

Mu and Beta Rhythm Topographies During Motor Imagery and Actual Movements

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Summary: People can learn to control the 8-12 Hz mu rhythm and/or the 18-25 Hz beta rhythm in the EEG recorded over sensorimotor cortex and use it to control a cursor on a video screen. Subjects often report using motor imagery to control cursor movement, particularly early in training. We compared in untrained subjects the EEG topographies associated with actual hand movement to those associated with imagined hand movement. Sixty-four EEG channels were recorded while each of 33 adults moved left- or right-hand or imagined doing so. Frequency-specific differences between movement or imagery and rest, and between right- and left-hand movement or imagery, were evaluated by scalp topographies of voltage and r spectra, and principal component analysis. Both movement and imagery were associated with mu and beta rhythm desynchronization. The mu topographies showed bilateral foci of desynchronization over sensorimotor cortices, while the beta topographies showed peak desynchronization over the vertex. Both mu and beta rhythm left/right differences showed bilateral central foci that were stronger on the right side. The independence of mu and beta rhythms was demonstrated by differences for movement and imagery for the subjects as a group and by principal components analysis. The results indicated that the effects of imagery were not simply an attenuated version of the effects of movement. They supply evidence that motor imagery could play an important role in EEG-based communication, and suggest that mu and beta rhythms might provide independent control signals.

Key words: Sensorimotor cortex; Mu rhythm; Beta rhythm; EEG; Imagery.

Introduction

In recent years, a variety of studies have addressed the possibility that scalp-recorded electroencephalographic (EEG) activity might be the basis for a brain-computer interface (BCI) that could be a new alternative communication channel for those lacking useful voluntary movement (Wolpaw et al. 1986, 1991; Farwell and Donchin 1988; McFarland et al. 1993; Pfurtscheller et al. 1993; Rockstroh et al. 1989; Sutter 1992; Wolpaw and McFarland 1994; Vaughan et al. 1996; Birbaumer et al. 1999). An EEG-based BCI system measures particular features of EEG activity and uses the results as a control signal. Our system uses 8-12 Hz mu rhythm activity recorded over sensorimotor cortex, and/or related 18-25 Hz beta rhythm activity, to control movement of a cursor on a computer screen. Part

of the original rationale for selection of the mu rhythm for this purpose was that it is produced in those cortical areas most directly concerned with normal motor control, and might therefore be well suited for use as a control signal. While mu rhythm-based cursor control does not appear to depend on concurrent muscle activity (e.g., Vaughan et al. 1998), subjects frequently report using motor imagery to control cursor movement, particularly early in training. To better understand the current and potential role of imagery in EEG-based communication, we set out to define the naive (i.e., pre-training) effects of motor imagery on mu and beta rhythm activity, and to compare these effects to those of actual movement.

The mu rhythm is traditionally defined as an 8-12 Hz rhythm recorded over sensorimotor cortex that decreases, or desynchronizes, with movement (Gastaut 1952; Niedermeyer 1997; Pfurtscheller and Aranibar 1979). Chatrian et al. (1959) noted that it also decreased during motor imagery. While the mu rhythm was initially thought to occur in only a minority of individuals (Chatrian et al. 1959; Chatrian 1976), computer-based signal processing (e.g., spectral analysis) reveals that it occurs in most normal adults (Kuhlman 1978; Pfurtscheller and Aranibar 1979; Pfurtscheller 1988). Furthermore, it is now clear that the mu rhythm is not a single EEG component, but rather a class of rhythms differing from each other in topography, frequency, and/or precise relationship to movement (Pfurtscheller 1989; Pfurtscheller 1998).

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Mu rhythms are usually associated with 18-25 Hz beta rhythm activity, and mu rhythms are typically not sinusoidal (Pfurtscheller et al. 1997). Modeling of non-sinusoidal waveforms by classical Fourier analysis requires the use of higher frequency harmonic components in addition to a fundamental frequency. Thus, beta rhythm activity associated with mu rhythms might result from the non-sinusoidal nature of mu rhythms, rather than from independent physiological processes (Juergens et al. 1995). However, recent studies indicate that some beta rhythms have their own distinct topographies and relationships to movement, and thus appear to be independent of mu rhythm activity (Pfurtscheller et al. 1994; Stancak et al. 1997; Pfurtscheller et al. 1997; Pfurtscheller 1998).

