An EEG-based method for graded cursor control

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Individuals were trained to modulate their EEGs in order to move a cursor on a video screen to intercept a moving target. EEG activity was recorded from the scalp over the central sulcus of the left hemisphere, and mu-rhythm amplitude was assessed three times per second by a fast Fourier transform. The cursor began at the midpoint of the right edge of the screen and moved up or down depending on mu-rhythm amplitude. A target of selected vertical length began at a random height on the left edge of the screen and moved horizontally across the screen in 8 sec. The subjects' task was to move the cursor along the right edge of the screen so as to intercept the moving target. After several weeks of training, 3 of the 4 subjects were able to perform this task with significant success. On average, these 3 subjects reduced the vertical target-cursor distance to 54% of its initial value. These results indicate that the mu rhythm can be used to control graded cursor movement and are additional evidence that with further development it might provide a new means of communication and control for individuals with severe motor disabilities.

Studies in both animals and humans have shown that brain electrical activity can be operantly conditioned. Single unit activity (Fetz, 1969), evoked potentials (Fox & Rudell, 1968), slow potentials (Roberts, Birbaumer, Rockstroh, Lutzenberger, & Elbert, 1989), and various EEG rhythms (Elbert & Rockstroh, 1984; Wyrwicka & Sterman, 1968) have all been conditioned. Black, Young, and Batenchuk (1970) and Dalton (1969) showed that EEG conditioning did not require mediation by conditioned motor responses by demonstrating that the hippocampal theta rhythm could be trained in animals given drugs that blocked movement.

A variety of uses for EEG conditioning have been proposed (Nowles & Kamiya, 1970; Sterman, MacDonald, & Stone, 1974). For example, Black (1971) suggested that such studies could help reveal the functional significance of certain EEG rhythms. No established practical application exists at present.

A number of studies have investigated the possibility of using EEG as a means of communication for individu-

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als with disabilities. Farwell and Donchin (1988) described a technique based on the visual evoked potential. Keirn and Aunon (1990) studied a method using the spontaneous EEG. Neither study explicitly involved conditioning. Dewan (1967) used feedback to train subjects to modulate the occipital alpha rhythm in order to transmit Morse code messages. Subjects were initially instructed to turn their eyes up without fixating in order to enhance the alpha rhythm. EEG modulation in this study was probably mediated by control of eye movements. Elder et al. (1986) trained subjects to modify EEG activity recorded between temporal and occipital regions of the head. Subjects increased or decreased EEG frequency for periods of 5 min at a time.

We are investigating the possibility that the mu rhythm of the EEG can provide the basis for a new communication method for individuals with little or no voluntary movement. The mu rhythm is an 8-12-Hz rhythm focused over sensorimotor cortex and detectable in a large majority of individuals (Pfurtscheller, 1989). It can be attenuated by movement and tactile stimulation (Jasper & Andrews, 1938; Pfurtscheller & Berghold, 1989) as well as by imagined movement (H. Gastaut, Naquet, & Y. Gastaut, 1965; Klass & Bickford, 1957). In an earlier study, we trained individuals to control vertical movement of a cursor on a video screen by changing mu-rhythm amplitude rapidly and accurately (Wolpaw, McFarland, Neat, & Forneris, 1991). The subject's task was to move the cursor up or

down in order to hit a target located at the top or bottom of the screen. Upward movement required large murhythm amplitudes, while downward movement required small murhythm amplitudes. In contrast to previous studies of human EEG conditioning, which sought to produce long-term increases or decreases in a specific EEG rhythm, this study trained subjects to produce both increases and decreases in murhythm amplitude within a period of a few seconds.

The present study concerns a more advanced form of mu-rhythm control. Subjects learned to use the mu rhythm to move a cursor up or down in order to intercept a target moving horizontally across the screen at a randomly determined height. Mu-rhythm amplitude was translated into cursor movement as in the previous experiment, but the nature of the target was different. Instead of being asked simply to move the cursor up or down until it reached the target at the top or bottom edge, subjects were asked to move the cursor up or down to a specific location and hold it there until the target arrived. Thus, while the previous study required only ballistic cursor movement, this study required graded movement.

METHOD

Subjects

Four normal adults between 25 and 38 years of age participated. Each had a prominent mu rhythm, a distinct 8-12-Hz peak over C3 and C4 (Jasper, 1958) that was attenuated by contralateral hand movements and was minimally affected by opening and closing the eyes (Jasper & Andrews, 1938; Pfurtscheller & Berghold, 1989). Each had achieved significant and reliable performance on the earlier ballistic cursor-movement task (Wolpaw et al., 1991). The study was approved by the Institutional Review Board of the New York State Department of Health. All subjects gave informed consent and were reimbursed for participation.

