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An EEG-based brain-computer interface for cursor control [1]

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Summary This study began development of a new communication and control modality for individuals with severe motor deficits. We trained normal subjects to use the 8–12 Hz mu rhythm recorded from the scalp over the central sulcus of one hemisphere to move a cursor from the center of a video screen to a target located at the top or bottom edge.

Mu rhythm amplitude was assessed by on-line frequency analysis and translated into cursor movement: larger amplitudes moved the cursor up and smaller amplitudes moved it down. Over several weeks, subjects learned to change mu rhythm amplitude quickly and accurately, so that the cursor typically reached the target in 3 sec.

The parameters that translated mu rhythm amplitudes into cursor movements were derived from evaluation of the distributions of amplitudes in response to top and bottom targets. The use of these distributions was a distinctive feature of this study and the key factor in its success.

Refinements in training procedures and in the distribution-based method used to translate mu rhythm amplitudes into cursor movements should further improve this 1-dimensional control. Achievement of 2-dimensional control is under study. The mu rhythm may provide a significant new communication and control option for disabled individuals.

Key words: EEG; Prosthesis; Operant conditioning; Mu rhythm; Sensorimotor rhythm; Computer control; Communication

A number of prosthetic techniques have been developed to assist individuals with severe motor disabilities or communication problems. These methods, such as those based on EMG recording, provide the brain with new channels for controlling the external environment (Loeb 1989). Their logical culmination is a technique that permits the brain to bypass entirely its normal output channels (Vidal 1973).

In theory, the brain's intentions should be discernible in the spontaneous EEG. In practice, however, the vast number of electrically active neuronal elements, the complex geometry of the brain and head, and the disconcerting trial-to-trial variability in brain operations severely limit the information discernible without averaging. This study explores another option. It does not attempt to interpret the spontaneous EEG; rather it attempts to teach individuals to produce EEG that can be easily interpreted.

Over the past 60 years, numerous studies have evaluated conditioning of a variety of EEG phenomena, including the visual alpha rhythm, slow potentials, and the mu rhythm (Durup and Fessard 1935; Travis et al. 1975; Kuhlman 1978a; Elbert et al. 1980; Niedermeyer and Lopes da Silva 1987). The 8–12 Hz mu rhythm, which is recorded over the central sulcus, appears to be the human analog of the 12–16 Hz sensorimotor rhythm described in cats (Gastaut 1952; Brazier 1963; Storm van Leeuwen et al. 1966; Kuhlman 1978b; Niedermeyer and Lopes da Silva 1987; Kozelka and Pedley 1990). Several factors suggest that the mu rhythm is particularly well suited to an effort to develop an EEG-based communication channel. First, it is recorded over those regions of cortex most directly related to motor function. Second, Kuhlman (1978a) found that humans can gradually increase mu rhythm amplitude over several months [2]. This control appeared to be separate from the rhythm's normal responsiveness to contralateral movement. Third, though earlier work concluded that the mu rhythm was present in only a minority of individuals (Chatrian 1976), more recent computer-based studies indicate its presense in nearly all adults (Pfurtscheller 1989).

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[2] A number of studies (Sterman et al. 1974; Finley et al. 1975; Lubar et al. 1981; Tansey 1984) have evaluated long-term conditioning of a 12–14 Hz 'sensorimotor rhythm,' primarily in regard to its possible therapeutic usefulness. The nature of this rhythm and its relevance to the present study are unclear.

We set out to determine whether people could develop the capacity to increase and decrease the mu rhythm reliably and rapidly. The hope was that, if such rapid bidirectional control could be developed, it would allow the mu rhythm to serve as a code for giving commands to a computer.

Encouraging preliminary efforts (Wolpaw et al. 1986) led to the present study. Its goal was to demonstrate that individuals can learn to use the mu rhythm to control movement of a cursor on a computer screen. We chose cursor movement because it is objective, easily implemented, and readily quantified, and can serve as a prototype for control of a wide variety of prosthetic devices. As will be seen, a distinguishing feature of this study, and the crucial element in its achievement of fast, accurate cursor control, was utilization of the distributions of mu rhythm amplitudes to define the parameters that translate the mu rhythm into cursor movement.