Several studies have examined mu and beta rhythm activity during motor imagery. Recording from subdural electrodes over sensorimotor cortex, Arroyo et al. (1993) found mu-rhythm desynchronization during actual movement but not during thinking about movement. Schupp et al. (1994) found that both handling an object and imagining handling it were associated with desynchronization in the 8-12 Hz band, but that the topographies of desynchronization differed. In contrast, Lang et al. (1996) reported that slow potentials associated with actual and imagined hand movements had similar topographies. Pfurtscheller and Neuper (1997) reported that both imagery and movement produce desynchronization in mu and beta bands over contralateral sensorimotor areas. Thus, the degree of similarity between the patterns of cortical activation associated with actual movement and those associated with motor imagery remains uncertain.

PET (positron emission tomography) and fMRI (functional magnetic resonance imaging) provide additional means for comparing cortical activation associated with actual movement to that associated with motor imagery. Reviewing data from imaging studies and from subjects with brain lesions, Kosslyn et al. (1995) concluded that the areas involved in perception and action are also involved in imagery. On the other hand, several studies suggest that activation of primary motor cortex occurs only with actual movement. Roland et al. (1980) found that, while blood flow changed in the supplementary motor area during both planning and execution of hand movement, it increased in the contralateral primary motor area only during actual movement. Roa et al. (1993), using fMRI, reported increased blood flow in primary motor cortex during movement but not during imagery; while Decety et al. (1994), using PET, found that blood flow in premotor cortex increased bilaterally during motor imagery. Deiber et al. (1998) have reported that PET activations in inferoparietal, pre-motor, and pre-frontal sites occur with movement imagery while additional activations in motor cortex and cerebellum occur with actual movement. These studies appear to be consistent with the EEG

data suggesting differences in cortical activation between actual movement and motor imagery. In contrast, Porro et al. (1996) reported fMRI activations of motor cortex in both movement and imagery conditions.

This study examined in a large number of adults the relationships of mu and beta rhythms to actual movement and to imagined movement. It focused on the similarities and differences between the effects of actual and imagined movement, on comparison of mu and beta rhythms in this regard, and on the effects of laterality of movement or imagery. The goal was to learn how imagery might contribute to EEG-based communication. Thus, our analyses were designed to reveal sources of useful information rather than to test alternative explanations of observed effects. Previous studies have used a variety of statistical tools to assess movement and imagery effects on EEG (e.g., Pfurtscheller 1988) and MEG (e.g., Salmelin and Hari 1994). We used primarily *r*, the correlation of the signal with a condition (such as motor imagery versus rest) (Winer 1971).

Methods

Data collection

Subjects were 33 adults (19 men and 14 women, 18-60 years old, mean age 39.6, SD 11.3) who had not undergone training in EEG-based cursor control. Three had had spinal cord injuries (at levels C4-5, C6-7, and T4, respectively) and were confined to wheel-chairs. One had amyotrophic lateral sclerosis (ALS) and one had multiple sclerosis (MS). Both of these subjects used wheelchairs but were not confined to them. The other 28 subjects had no significant neurological disability. All gave informed consent for the study, which had been reviewed and approved by the New York State Department of Health Institutional Review Board.

Each subject sat in a reclining chair facing a video screen, while scalp electrodes recorded the 64 channels of EEG shown in figure 1 (Sharbrough et al. 1991). Subjects were instructed to relax, to look at the video screen, and to try to avoid blinking during trials. Data collection lasted 17 min, and was divided into 6 two-min runs separated by one-min breaks. Each run consisted of 15 4-sec trials separated by 4-sec intertrial intervals. During the trials, a vertical bar was present on the left or right edge of the screen. During the intertrial intervals, the screen was blank. Three movement runs were interspersed with three imagery runs. During the trials of the movement runs, the subject repeatedly opened and closed the hand ipsilateral to the target. During the trials of the imagery runs, the subject imagined doing so. During the intertrial intervals, the subject did neither and simply tried to relax. All EEG channels were referred to a reference electrode on the

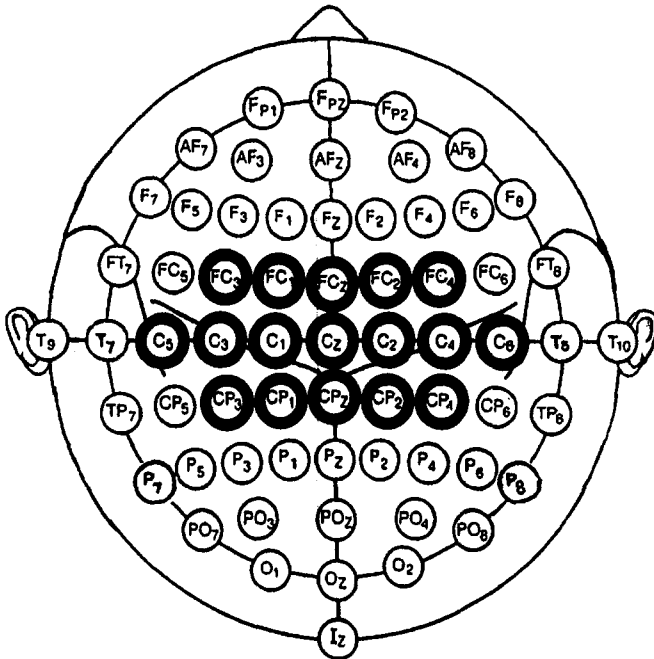


Figure 1. The 64 electrodes used in the present study (after Sharbrough et al. 1991). The 17 electrodes used for analysis of variance and principal component analysis are shaded.

