterion was reevaluated at the end of each 30-second period; the mean theta ratio for that period replaced the criterion if the new value differed from criterion in the desired direction. Thus, the program produced a shaping function, forcing the EEG to more extreme values if a constant level of reinforcement was to be maintained. In these conditioning sessions, subjects were asked to sit quietly with their eyes open and refrain from moving.

After EEG training, radar monitoring performance of subjects was tested on separate days in two critical sessions: EEG-regulated monitoring and EEG-unregulated monitoring. Half the subjects in each group were tested first for regulated, then for unregulated monitoring; the remainder were tested in the reverse order. The structure of the EEG-unregulated monitoring session was identical with that of the preliminary monitoring session, except that EEG was concurrently recorded and analyzed. In the EEG-regulated monitoring session, a 5-minute period of practice at concurrently performing the monitoring and EEG regulation tasks was provided. Group-appropriate EEG-contingent reinforcement was available throughout the vigilance test. The theta ratio criterion could be reset every 300 seconds to become more stringent if warranted. Subjects were instructed to perform as effectively as possible in both the EEG and the monitoring tasks.

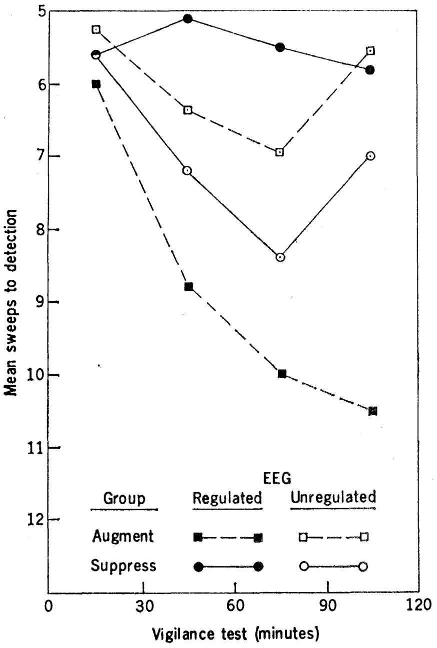

Fig. 2. Mean number of sweeps to detect targets as a function of time in the vigilance test for the theta augment group and the theta suppress group with regulated and unregulated EEG (ordinate scale inverted).

The EEG reinforcement procedures led to a selective alteration of the theta ratio (Fig. 1). As predicted, the theta suppress group showed significantly less occipital theta activity while simultaneously performing the monitoring task and regulating EEG than while performing the monitoring task alone ($t = 1.97$; d.f. = 11; $P < .05$). The theta augment group produced more theta activity in the monitoring task while regulating ($t = 1.81$; d.f. = 6; $P < .10$). Thus, EEG-contingent reinforcement appears effective in inducing discriminate control of theta frequency activity in the occipital EEG of subjects simultaneously performing a prolonged radar monitoring task.

Striking changes in monitoring performance accompanied regulation of theta activity (Fig. 2). The incidence of theta frequency activity in the occipital EEG is inversely related to monitoring efficiency. The poorest performance in any condition was exhibited by the theta augment group while regulating EEG. Conversely, the best monitoring performance was shown by the theta suppress group while regulating. These groups performed at intermediate levels in the absence of EEG-contingent reinforcement (unregulated conditions). Statistical analyses confirmed these observations. The mean vigilance test performance of the theta augment group was significantly worse while regulating EEG ($t = 2.84$; d.f. = 6; $P < .025$). The opposite was true of the theta suppress group ($t = 2.50$; d.f. = 11; $P < .025$). During the EEG-unregulated monitoring session, the mean vigilance test performances of these two groups were not significantly different ($t = 1.31$; d.f. = 17; $P > .20$).

Several points deserve emphasis. First, the experimental design provides assurance that the performance-enhancing effects of EEG regulation in the theta suppress group are attributable to the contingency of the EEG reinforcement. All other factors were shared by the theta augment group, for which EEG regulation produced a marked deterioration in monitoring performance. Thus, the possible role of nonspecific factors (for instance, the presence of the feedback tone or a secondary task) in accounting for these results is precluded.

Second, the performance-enhancement effects of theta suppression regulation appeared robust and consistent. In the third half-hour of the watch, before the often observed (*1*) end spurt appeared in the unregulated conditions, theta suppression shortened time to detection by 18 seconds (3 sweeps) on the average, and by 90 seconds (15 sweeps) for the subject who performed most poorly in the unregulated condition. The consistency of this effect is demonstrated by the fact that nine of twelve subjects detected targets more rapidly while concurrently suppressing theta activity. The three subjects who showed no improvement during EEG regulation were the first, third, and fourth most efficient performers in the unregulated condition. Theta suppression appears to benefit those subjects who are otherwise most likely to show degraded performance in the absence of such regulation.