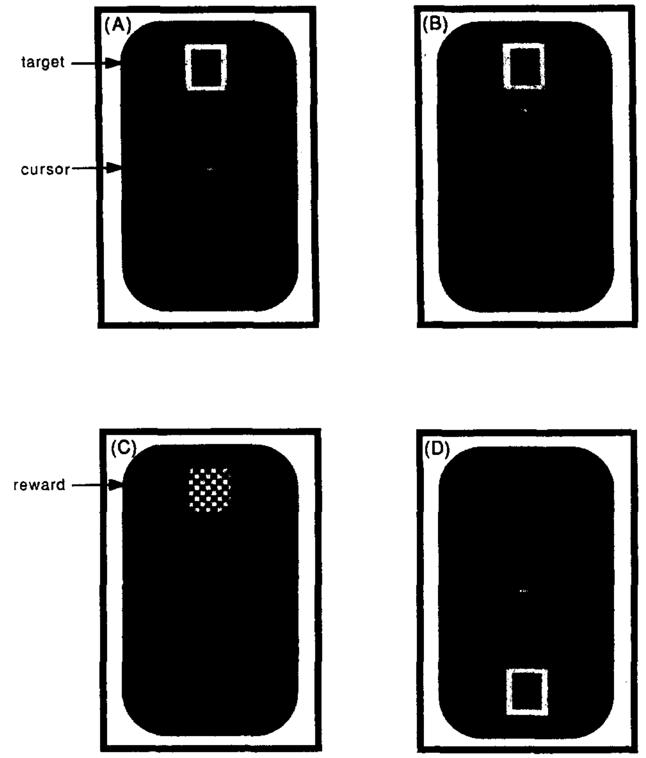

Fig. 1. Video screen seen by subject. A: run begins with cursor in center of screen and target at top (or bottom). B: cursor, controlled by subject's mu rhythm, moves toward target. C: when cursor hits target, target flashes in a checkerboard pattern. D: after a brief pause, cursor reappears in center of screen and new target appears. (If cursor reaches wrong edge of screen, an error is registered, cursor reappears in center, and target remains where it was.)

Methods

This section describes equipment and procedures with emphasis on physiological aspects. Description and discussion, from an engineering perspective, of the hardware and software system developed to translate the mu rhythm into cursor movement appears elsewhere (Neat et al. 1990).

Subjects

In preliminary investigations aimed at determining the best location and montage for recording the mu rhythm, we evaluated EEG over the scalp in 60 normal adult volunteers. In accord with standard descriptions (Storm van Leeuwen et al. 1966; Kuhlman 1978b; Niedermeyer and Lopes da Silva 1987; Kozelka and Pedley 1990), the mu rhythm, defined as 8–12 Hz activity over sensorimotor cortex that was not dependent on whether eyes were open or closed and could be blocked by movement of the contralateral hand, was best recorded across central sulcus near 10/20 location C3 or C4 (Jasper 1958).

Four men and one woman, ages 25–38, from the preliminary population comprised the study group. Each had stable, artifact-free EEG and a mu rhythm that was detectable by eye and was visible as a well-defined peak in the EEG frequency spectrum (e.g., Fig. 3).

The subject sat in a comfortable reclining chair that supported head, neck, and torso at an angle of about 60° from the horizontal, and watched a video screen (28.5 cm diagonal) 2 m away. Each participated for three 45 min sessions/week over a period of 2 months.

The study was approved by the Institutional Review Board of the New York State Department of Health, and subjects gave informed consent. They were paid for participation and also received modest bonuses for especially good performance.

Hardware and software and system operation

Bipolar EEG was recorded by 1 cm Grass gold disk electrodes placed 3 cm anterior and posterior to C3 (which was chosen in preference to C4 simply because subjects were right-handed). The signal was amplified by a Grass Model 8 electroencephalograph (bandpass 5–35 Hz for most runs, 1–300 Hz for those aimed at detecting EMG and other contamination), displayed on paper, and digitized (384 Hz) by a digital signal processing (DSP) board (Spectrum Signal Processing Inc. TMS320C25) that operated in parallel with an IBM PC/AT computer. The computer also controlled two video screens, one belonging to the subject and one to the system operator, and stored complete performance data on a hard disk.

As seen in Fig. 1, the subject's screen showed a cursor that normally began in the center of the screen and could move 38 steps up or 38 steps down, i.e., to the top or bottom of the screen. Thus, the full bottom-to-top distance was 76 cursor steps. A target, consisting of a small open square, was located at the top end or bottom end of the cursor's path. The operator's screen displayed the current parameters as described below and provided a continually updated summary of the subject's performance.

The system operated under the program Gabriel, which was written specifically for this application. In the standard operating mode, the DSP board digitized the EEG channel continuously, performed a nearly instantaneous frequency analysis on every 333 msec segment, and provided to the computer the segment's mu rhythm power, defined as the power at 9 Hz. (With 333 msec segments, frequency resolution was 3 Hz, so that the power at 9 Hz was nearly equal to mu rhythm power.)