right ear (amplification 20,000; bandpass 1-60 Hz), digitized at 128 Hz, and stored for later analysis.

Data analysis

The data were first converted to a reference-free form by a Laplacian algorithm (Hjorth 1975) that used the set of four next-nearest neighbor electrodes (e.g., for electrode C3, these were F3, T7, CZ and P3) (McFarland et al. 1997). This algorithm has spatial filter characteristics suited to the topographical extent of mu and central beta rhythms (McFarland et al. 1997). The Laplacian was computed according to the formula,

$$V_i^{LAP} = V_i^{CR} - \sum_{j \in S_i} g_{ij} V_j^{CR}$$

where

$$g_{ij} = 1/d_{ij} / \sum_{j \in S_i} 1/d_{ij},$$

S_i is the set of electrodes surrounding the i th electrode and d_{ij} is the distance between electrodes i and j .

The Laplacian waveforms were then subjected to an autoregressive spectral analysis (maximum entropy method (MEM) (Marple 1987)). Every 200-msec segment from each channel was analyzed by the autoregressive algorithm, and the square root of power in 3-Hz wide or 1-Hz wide frequency bands was calculated. The bands

centered at 12 and 24 Hz received the most attention, because they reflect mu rhythm activity and beta rhythm activity, respectively (Gastaut 1952; Kuhlman 1978; Pfurtscheller and Berghold 1989; Arroyo et al. 1993). These values were at the peaks in the spectra obtained by averaging the spectra of the individual subjects. Inspection of adjacent bands revealed similar trends.

We calculated at all frequencies for selected electrodes and at selected frequencies for all electrodes the values of r for movement versus rest (i.e., the intertrial interval), imagery versus rest, left versus right movement, and left versus right imagery. As noted above, r is the correlation between the signal and a model of the data (e.g., movement or no movement, right or left imagery, etc.), and thus provides an index of the signal-to-noise ratio (Winer 1971)). We used r (rather than r^2 as in our previous studies (e.g., Wolpaw et al. 1991)) in order to preserve the sign (i.e., direction) of the relationship. We used r primarily as a measure of information content in the frequencies and channels of interest, rather than as a means of determining statistical significance. The goal was to identify sources of information that could be used for communication.

Results

Comparisons of left and right movement and imagery with rest

Figure 2a shows for all subjects the r topographies for left-hand movement versus rest (i.e. the intertrial interval) and right-hand movement versus rest for the mu and beta rhythm frequency bands (i.e. 3-Hz bands centered at 12 and 24 Hz respectively). Values of r are positive (red) when activity is lower during movement than during rest (i.e., the EEG desynchronizes during movement). Left- or right-hand movement is associated with bilateral desynchronization in the mu band that is greater on the contralateral side. They are also associated with more diffuse centrally focused desynchronization in the beta band that is slightly stronger on the contralateral side. The hemispheric asymmetries are greater with right-hand movement than with left-hand movement. In individual subjects the beta desynchronization is more sharply focused. The diffuse focus seen in figure 2a reflects inter-individual variations.

To complement figure 2a, which shows the topographical specificity of movement effects, figure 3 shows their spectral specificity. It displays voltage and r spectra for the CZ, CP3 and CP4 electrodes, which are at the centers of the foci seen in figure 2a. At the lateral sites CP3 and CP4, left- or right-hand movement is associated with both mu and beta desynchronizations that are greater contralaterally. The hemispheric asymmetries are greater for right-hand movement than for left-hand movement.