Finally, the degraded monitoring performance of the theta augment group during EEG regulation extends the relationship between theta activity and monitoring efficiency under monotonous conditions. Regulated theta augmentation apparently causes a substantial deterioration of monitoring efficiency. Bidirectional experimental manipulation of theta activity in the occipital-parietal EEG seems to affect monitoring performance in a profound and systematic manner. The theta rhythm may be associated with presumed arousal processes that determine monitoring efficiency under monotonous conditions. This is the first demonstration, to our knowledge, of a lawful relationship between operantly regulated cortical phenomena and performance in man.

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Coupling between Cortical Potentials from Different Areas

Abstract. *At any instant, the electroencephalogram can be classified as to (i) polarity and (ii) direction of change in polarity. This classification provides a way to measure coupling between cortical areas. The technique is simple, yet of wide potential utility for studying functional relationships between cortical areas. The results of applying this technique suggest how the potentials giving rise to the electroencephalogram may play a role in information processing in the central nervous system.*

Suppose that the electroencephalogram (EEG) does reflect signals that are used by the brain, and is not just a sign of metabolic activity. The wavelike qualities of the EEG are not likely to be effective carriers of information. A 10-hertz wave needs at least 100 msec to be established, and that is too slow a rate to account for complex information processing in the brain. Indeed, wavelike EEG activity generally indicates information processing more by its absence than by its presence (for instance, alpha blocking).

Sensitivity of neural activity to intrinsic fields such as those generated by the EEG is suggested by Kaczmarek and Adey (*1*). We were thus led to examine the more or less instantaneous aspects of the EEG for evidence of relationships between EEG and information processing. When two areas of the brain are in active functional communication, then some sensible relationship should exist between the EEG's from these two areas. The two EEG's can, at any instant, be classified on the basis of polarity and direction of change of potential (that is, slope), and the results of such a classification can be used to measure coupling. By experimentally changing functional communication between the two areas, we can determine whether our measure of coupling changes as functional coupling changes. This last procedure serves to test the hypothesis about the relationship of the EEG to information processing in the brain.

To measure coupling between two EEG channels, the two channels were sampled every 4 msec. Each of the two samples was classified as to whether its polarity was positive (+) or negative (−), and as to whether its voltage was greater (↑) or smaller (↓) than the preceding sample from the same channel. Each sample could thus be classified in one of four categories (+↑, +↓, −↑, and −↓), and the contingencies (between the two channels) were tallied into a 4 by 4 table for a fixed number of samples. The degree of coupling between the two channels could be computed from the contingency table in a variety of ways (chi square, correlations, and so forth). We measured coupling by using the coefficient of information transmission or uncertainty reduction (*2*) because of its computational simplicity.

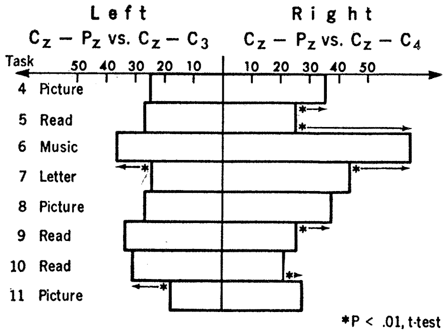

Fig. 1. Coefficients of information transmission for subject R.P.

Functional communications between visual area and each of the left and right hemispheres were manipulated by assigning verbal (left hemisphere) and spatial (right hemisphere) tasks to the subjects (*3*). We recorded EEG's from three derivations, one at the posterior midline near the visual cortex (P_z) and one each at the middle of the right (C_4) and left (C_3) hemispheres, all with the vertex (C_z) as reference. The choices of C_z as reference and of P_z as near visual cortex were made to avoid contamination from muscle artifact as much as possible. The nine subjects were right-handed and familiar with current concepts of the differentiation of hemispheric function. During the early part of each sitting, we tried pilot procedures (such as reversing Necker cubes and sorting photographs), but during the latter part of the sitting, all subjects were given four standard tasks to perform on command. These tasks were (i) read—silently reading interesting text as rapidly as possible; (ii) picture—examining interesting details of a picture; (iii) music—listening to Mozart with eyes closed; and (iv) letter—composing a letter mentally with eyes closed. Read and picture were each done twice; letter and music, only once.

The read task was designed to call for verbal propositional processing of visual data and hence to enhance occipital-left hemisphere coupling, whereas the picture task was intended to be "visual-appositional" (*3*) so as to enhance occipital-right hemisphere coupling. Little instruction was required for read, but for picture the subject was urged to notice details and to relate them to himself in an appositional way. After the first picture trial, the subject was interrogated as to how well he avoided verbal associations. He