The computer determined the segment's mu rhythm amplitude (i.e., square root of power and expressed in volts) and compared it with 5 voltage ranges preset by the operator (such as 0–1 μV, 1–2 μV, 2–3 μV, 3–4 μV, and > 4 μV). On the basis of this comparison, it translated the amplitude into one of 5 possible cursor movements (measured in steps). The voltage ranges and their corresponding cursor movements were preset by the operator so that high mu rhythm amplitudes moved the cursor up and low amplitudes moved it down (see below).

If the cursor reached the target, the target flashed in a checkerboard pattern to indicate a hit, and after a brief pause the cursor reappeared in the center of the screen and a new target appeared at the top or the bottom. If the cursor reached the bottom of the screen when the target was at the top, or vice versa, an error was registered, the cursor reappeared in the center of the screen, and the target remained where it was.

A standard run lasted 3 min, and a day's session consisted of a warm-up run followed by 6–7 data runs. Runs were separated by 1 min breaks. The target sequence during a run either followed a preset 8-bit pattern or was random. In each run, numbers of top and bottom targets were equal or nearly equal (not counting targets repeated due to errors). Complete data were stored on disk, including cursor movement parameters (voltage ranges and resulting movements), mu rhythm amplitude for each 333 msec time segment, target sequence, and target hit and error totals and rates. Performance summaries for single runs, single days, and groups of days were calculated and plotted off-line.

Training protocol

In order to help the subject acquire control over the mu rhythm, the protocol was simplified for the first 2–3 sessions. For these sessions, the cursor started at the bottom of the screen, the target was at the top, and the cursor could only move up. The voltage ranges were set so that, when the subject simply watched the screen, spontaneous mu rhythm amplitudes varied across the 5 ranges. The resulting movements were set so that higher mu rhythm amplitudes caused upward movement, and lower mu rhythm amplitudes caused no movement. For the first half of the first session, the subject simply watched the cursor progress fitfully upward and hit the target, and tried to discern relationships between his/her mental states and cursor movements. For the remainder of the first session, and for the next 1–2 sessions, the subject was asked to make the cursor move up the screen as fast as possible, so that it hit more targets in each 3 min run.

After these simplified introductory sessions, the cursor always began in the center of the screen, movement parameters were set so that the cursor could move down as well as up, and targets appeared at the top or at the bottom of the video screen. Initially, top and bottom targets alternated. Later in training they were interspersed randomly. The subject was asked to hit each target as quickly as possible. Over the course of the next 15–20 sessions, and as subject performance improved, the operator modified the voltage ranges and/or the resulting cursor movements to help the subject maximize the number of hits and minimize the number of errors.

Data analysis: subject performance and system performance

The results were used to assess both subject performance and system performance. Subject performance was measured by the difference between the distribution of mu rhythm amplitudes when the subject was trying to move the cursor to a target at the top of the screen (the 'up distribution') and the distribution of mu rhythm amplitudes when the subject was trying to move the cursor to a target at the bottom of the screen (the 'down distribution'). In the absence of mu rhythm control, these two distributions were the same. As the subject learned to control the mu rhythm, they diverged. The magnitude of divergence was indicated by the difference between the means of the two distributions and by the fraction of total variance due to this difference (r^2, i.e., the fraction of non-overlap; Winer 1962).

System performance was measured by how well the system (hardware, software, and operator) allowed the subject to communicate, i.e., how well the system made use of the difference between the up and down distributions. System performance was a combination of accuracy (hits/(hits + errors)) and rapidity (hits/min) of cursor movement. In the absence of any mu rhythm control, accuracy would have been 50% or less, since there were equal numbers of top and bottom targets (not counting errors), and after an error the target remained in the same position for the next trial.

The next section describes both subject performance and system performance, as defined above.

Results

Effects of training

Four of the 5 subjects gradually acquired impressive control over the mu rhythm. The remaining subject was not successful in acquiring control and discontinued the study after 3 weeks. The 4 successful subjects learned to alter mu rhythm amplitude quickly and appropriately in response to the top or bottom target. This ability was reflected in subject performance (difference between mu rhythm amplitude distributions for top and bottom targets) and in system performance (accuracy and rate).

Fig. 2 shows the final day's data for each of these 4 subjects (A–D). The two histograms indicate subject performance: the solid line is the mu rhythm amplitude distribution when the target was at the bottom, and the dashed line is the distribution when the target was at the top. System performance is indicated by the values for accuracy and rate. Shown for subject C are the operator-defined parameters that translated this subject's mu rhythm amplitude into cursor movement: the 5 voltage ranges and their resulting movements in cursor steps. The subjects are arranged in order of performance. While the results are best in A, B, and C, those in D are particularly striking, because modest subject performance (i.e., a small distribution difference) still supports substantial system performance (i.e., rate and accuracy).