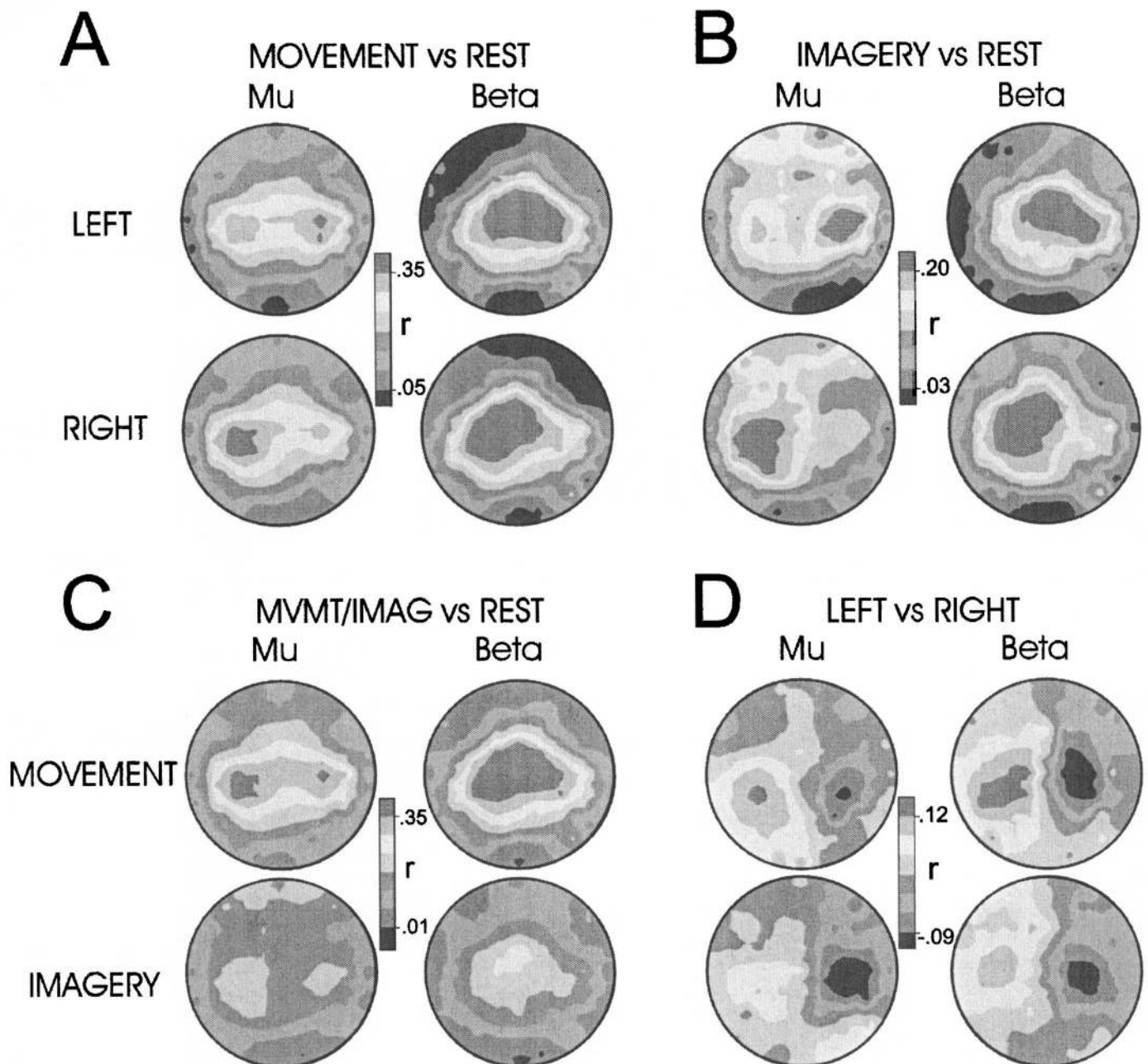


Figure 2. Topographies of r for mu and beta band activity (i.e., 3-Hz wide bands centered at 12 and 24 Hz, respectively). A. Left-hand movement versus rest (i.e., the inter-trial Interval) and right-hand movement versus rest. Values of r are larger (red) when activity is lower during movement than during rest (i.e., when movement produces desynchronization). B. Left-hand imagery versus rest (i.e., intertrial period) and right-hand imagery versus rest. Values of r are larger (red) when activity is lower during movement than during rest (i.e., when movement produces desynchronization). C. Movement versus rest (i.e., intertrial period) and imagery versus rest. Values of r are larger (red) when activity is lower during movement than during rest. D. Right- versus left-hand movement and imagery. Values of r are larger (red) when activity is greater during left-hand movement than during right-hand movement.

At the central site, Cz, left- or right-hand movement is associated with mainly beta desynchronization.