Apparatus

Bipolar EEG was recorded with 1-cm gold-plated Grass electrodes located 3 cm anterior and posterior to C3 of the International 10-20 system (i.e., spanning the central sulcus; Jasper, 1958). The signal was amplified by a Grass Model 8-24D polygraph with the analog filters set to 1 and 70 Hz and digitized by a 32-channel analog input board that communicated with a TMS320C25 digital signal processing (DSP) board (both from Spectrum Inc.). The DSP board sampled the EEG at 384 Hz. Three times per second, a 128-point fast Fourier transform was performed in real time and passed to an IBM PC/AT. The PC/AT system had a monochrome screen that the subject watched and a color screen that the operator used to monitor the subject's performance. The DSP board was programmed with an assembler, and the PC/AT system was programmed in Turbo C. This system is described in greater detail elsewhere (Neat, McFarland, Forneris, & Wolpaw, 1990).

Procedure

The subject sat in a reclining chair in front of the monochrome screen. The monochrome screen was turned sideways to give 80 vertical steps and 24 horizontal steps for cursor movement. At the start of each trial, a target consisting of a vertical bar appeared at a random height on the left edge of the screen and a cursor appeared at the midpoint of the right edge (see Figure 1). Over the next 8 sec, the target moved horizontally across the screen to the right edge and the cursor moved vertically depending on the subject's murhythm amplitude. The subject was instructed to move the cursor so that it intercepted the target when the target reached the right edge. If the cursor did intercept the target, the screen flashed for 1 sec. If it missed, the screen went blank for 1 sec.

The DSP board provided the voltage (square root of the power) from the bin centered at 9 Hz (resolution 3 Hz) to the PC/AT three times per second. This 3-Hz resolution is a consequence of the duration of the data record (Walter, 1987), and the FFT bin can be viewed as a bandpass filter centered at 9 Hz and gradually tapering to 6 and 12 Hz. The PC/AT translated this value into cursor movement by determining which of five operator-defined voltage ranges it fit into and then producing the cursor movement assigned to that voltage range. For example, a voltage less than 1.5 μ V might move the cursor three steps down, a voltage between 1.5 and 3 μ V

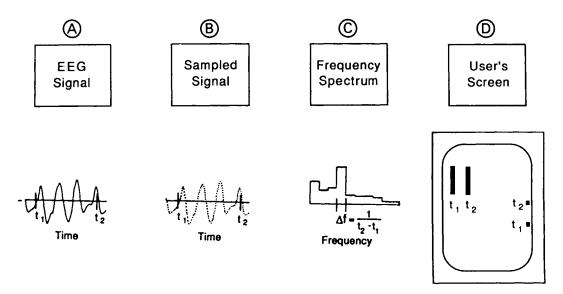


Figure 1. Basic components of the system. The signal is sampled, frequency analysis is performed by fast Fourier transform, and the voltage at a specific frequency (e.g., 9 Hz) is converted to cursor movement. These operations are performed by separate parallel processes run on a DSP board and a PC/AT.

might cause no movement, a voltage between 3 and 4 μ V might move it three steps up, a voltage between 4 and 5 μ V might move it six steps up, and a voltage above 5 μ V might move it nine steps up. These voltage ranges and corresponding cursor movements were chosen by the operator on the basis of the subject's previous performance. They were entered during the rest periods between 2-min runs.

Figure 1 summarizes the process. It shows the continuous EEG waveform recorded from the scalp (A), sampling of the waveform (B), conversion from the time domain to the frequency domain (C), and conversion from voltage at a specific frequency to cursor movement (D).

A standard session consisted of eight 2-min performance periods separated by 1-min rest periods. At the start of training, the target was relatively large (e.g., 24 vertical steps or 30% of the vertical range) so that the subject had modest initial success despite poor initial performance. As training progressed, target size was gradually decreased between sessions (e.g., down to 13 characters). Target location, cursor location, and EEG voltage at 9 Hz were stored on disk three times per second.

RESULTS

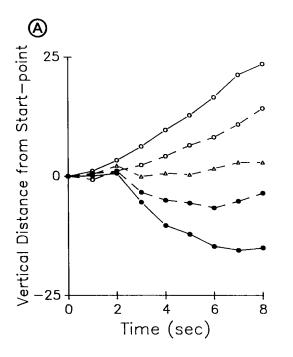
Each subject participated in eight sessions over a period of several weeks. As noted above, all 4 subjects had already mastered the stationary-target task (Wolpaw et al., 1991). The data presented here are for each subject's eighth and final session and thus reflect the level of performance attained.