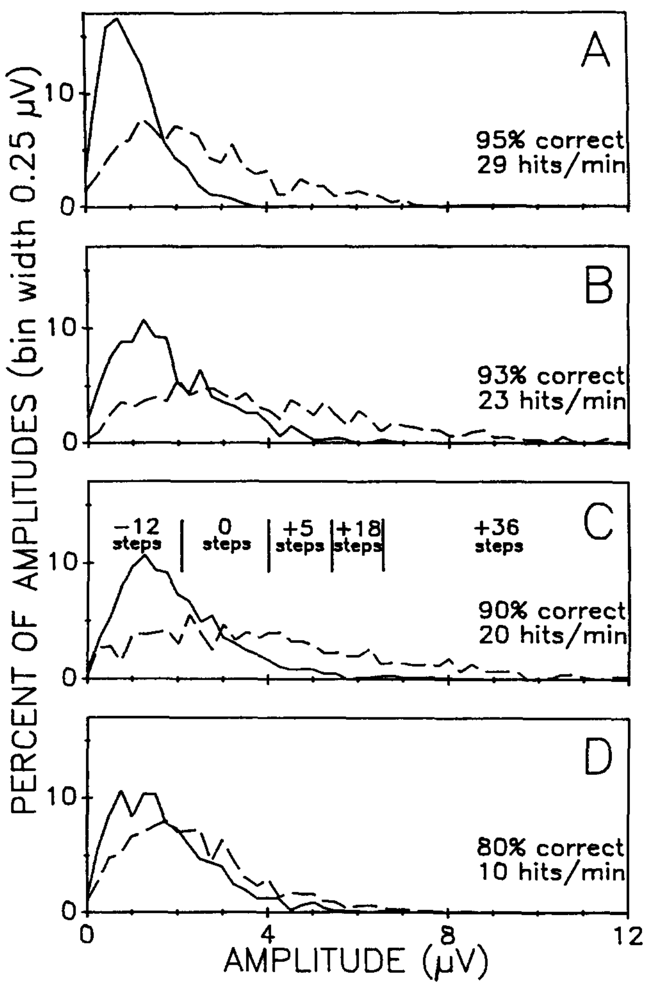

Fig. 2. Final training day (i.e., 6 or 7 runs of 3 min) for each subject (A–D). Subject performance is indicated by the difference between the two histograms, which are mu rhythm amplitude distributions when target was at bottom (solid) or at top (dashed). System performance (i.e., accuracy (hits/(hits + errors)) and rate (hits/min) is indicated. In C, vertical lines demarcate voltage ranges used to select cursor movements in steps up (+) or down (−) for this subject. (Total number of steps from bottom to top was 76.) Subjects are arranged in order of performance. Thus, A has the largest distribution difference, highest accuracy, and highest rate. Even for D, in which the distribution difference is small, accuracy and rate are substantial.

TABLE I

Comparison of up and down mu rhythm amplitude distributions for final day.

Subject	Mean amplitude (μV)		r^2
	Up	Down	
A	3.10	1.52	0.23 ($P \ll 0.001$)
B	4.17	1.95	0.22 ($P \ll 0.001$)
C	3.68	1.80	0.20 ($P \ll 0.001$)
D	2.40	1.75	0.06 ($P \ll 0.001$)

Table I further describes performance of subjects A–D for this final day by giving the mean values of the up and down distributions, the fraction of total variance attributable to the difference in the means (r^2, i.e., the fraction of non-overlap), and the significance of the difference (Winer 1962). For each subject, the means are clearly different. The magnitude of the difference corresponds well with system performance as seen in Fig. 2.

As Fig. 3 illustrates, the frequency spectra and EEG traces accompanying top and bottom targets reflected the mu rhythm amplitude difference evident in the up and down distributions, and also indicated that the effects of training were focused on the 8–12 Hz frequency band of the mu rhythm. There was little or no difference at higher or lower frequencies. Thus, subjects achieved quite selective, narrow-band modulation of the EEG.

Operator selection of parameters translating mu rhythm into cursor movement

The operator tried to set voltage ranges and resulting movements so that system performance (i.e., accuracy and rate) was as high as possible, given the subject's level of mu rhythm control. Thus, the lowest voltage range and its resulting movement were chosen so that the large numbers of low mu rhythm amplitudes found in both up and down distributions (e.g., Fig. 2C) caused modest downward movements. The next voltage range caused no movement. The 3 higher ranges were selected