Figure 2b shows for all subjects the r topographies for left-hand imagery versus rest and right-hand imag-

ery versus rest for the mu and beta rhythm bands. The data are qualitatively similar to those of movement, but smaller in magnitude. The tendency for greater desynchronization on the contralateral side is more

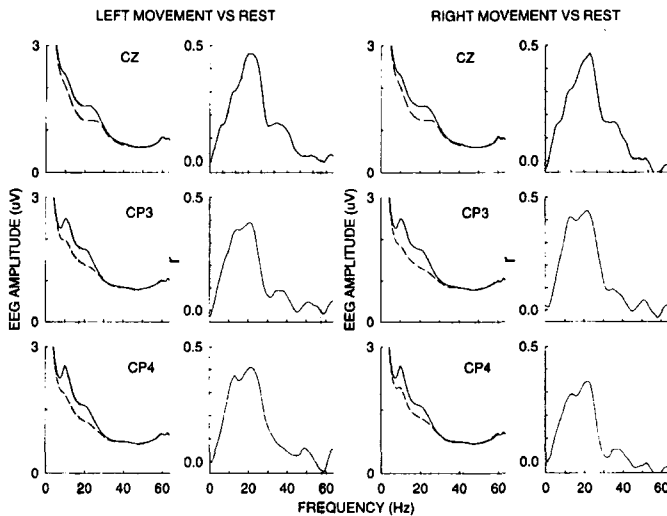


Figure 3. Voltage spectra for left-hand movement (dashed) versus rest (solid) and for right-hand movement (dashed) versus rest. For this analysis, the autoregressive function was evaluated at 1-Hz intervals.

prominent for imagery than for movement. For the mu rhythm band, hemispheric asymmetry is more prominent with right hand imagery, while for the beta rhythm band, hemispheric asymmetry is more prominent with left hand imagery. In addition, 11-13 Hz activity shows greater frontal desynchronization during imagery than during movement. Spectra from frontal channels FP1 and FP2 indicate that this activity is greatest at 2-4 Hz, and thus probably reflects eye movements and/or blinks occurring during the intertrial interval.

To complement figure 2b, which shows the topographical specificity of movement effects, figure 4 shows their spectral specificity. It displays voltage and r spectra for the electrodes at CZ, CP3 and CP4. The spectra are similar to those for movement. At the lateral electrodes, CP3 and CP4, left- and right-hand imagery is associated with both mu and beta desynchronizations which are greater contralaterally. At the central site, Cz, left- or right-hand imagery is mainly associated with beta desynchronization.

Comparisons of movement to rest and imagery to rest

Figure 2c shows for all subjects the r topographies for movement (right and left) versus rest and imagery versus rest for the mu and beta rhythm frequency bands (i.e., 3-Hz bands centered at 12 and 24 Hz, respectively). This comparison reveals aspects of the EEG response common to both left- and right-hand movement. The mu and beta topographies are much different. For mu rhythm activity, both movement and imagery are associated with two foci of desynchronization, one over sensorimotor cortex on each side. The left focus is slightly stronger (as in fig-

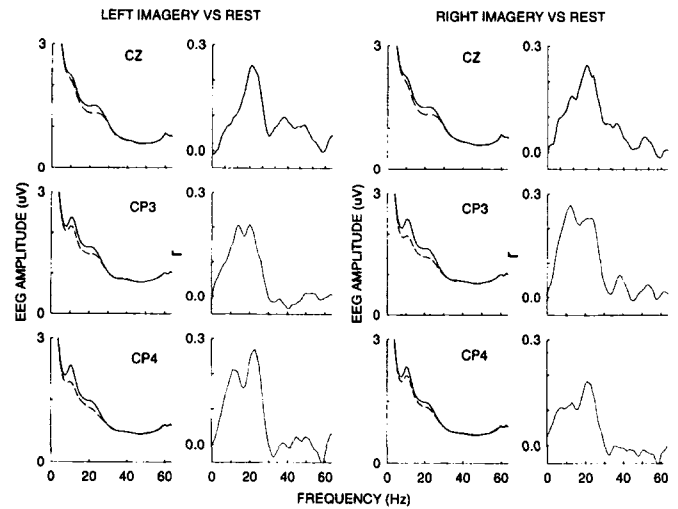


Figure 4. Voltage spectra for left-hand imagery (dashed) and rest (solid) and right-hand imagery (dashed) and rest (solid), with corresponding r spectra for left-hand imagery versus rest and right-hand imagery versus rest. For this analysis, the autoregressive function was evaluated at 1-Hz intervals.

ure 2b, the frontal desynchronization with imagery is attributable to a reduction in eyeblinks). In contrast, for beta rhythm activity, both movement and imagery are associated with more diffuse desynchronization focused over the vertex and extending more to the left than to the right. At the same time, the mu and beta rhythm topographies are similar for movement and imagery: the bilateral mu foci and centralized beta focus are seen in both. The difference is that the foci are stronger for movement than for imagery. Table I gives the locations and values of the maximum r at the center of the mu and beta foci for movement versus rest and imagery versus rest. For both movement and imagery, mu desynchronization is greatest at CP3 and beta desynchronization is greatest at CZ.