Figure 2A shows the average position of the cursor in vertical steps as a function of time since trial initiation. Data are presented separately for trials in which the center of the target was in the top fifth, upper middle, middle,

lower middle, and lower fifth of the screen. The data were partitioned in this way in order to determine if the subjects had achieved graded cursor control. Figure 2B shows the average absolute distance of the cursor from the center of the target as a function of time since trial initiation, again presented separately for targets in each fifth of the screen. Since this measure is computed from the center of the target, it is independent of target size.

An analysis of variance (ANOVA) on the cursor-position data with time and target height as within-subject effects indicated that both the effects of target height (p < .001) and the interaction between target height and time (p < .001) were significant. The interaction was evaluated in terms of the linear trend with respect to time. The linear component of the slope of cursor position over time for each fifth of the screen was found to be significantly different from that associated with each adjacent fifth of the screen (p < .01). These results indicate that the subjects produced five distinct average paths in response to the five target zones. It should be noted that division of the target location into five zones is arbitrary, and four or six zones would illustrate as well the graded nature of the subjects' cursor control.

The cursor-target-distance data were evaluated with an ANOVA with time and target height as within-subject effects. Both the effects of time (p < .01) and the interaction between target height and time (p < .001) were significant. The interaction was evaluated in terms of linear trends with respect to time, but in this case we tested the hypothesis that the slopes were zero. The upper fifth, upper middle, and lower fifth functions all had signifi-



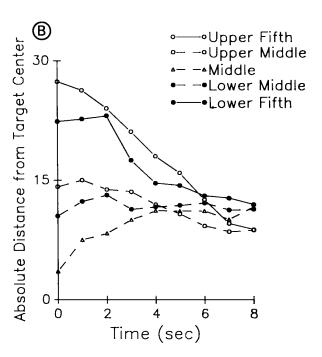


Figure 2. (A) Average cursor vertical distance from the start point in steps for all subjects as a function of time since the beginning of the trial. The average cursor position is shown separately for targets in each fifth of the vertical dimension of the screen. (B) Absolute distance from the center of the target as a function of time from the beginning of the trial. Data are from the final session. The absolute distance is shown separately for targets in each fifth of the screen.

Table 1
Performance of Individual Subjects in Final Session

Subject	Target Size	Targets Hit (%)	Distance in Cursor Steps	
			Start	Finish
Α	13	75.0	15.9	6.1*
В	15	56.3	15.5	8.8*
С	13	49.0	14.2	9.6*
D	17	39.1	18.3	17.8

*p < .001 from start by F test.

cant negative slopes (p < .01), indicating convergence on the targets. The lower middle function was not significantly different from zero, and the slope of the middle segment had a significant positive slope (p < .01). These results are consistent with Figure 2A, which suggests that overall the subjects were able to move the cursor so as converge on the target.

Table 1 shows individual performance measures for each subject, including final target size, percentage of targets hit, and average absolute distance (in cursor steps) between the center of the target and the cursor at the beginning and at the end of a trial. The data show that all subjects reduced the cursor to target distance, with 3 of the 4 subjects showing substantial and significant reductions.

Figure 3 shows the cross-correlation of mu-rhythm amplitude with signed vertical distance between cursor and target. Values were computed as r^2 (Winer, 1962) as a function of 0.33-sec time lags. Large positive distances between target and cursor (i.e., target far above cursor) required the subject to produce large mu-rhythm amplitudes in order to move the cursor up to the target. Conversely, large negative distances between the target and the cursor (i.e., target far below the cursor) required small mu-rhythm amplitudes to move the cursor down to the target. In terms of systems analysis, the cross-correlation function represents the transfer function of our human subjects. The observed positive correlations between target-cursor distance and subsequent mu-rhythm amplitude pro-

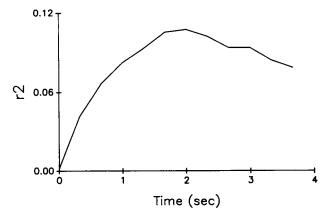


Figure 3. Cross-correlation of mu-rhythm amplitude with signed distance between the cursor and the target (target-cursor position). Data are from the final session for all subjects. The positive correlation indicates that when the target is above the cursor, large murhythm amplitudes occur, and when the target is below the cursor, small mu-rhythm amplitudes occur.

vides a further indication that the subjects modulated their EEG in a manner appropriate to the task. It is important to note that this analysis is with respect to each $\frac{1}{3}$ -sec increment. These small changes over the 24 intervals that make up the 8-sec trial resulted in a final $r^2 = .59$ for the covariation between cursor position and target location (p < .001).