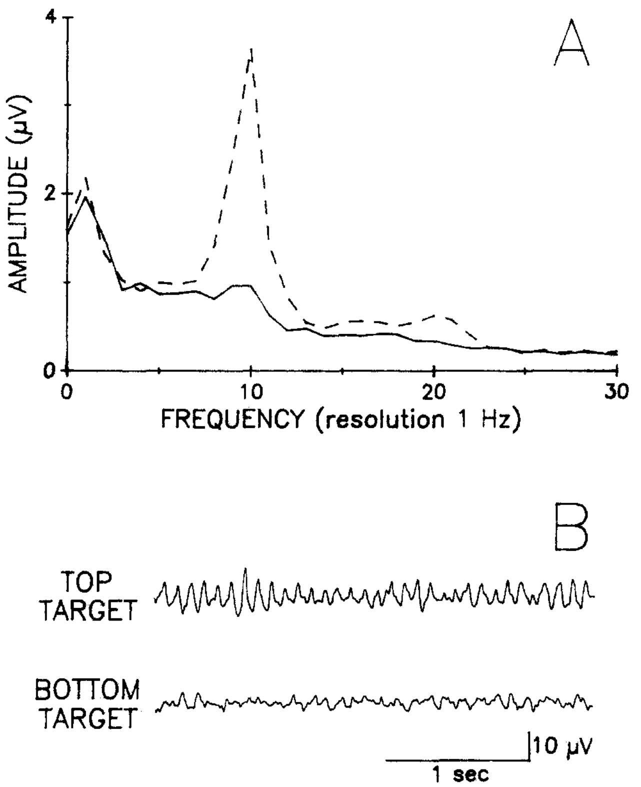

Fig. 3. A: frequency spectra for subject A when the target is at the bottom (solid) and at the top (dashed). The main difference between the two spectra is in the mu rhythm peak. Differences at higher and lower frequencies are absent or minimal. B: sample EEG traces of subject A accompanying top or bottom targets. The mu rhythm is prominent with the top target, and minimal or absent with the bottom target. (In order to achieve the 1 Hz resolution shown here, frequency analysis was performed on 1 sec segments, rather than on the standard 333 msec segments, and cursor movements were correspondingly less frequent.)

so that the less common high mu rhythm amplitudes caused modest, large, or very large upward movements. In the down distribution, i.e., when the target was at the bottom, these high amplitudes were infrequent, so that net movement was down. In the up distribution, i.e., when the target was at the top, these high amplitudes were more frequent, so that net movement was up. As training progressed and the mu rhythm amplitude distributions diverged, the operator periodically changed voltage ranges and resulting movements so as to take advantage of the greater difference between the two distributions. For example, when mu rhythm amplitudes greater than 5 μV disappeared from the down distribution of the subject in Fig. 2A, amplitudes over 5 μV were set to produce very large upward movements, without risk of causing errors when the target was at the bottom.

As described above, subject performance improved steadily over the course of training. In addition, it displayed some spontaneous variation across sessions and within sessions. The effects of this modest variability on system performance were reduced by ad hoc adjustments of voltage ranges and resulting movements. As training progressed, this variability declined, and both subject performance and system performance became more and more stable.

Subject strategies

Subjects reported that they adopted various strategies, such as thinking about a certain activity (e.g., lifting weights) to move the cursor down, and thinking about relaxing to move it up. As training progressed, several reported that such imagery was no longer needed.

Several possible artifactual contributions to mu rhythm control were ruled out. First, as Fig. 3 illustrates, wide-band frequency analysis (analog filters 1–300 Hz, frequency analysis up to 192 Hz), performed on each subject during performance on 3 separate days, detected no increase in higher frequency (i.e., EMG range) activity associated with high or with low mu rhythm amplitude. In addition, the mu rhythm peak was not reproduced by eye-blinks or by actions that increased local EMG activity, such as jaw clenching or