To complement figure 2c, which shows the topographical specificity of movement and imagery effects, figure 5 shows their spectral specificity. It displays the voltage spectra for movement, imagery, and rest for the electrodes at the centers of the foci seen in figure 2c, and also displays the corresponding r spectra for movement versus rest and imagery versus rest. The differences between movement and rest and between imagery and rest are both confined to the 8-28 Hz frequency range and are focused in the 8-12 Hz mu rhythm band and 18-25 Hz beta rhythm band. (Individuals usually show much sharper spectral peaks than those seen in these group averages.) As expected from the topographies in figure 2c, the r values at CZ are higher in the beta band than in the mu band, while those at CP3 and CP4 show two peaks, one in the mu band and one in the beta band. At all three locations, the voltage and r spectra for movement versus

Table 1. Locations and r values for centers of topographic foci for mu and beta frequency bands for movement or imagery versus rest.

Condition	Frequency Band	Location	r
Movement	Mu	CP3	0.398
Imagery	Mu	CP3	0.239
Movement	Beta	FCZ	0.470
Imagery	Beta	FCZ	0.274

rest and imagery versus rest are similar, except that the voltage differences and r values for movement versus rest are nearly twice those for imagery versus rest.

To evaluate further the data summarized in figures 2c and 5, we performed an analysis of variance with frequency band (i.e., mu or beta), instruction (i.e., movement or imagery or rest), and channel (i.e., the subset of 17 electrodes over central areas shaded in figure 1: FC3, FC1, FCZ, FC2, FC4, C5, C3, C1, CZ, C2, C4, C6, CP3, CP1, CPZ, CP2, CP4) as within-subject effects. We found significant main effects for instruction ($F=27.67$, $df=1/32$, $p<0.0001$), and channel ($F=8.78$, $df=16/512$, $p<0.0001$). In addition, significant interactions were detected between frequency and channel ($F=8.32$, $df=16/512$, $p<0.0001$), between channel and instruction ($F=4.43$, $df=16/512$, $p<0.0001$), and between frequency, instruction, and channel ($F=1.94$, $df=16/512$, $p<0.02$).

While the previous analyses illustrate overall trends in the data, inspection of the data from individual subjects

reveals marked individual differences. To assess the covariation between movement and imagery effects on mu and beta rhythms across subjects, we performed principal components analysis with varimax rotation on the r values of the individual subjects for movement versus rest and imagery versus rest for the mu and beta frequency bands of the 17 central electrodes indicated in figure 1. Since the covariance was based upon subject differences, these factors reflect individual differences in magnitude of effects. The r values for these electrodes were included as separate variables for each of the four conditions (i.e., movement/mu, imagery/mu, movement/beta, imagery/beta). Thus, the analysis included 68 variables. Eleven factors had eigenvalues greater than one. We evaluated the first four factors. These accounted for 17.5%, 13.7%, and 10.1% and 5.8% of the variance in the matrix, respectively. For factor 1, loadings ≥ 0.80 were found for values of 14 electrodes associated with mu band reactivity to movement. The other three electrodes had loadings between 0.70 and 0.80 for mu reactivity during movement. For this first factor, all loadings were below 0.70 during the other conditions. We concluded that this first factor is related to individual differences in movement effects on mu rhythm activity. For factor 2, loadings ≥ 0.80 were found for values at FC2, C2 for the mu band during imagery. C6 had a loading of 0.78 during this condition. All other conditions had loadings below 0.70 on this factor. We concluded that the second factor was related to individual differences in imagery effects on mu rhythm activity. For factor 3, loadings ≥ 0.80 were found for CZ and C2 for the beta band during movement. CPZ had a loading of 0.74 during this condition. All other conditions had loadings below 0.70 on the third factor. We concluded that this factor was related to individual differences in movement effects on beta rhythm activity. Factor 4 had loadings of 0.79 for FC3 and 0.71 for FC4 beta band reactivity to imagery. All other loadings were below 0.70. We concluded that this factor was related to individual differences in beta reactivity to imagery. Factor 5 did not have any loadings above 0.70 and accounted for only 4.23% of the variance in the correlation matrix. We did not attempt to interpret it or other less influential fac-