DISCUSSION

The present study shows that individuals can learn to modulate EEG rapidly and in a graded fashion in order to intercept a target moving horizontally across a video screen at a randomly selected height. This finding suggests that a more precise form of control is possible than that shown in earlier studies of EEG operant conditioning (e.g., Elbert & Rockstroh, 1984; Wyrwicka & Sterman, 1968). While the present results were obtained in individuals with pronounced mu rhythms, available evidence (Pfurtscheller, 1989; Wolpaw et al., 1991) suggests that most individuals may be able to achieve such rapid and precise control.

One of the principal issues in the human EEG conditioning literature is the nature of what the subject actually learns to do in order to modulate the EEG. Lynch and Paskewitz (1971) suggested that the observed EEG effects are secondary to other behaviors that are directly conditioned. Indeed, the study by Dewan (1967) indicates that this is a very effective way to modulate the EEG. However, as noted earlier, several animal studies have demonstrated EEG conditioning in the presence of complete paralysis (Black et al., 1970; Dalton, 1969). Such a definitive test was clearly not possible with our human subjects. In the present study, the absence of visual reactivity in the EEG channel used makes mediation by eye movements unlikely, but subtle movements of other muscles could conceivably have played a role. However, the subjects' statements and our own observations suggested that such movements did not occur. In the early stages of training, the subjects reported using motor imagery to control cursor movement, as we had suggested to them. Later, such imagery was often no longer needed. The issue of mediation by movement is important for the possible prosthetic use of EEG conditioning by disabled individuals. Final resolution may well come with attempts to apply this technology to assist individuals with severe motor impairments (e.g., total paralysis).

In contrast to previous studies of EEG conditioning, our studies require rapid phasic control. Earlier studies have required either increased or decreased activity for periods lasting at least several minutes (Elder et al., 1986; Kuhlman, 1978; Nowles & Kamiya, 1970; Plotkin & Rice, 1981). Our experience suggests that rapid phasic control of mu-rhythm amplitude is easier to achieve than long-term increases or decreases. Such phasic control is particularly suited for communication. The ultimate value of EEG-based communication depends on how rapidly and accurately subjects can control their EEG, as well as on whether subjects can learn to control more than one channel at a time.

In this study and in previous work (Wolpaw et al., 1991), a human operator defined the parameters the system used to translate mu-rhythm amplitude into cursor movement. Parameter selection was based upon a subject's previous performance and was updated during the pauses between runs. Currently we are testing an algorithm that performs this evaluation without the intervention of the operator. Replacement of the human operator is highly desirable for two reasons. First, with a human operator, the process used to arrive at the parameters is not well defined, and success depends on the operator's experience and skill. In contrast, the operation of an explicit algorithm is precisely specified and can be evaluated. Second, the need for a human operator would severely limit the utility of this system for assisting disabled individuals. Thus, replacement of the operator with an explicit algorithm is an important step in the development of this technology. It should be noted that in either case, the process we are describing here can be regarded as the interaction between two adaptive controllers (Neat et al., 1990), the subject and the system. This interaction is a distinctive feature of the system and a key feature to its success.

These results demonstrate that individuals are able to control mu-rhythm amplitude in a single channel in a graded fashion with an impressive degree of precision. At present, we are exploring multichannel EEG control of two-dimensional cursor movement (McFarland, Neat, & Wolpaw, 1991). This work may eventually lead to a new means of communication and control for individuals with severe motor impairments.

REFERENCES

- BLACK, A. H. (1971). The direct control of neural processes by reward and punishment. *American Scientist*, 59, 236-245.
- BLACK, A. H., YOUNG, G. A., & BATENCHUK, C. (1970). Avoidance training of hippocampal theta waves in flaxedilized dogs and its relation to skeletal movement. *Journal of Comparative & Physiological Psychology*, 70, 15-24.
- DALTON, A. J. (1969). Discriminative conditioning of hippocampal electrical activity in curarized dogs. Communications in Behavioral Biology, 3, 283-287.
- DEWAN, A. J. (1967). Occipital alpha rhythm, eye position and lens accommodation. *Nature*, 214, 975-977.
- ELBERT, T., & ROCKSTROH, B. (1984). Classification and overview of CNS electrical activity tested on operant conditioning. In T. Elbert, B. Rockstroh, W. Lutzenberger, & N. Birbaumer (Eds.), Self-regulation of the brain and behavior (pp. 59-63). New York:Springer-Verlag.
- ELDER, S. T., LASHLEY, J. K., KEDOURI, N., REGENBOGEN, D., MARTYN, S., ROUNDTREE, G., & GRENIER, C. (1986). Can subjects be trained to communicate through the use of EEG biofeedback? Clinical Biofeedback & Health, 9, 42-47.
- FARWELL, L. A., & DONCHIN, E. (1988). Talking off the top of your head: Toward a mental prosthesis utilizing event-related brain potentials. *Electroencephalography & Clinical Neurophysiology*, 70, 510-523.
- FETZ, E. E. (1969). Operant conditioning of cortical unit activity. Science, 9, 55-57.