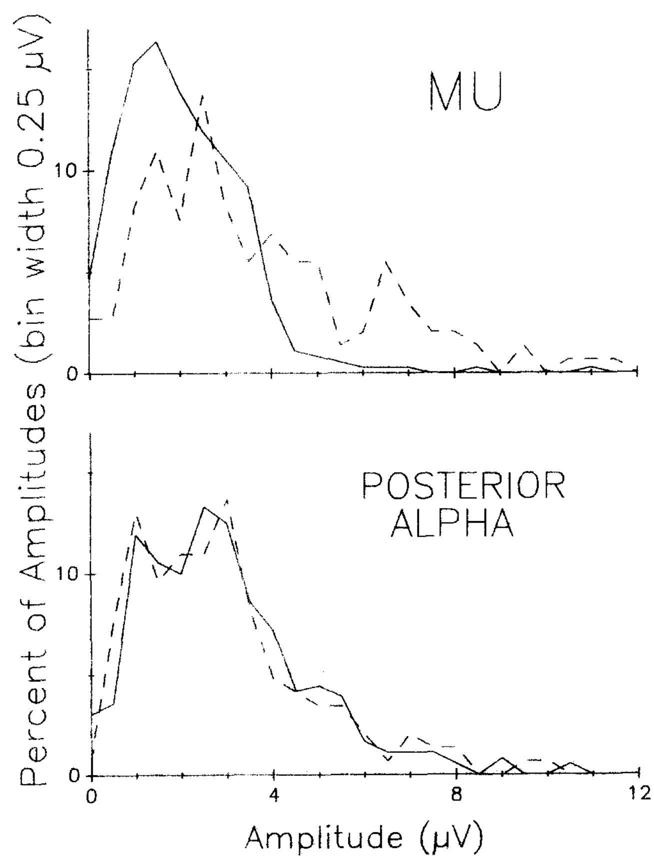

Fig. 4. Mu rhythm distributions and concurrent posterior (i.e., visual) alpha rhythm distributions for subject D during performance, when target was at bottom (solid) or at top (dashed). Posterior alpha rhythm was recorded by electrodes 3 cm to the right and left of 10/20 location Oz (Jasper 1958). Substantial, target-appropriate difference is evident between the mu rhythm distributions, but not between the alpha rhythm distributions.

contraction of neck muscles. Second, subjects' statements and our own observations indicated that subjects were not making contralateral movements to influence (i.e., reduce) the mu rhythm. (Furthermore, after training, the mean amplitude of the up distribution was slightly higher (an average of 8%) than the mean amplitude of the distribution obtained in the relaxed state prior to training.) Third, as Fig. 4 illustrates, posterior scalp recordings during performance indicated that changes in the visual alpha rhythm did not account for the mu rhythm control achieved.

Discussion

Previous studies have demonstrated voluntary control over a variety of EEG phenomena, including the ability to produce chronic increase in mu rhythm amplitude (Durup and Fessard 1935; Travis et al. 1975; Kuhlman 1978a; Elbert et al. 1980; Niedermeyer and Lopes da Silva 1987). The present study is significant for two reasons. First, it demonstrates that individuals can learn to increase or decrease mu rhythm amplitude very quickly and appropriately in response to a top or bottom target respectively. The mu rhythm amplitude distributions accompanying top and bottom targets overlap (Fig. 2), nevertheless they are clearly different (Table I). The magnitude of the difference appears consistent with the magnitude of the mu rhythm increase achieved by chronic conditioning (Kuhlman 1978a). Second, the results show that, with appropriate criteria for converting mu rhythm amplitude to cursor movement, the difference between the distributions can allow a subject to control an external device with a high degree of accuracy. The criteria which translate mu rhythm amplitudes into specific commands (e.g., 'move the cursor up 10 steps') are derived from evaluation of the two mu rhythm amplitude distributions.

This study's use of an internally generated rhythm distinguishes it from recent efforts to develop a new communication channel based on evoked potential analysis (Farwell and Donchin 1988). Because the mu rhythm is an endogenous phenomenon, the present system does not require a carefully structured, stereotyped sensory input (i.e., an evoking stimulus) as evoked potential-based communication systems do.

The mu rhythm control developed in the present study is of the simplest form, 1-dimensional, i.e., amplitude increase or decrease. In its current state, it could operate the single-switch systems designed for those with severe motor impairments (e.g., high-cervical spinal cord injury). The level of accuracy considered acceptable and used to help select voltage ranges and resulting movements would depend on the specific application.

The ultimate value of mu rhythm control as a means of communication depends on two factors: its limits in speed and accuracy, and the effectiveness with which it can be applied to specific control tasks. This discussion focuses on the first factor. The second factor is ultimately contingent on the first and is not our primary concern at this early stage of development.

Possible improvements in 1-dimensional control

The speed and accuracy of cursor control by the present system depends on proper selection of voltage ranges and movements. Selection should take into account the up and down distributions, the difference between them, and any correlations that exist between the mu rhythm amplitudes of successive time segments.

The complexity of the problem may be illustrated by considering selection of voltage ranges and resulting movements in Fig. 2A. Choice of the highest voltage range and its movement is straightforward: since only the up distribution has mu rhythm amplitudes over 5 μV, any amplitude over 5 μV should cause upward movement great enough to hit the top target whatever the current cursor position. However, choice of the second voltage range and its movement is much more difficult. From 3 to 5 μV, the two distributions overlap, but the up distribution has much greater representation (i.e., area). Setting amplitudes in this range to cause relatively large upward movements will facilitate hitting top targets, but will increase the number of errors when the target is at the bottom. The number of errors will also depend on the extent to which higher-amplitude time segments in the down distribution occur in groups. The best lower limit for this second voltage range is not clear, nor is the optimum size of the associated cursor movement. The correct answers depend on the forms of both distributions and on the values chosen for the other ranges and their movements. Perhaps 8 or 10 voltage ranges would give better control, or perhaps movement should be a continuous function of mu rhythm amplitude.