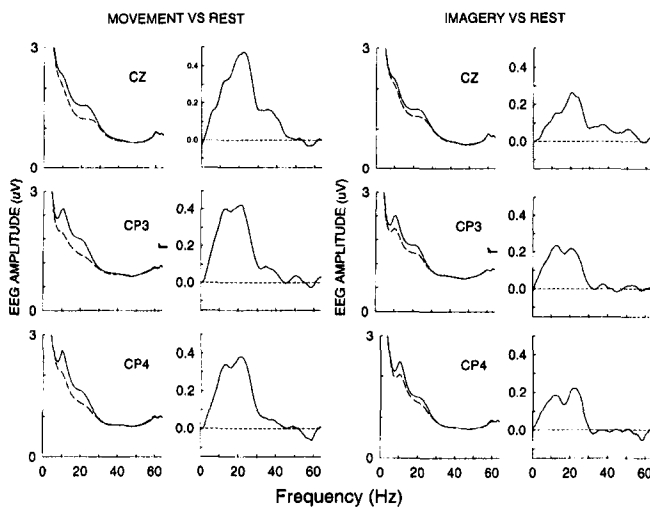


Figure 5. Voltage spectra for movement (dashed) and rest (solid) and imagery (dashed) and rest (solid), with corresponding r spectra for movement versus rest and imagery versus rest. For this analysis, the autoregressive function was evaluated at 1-Hz intervals.

Table II. Locations and *r* values for centers of topographic for mu and beta frequency bands for right versus left movement or imagery.

Condition	Frequency Band	Side	Location	<i>r</i>
Movement	Mu	Left	CP3	0.147
Movement	Mu	Right	CP4	-0.118
Imagery	Mu	Left	CP3	0.092
Imagery	Mu	Right	C4	-0.150
Movement	Beta	Left	C1	0.154
Movement	Beta	Right	CP4	-0.124
Imagery	Beta	Left	C3	0.122
Imagery	Beta	Right	C4	-0.114

tors. The first four factors indicated that individual differences in mu and beta band effects of movement and imagery were clearly dissociable.

Comparisons of right and left movement and imagery

Figure 2d shows for all subjects the *r* topographies for right- versus left-hand movement and for right- versus left-hand imagery for the mu and beta rhythm frequency bands. In the mu band, right/left differences for movement and imagery are similar in location and magnitude. Both show foci over the right central or postcentral region

(e.g., CP4), and over the left postcentral region and more posteriorly. The similarity between movement and imagery in the magnitude of the right/left difference in the mu band contrasts with the results displayed in figure 2c, in which the movement versus rest difference is much larger than the imagery versus rest difference. The right/left differences for movement in the beta band are similar to those in the mu band. Right/left differences for imagery in the beta band are similar and slightly smaller. Also of interest is the right posterior focus in the mu imagery condition opposite in sign to the central component. This appears to represent an event-related synchronization similar to that described by Pfurtscheller (1996). Table II shows the location and values of *r* for the foci of the mu and beta topographies for right versus left movement and imagery. In sum, mu and beta band right/left differences are similar in location for movement and imagery, while the magnitudes of the differences are slightly greater for movement.

To complement figure 2d, which shows the topographical specificity of movement and imagery effects, figure 6 shows their spectral specificity. It displays the voltage spectra for right and left movement and imagery for CZ and for electrodes at or near the centers of the foci (e.g., CP3 and CP4), and also displays the corresponding *r* spectra for right versus left movement and imagery. As expected, contralateral movement is associated with desynchronization.

To evaluate further the data of figure 2d, we performed an analysis of variance with frequency band (i.e., mu or beta), instruction (i.e., right or left movement or imagery), and channels (i.e., see above and figure 1) as within-subject factors. We found significant effects for channel ($F=18.54, df=16/512, p<0.0001$). In addition, the interaction between channel and frequency was significant ($F=3.04, df=16/512, p<0.0001$).

To assess the covariation between movement and imagery effects on mu and beta rhythms across subjects,

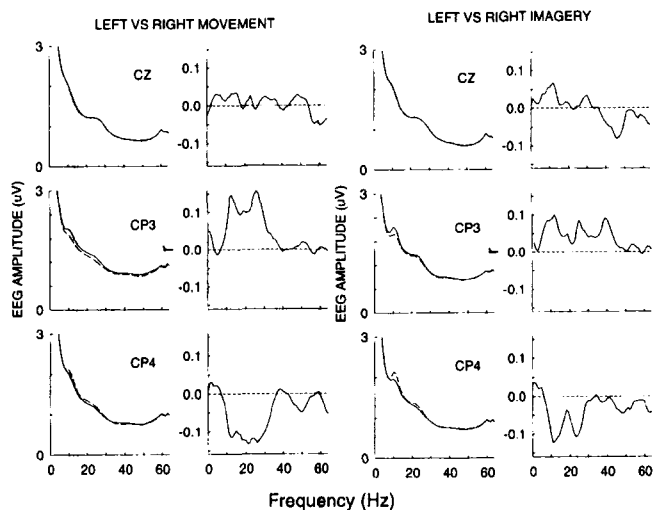


Figure 6. Voltage spectra for right-hand (dashed) and left-hand (solid) movement and right-hand (dashed) and left-hand (solid) imagery, with corresponding *r* spectra for right- versus left-hand movement and right- versus left-hand imagery. For this analysis, the autoregressive function was evaluated at 1-Hz intervals.