- Fox, S. S., & RUDELL, A. P. (1968). Operant controlled neural event: Formal and systematic approach to electrical coding of behavior in brain. *Science*, 162, 1299-1302.
- GASTAUT, H., NAQUET, R., & GASTAUT, Y. (1965). A study of the murhythm in subjects lacking one or more limbs. *Electroencephalography & Clinical Neurophysiology*, 18, 720-721.
- JASPER, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography & Clinical Neurophysiology*, 10, 371-375.
- JASPER, H., & ANDREWS, H. (1938). Electroencephalography: III. Normal differentiation of occipital and precentral regions in man. Archives of Neurology & Psychiatry, 39, 96-115.
- KEIRN, Z. A., & AUNON, J. I. (1990). Man-machine communication through brain-wave processing. *IEEE Engineering in Medicine & Biology Magazine*, 9, 55-57.
- KLASS, D., & BICKFORD, R. (1957). Observations on the rolandic arceau rhythm. *Electroencephalography & Clinical Neurophysiology*, 9, 570.
- KUHLMAN, W. N. (1978). EEG feedback training: Enhancement of somato-sensory cortical activity. Electroencephalography & Clinical Neurophysiology, 45, 290-294.
- LYNCH, J. L., & PASKEWITZ, D. A. (1971). On the mechanisms of the feedback control of human brain wave activity. *Journal of Nervous & Mental Disease*, **153**, 205-217.
- McFarland, D. J., Neat, G. W., & Wolpaw, J. R. (1991). A braincomputer interface for cursor control. Society for Neuroscience Abstracts, 21, 1047.
- NEAT, G. W., McFARLAND, D. J., FORNERIS, C. A., & WOLPAW, J. R. (1990). EEG-based brain-to-computer communication: System description. Proceedings of the IEEE Engineering in Medicine & Biology Society, 5, 2298-2300.
- Nowles, D. P., & Kamiya, J. (1970). The control of electroencephalographic alpha rhythms through auditory feedback and the associated mental activity. *Psychophysiology*, **6**, 476-483.
- PFURTSCHELLER, G. (1989). Functional topography during sensorimotor activation studied with event-related desynchronization mapping. Journal of Clinical Neurophysiology, 6, 75-84.
- PFURTSCHELLER, G., & BERGHOLD, A. (1989). Patterns of cortical activation during planning of voluntary movement. *Electroencephalog-raphy & Clinical Neurophysiology*, 72, 250-258.
- PLOTKIN, W. B., & RICE, K. M. (1981). Biofeedback as a placebo: Anxiety reduction facilitated by training in either suppression or enhancement of alpha brainwaves. *Journal of Consulting & Clinical Psychology*, 49, 590-596.
- ROBERTS, L. E., BIRBAUMER, N., ROCKSTROH, B., LUTZEN-BERGER, W., & ELBERT, T. (1989). Self-report during feedback regulation of slow cortical potentials. *Psychophysiology*, **26**, 392-403.
- STERMAN, M. B., MACDONALD, L. R., & STONE, R. K. (1974). Bio-feedback training of sensorimotor EEG in man and its effect on epilepsy. *Epilepsia*, 15, 395-416.
- WALTER, D. O. (1987). Introduction to computer analysis in electroencephalography. In E. Niedermeyer & F. Lopes da Silva (Eds.), Electroencephalography: Basic principles, clinical applications and related fields (2nd ed., pp. 251-293). Baltimore: Urban & Schwarzenberg.
- Winer, B. J. (1962). Statistical principles in experimental design (2nd ed.). New York: McGraw-Hill.
- WOLPAW, J. R., McFarland, D. J., Neat, G. W., & Forneris, C. A. (1991). An EEG-based brain-computer interface for cursor control. Electroencephalography & Clinical Neurophysiology, 78, 252-259.
- WYRWICKA, W., & STERMAN, M. B. (1968). Instrumental conditioning of sensorimotor cortex EEG spindles in the waking cat. *Physiology & Behavior*, 3, 703-707.

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