At present, as described in Results, the operator sets the voltage ranges and resulting movements based on examination of the up and down distributions. This is not an ideal solution, though it appears to be reasonably effective (as indicated by the fact that even the small distribution difference in Fig. 3D gave substantial cursor control). Using the data stored in the current study to simulate runs, we are evaluating several options for formalizing the selection of these parameters and transferring this selection to software. This transfer should increase rate and allow accuracy to be matched closely to the demands of a particular application. It should also improve the stability of performance, because parameters can then be automatically adjusted on-line at appropriate intervals in response to any spontaneous variations in the mu rhythm or other aspects of subject performance. Program control of parameter selection will help move toward what must be considered an important goal if mu rhythm communication is to be of significant practical use: the disappearance of the human operator. The final functioning system should consist only of hardware, software, and subject (i.e., user). Studies now underway with a first-generation algorithm are yielding system performance for trained subjects comparable to that provided by the on-line operator.

We are exploring use of shorter time segments, i.e., more frequent cursor movements. Initial data suggest that a change from 3 movements/sec to 5 movements/sec increases rate substantially with little or no decrease in accuracy, but further work is needed. This improvement might be coupled with and facilitated by development of a more sophisticated means than simple frequency analysis for detecting the mu rhythm, such as recognition of the beginning of a mu rhythm burst.

We have also begun to explore possibilities for improving 1-dimensional control so that the subject can move the cursor up or down to a specified location and then hold it in place to await the arrival of a moving target. If the encouraging initial data (McFarland et al. 1990) are confirmed, this additional element of control should significantly increase the range and sophistication of applications.

Recent studies indicate that most or all adults possess a detectable mu rhythm (Pfurtscheller 1989), and our experience as described here and in subsequent studies suggests that most can achieve significant control over it. At the same time, our data clearly imply that subjects differ in their ability to acquire mu rhythm control (e.g., Fig. 2A versus Fig. 2D). Training methods are presumably also important in determining final performance level. The methods used in this initial study can probably be substantially improved by formalization of parameter selection criteria, development of more specific instructions and suggestions for the subject in regard to achieving mu rhythm control, adjustments in the spacing and intensity of sessions, and other modifications. The relationships between mu rhythm and contralateral movement (including imagining or planning such movement) and between mu rhythm and attention should be relevant to the design of training procedures (Pfurtscheller and Klimesch 1989; Kozelka and Pedley 1990). Depending to a large extent on the nature of their impairment, disabled individuals may prove more or less able than others to acquire mu rhythm control. For example, those with spinal cord transection might be particularly adept because much of sensorimotor cortex is no longer committed to its normal tasks.

From an engineering perspective, this new communication channel depends on the interaction of two adaptive controllers: the subject who is attempting to produce mu rhythm amplitudes that will move the cursor to the target, and the system of program and operator, which is attempting to translate the subject's control of mu rhythm amplitude into rapid and accurate cursor movement. Analysis of these interactions (Neat et al. 1990) should facilitate training and improve final performance.

Potential improvements beyond 1-dimensional control

Development of ability to hold in place with 1-dimensional control, as described above, would allow 2-dimensional movement (holding in place could cause the cursor to change direction by 90°). However, the possibilities for very extensive development and use of mu rhythm communication ultimately hinge on achievement of multichannel capability.

While the mu rhythm, like the visual alpha rhythm, tends to occur over wide areas of cortex and over both hemispheres, topographic differences do occur (Storm van Leeuwen et al. 1978; Niedermeyer and Lopes da Silva 1987; Pfurtscheller 1989). Furthermore, a number of different mu rhythms may exist (Pfurtscheller 1989). Thus, it may be possible for an individual to learn to control simultaneously mu rhythm amplitudes at two or more scalp locations. The most logical initial locations are homologous placements over the two hemispheres. Our present efforts are focusing on the possibility of achieving independent or partially independent mu rhythm control of two such locations and on methods for using the mu rhythm amplitudes at these sites to give 2-dimensional cursor control.

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References

Brazier, M.A.B. The problem of periodicity in the electroencephalogram: studies in the cat. Electroenceph. clin. Neurophysiol., 1963, 15: 287–298.

Chatrian, G.E. The mu rhythm. In: A. Rémond (Ed.), Handbook of Electroencephalography and Clinical Neurophysiology. The EEG of the Waking Adult. Elsevier, Amsterdam, 1976: 46–69.

Durup, G. and Fessard, A. A l'électroencéphalogramme de l'homme. Ann. Psychol., 1935, 36: 1–31.

Elbert, T., Rockstroh, B., Lutzenberger, W. and Birbaumer, N. Biofeedback of slow cortical potentials. Electroenceph. clin. Neurophysiol., 1980, 48: 293–301.

Farwell, L.A. and Donchin, E. Taking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. Electroenceph. clin. Neurophysiol., 1988, 70: 510–523.

Finley, W.W., Smith, H.A. and Etherton, M.D. Reduction of seizures and normalization of EEG in a severe epileptic following sensorimotor biofeedback training. Biol. Psychol., 1975, 2: 189–203.

Gastaut, H. Etude électrocorticographique de la réactivité des rythmes rolandiques. Rev. Neurol., 1952, 87: 176–182.

Jasper, H.H. The ten-twenty electrode system of the International Federation. Electroenceph. clin. Neurophysiol., 1958, 10: 371–375.

Kozelka, J.W. and Pedley, T.A. Beta and mu rhythms. J. Clin. Neurophysiol., 1990, 7: 191–207.

Kuhlman, W.N. EEG feedback training: enhancement of somatosensory cortical activity. Electroenceph. clin. Neurophysiol., 1978a, 45: 290–294.

Kuhlman, W.N. Functional topography of the human mu rhythm. Electroenceph. clin. Neurophysiol., 1978b, 44: 83–93.

Loeb, G.E. Neural prosthetic interfaces with the nervous system. Trends Neurosci., 1989, 12: 195–201.

Lubar, J.F., Shabsin, H.S., Natelson, S.E., Holder, G.S., Whitsett, S.F., Pamplin, W.E. and Krulidowski, D.I. EEG operant conditioning in intractable epileptics. Arch. Neurol., 1981, 38: 700–704.

McFarland, D.J., Neat, G.W., Forneris, C.A., and Wolpaw, J.R. A brain-computer interface for cursor control. Soc. Neurosci. Abst., 1990, 16: 27.

Neat, G.W., McFarland, D.J., Forneris, C.A. and Wolpaw, J.R. EEG-based brain-to-computer communication: system description. Proc. IEEE Eng. Med. Biol. Soc., 1990, 5: 2298–2230.

Niedermeyer, E. and Lopes da Silva, F. Electroencephalography, 2nd Edn. Urban and Schwarzenberg, Baltimore, MD, 1987: 103–106.

Pfurtscheller, G. Functional topography during sensorimotor activation studied with event-related desynchronization mapping. J. Clin. Neurophysiol., 1989, 6: 75–84.

Pfurtscheller, G. and Klimesch, W. Cortical activation pattern during reading and recognition of words studied with dynamic event-related desynchronization mapping. In: K. Maurer (Ed.), Topographic Brain Mapping of EEG and Evoked Potentials. Springer, Heidelberg, 1989: 305–313.

Sterman, M.B., MacDonald, L.R. and Stone, R.K. Biofeedback training of sensorimotor EEG in man and its effect on epilepsy. Epilepsia, 1974, 15: 395–416.

Storm van Leeuwen, W., Bickford, R., Brazier, M., Cobb, W.A., Dondey, M., Gastaut, H., Gloor, P., Henry, C.E., Hess, R., Knott, J.R., Kugler, J., Lairy, G.C., Loeb, C., Magnus, O., Oller Daurella, L., Petsche, H., Schwab, R., Walter, W.G. and Widén, L. Proposal for an EEG terminology by the terminology committee of the International Federation for Electroencephalography and Clinical Neurophysiology. Electroenceph. clin. Neurophysiol., 1966, 20: 306–310.

Storm van Leeuwen, W., Wieneke, G., Spoelstra, P. and Versteeg, H. Lack of bilateral coherence of mu rhythm. Electroenceph. clin. Neurophysiol., 1978, 44: 140–146.

Tansey, M.A. EEG sensorimotor rhythm biofeedback training: some effects on the neurologic precursors of learning disabilities. Int. J. Psychophysiol., 1984, 1: 163–177.

Travis, T.A., Kondo, C.Y. and Knott, J.R. Alpha enhancement research: a review. Biol. Psychiat., 1975, 10: 69–89.

Vidal, J.J. Toward direct brain-computer communication. Annu. Rev. Biophys. Bioeng., 1973, 2: 157–180.

Winer, B.J. Statistical Principles in Experimental Design, 2nd Edn. McGraw-Hill, New York, 1962: 105–120.

Wolpaw, J.R., McFarland, D.J. and Cacace, A.T. Preliminary studies for a direct brain-to-computer parallel interface. In: M.S. Neff and J. Sinocchi (Eds.), Projects for Persons with Disabilities (IBM Technical Symposium). IBM Corporation, 1986: 11–20.