we performed principal components analysis with varimax rotation on the r values of the individual subjects for right and left movement and right and left imagery for the mu and beta frequency bands of 17 central electrodes (i.e., figure 1). The r values for these electrodes were included as separate variables for each of the four conditions (i.e., movement/mu, movement/beta, imagery/mu, imagery/beta), so that there were 68 variables in the analysis. Eighteen factors had eigenvalues greater than one. We interpreted only the first two factors, which accounted for 6.6 and 6.4 percent of the variance in the matrix. For the first factor, loadings >0.80 were found for FC3 in the beta band for movement, and values between 0.70 and 0.80 were found for FC1, C3 and CP3 for this same condition. We conclude that this factor reflects individual differences in the lateralized effects of movement on beta rhythm activity. The second factor had a loading of 0.83 on C4 for the mu band response to movement and loadings of 0.71 on CPZ and 0.77 on CP4 for the same condition. We concluded that this second factor is associated with individual differences in the lateralized effects of movement on the mu rhythm. All loadings on the third factor were less than 0.70. We did not interpret this factor or any other factors.

The data of subjects with spinal cord injury, MS, or ALS were not discernibly different from those of others. They displayed the same movement and imagery effects described above. Furthermore, inspection of group mean topographies and spectra revealed no prominent differences between right- and left-handed subjects.

Discussion

The results show that both movement and imagery are accompanied by desynchronization over sensorimotor cortical areas in both mu and beta bands. At the same time, the topographies of desynchronization are clearly different for the two frequency bands. Mu rhythm desynchronization is sharply focused at lateral postcentral sites (CP3 and CP4), while beta rhythm desynchronization has a more diffuse focus centered at the vertex. This difference indicates that beta rhythm activity is not a harmonic resulting from the non-sinusoidal waveform of mu rhythm activity. The principal components analysis provides further evidence for the independence of beta rhythm activity.

In general, the results indicate that the patterns of mu and beta band desynchronization with motor imagery are similar to those with actual movement. This finding is consistent with the conclusion of Kosslyn et al. (1995) that imagery and movement are associated with activation of the same cortical regions. At the same time, differences between the effects of movement and imagery were apparent.

The differences between movement and rest and be-

tween imagery and rest, as reflected in the r topographies and spectra, were similar in form but different in magnitude. The imagery/rest difference was considerably smaller than the movement/rest difference. This was true for both mu rhythm and beta rhythm frequency bands. On the other hand, for both mu and beta rhythms, right-hand/left-hand differences were nearly as great for imagery as for movement.

Because movement or imagery continued for a relatively lengthy period (i.e., 4 sec) following the presentation of the instruction (i.e., the right or left target) the present data are largely simultaneous with movement or imagery. Only the first part of this period (i.e., the time required for the subject to respond to the stimulus) occurred before movement or imagery. In contrast, Pfurtscheller and Berghold (1989) found differences between right- and left-hand movement only during movement preparation; movement itself was accompanied by bilateral mu rhythm desynchronization. Stancak and Pfurtscheller (1996) reported lateralized effects during motor preparation to be greater with slow than with rapid movements, and Pulvermuller et al. (1995) noted that lateralized mu desynchronization occurred during simple, but not complex, motor tasks. In the present study, movement was associated with lateralized effects, but these effects were not as marked as the overall bilateral effect (i.e., the movement or imagery versus rest difference). Thus, in terms of possibilities for EEG-based communication, motor imagery of either hand might provide a more robust control signal than that provided by differences between left- and right-hand motor imagery.

The topographic and spectral data presented here are based on group averages. These group averages sum individual subject effects that are more focused topographically and spectrally. The principal components analysis reveals marked individual differences in these effects. In addition, this analysis indicates that movement and imagery and mu and beta bands are clearly dissociated in terms of individual differences. For example, individuals with a large movement effect on the mu rhythm do not necessarily show a large imagery effect on the mu rhythm.

The right/left differences are significant in another respect. The movement versus rest and imagery versus rest differences suggest that imagery is simply a lesser form of movement: movement and imagery effects are similar in frequency and topography, but movement effects are much greater. The right/left differences indicate that this simple interpretation is not adequate. In the mu band at least, right/left differences for movement and imagery are comparable in magnitude as well as in location. Thus, unlike the results for movement, right/left imagery differences are nearly as great as imagery/rest differences. These results, combined with

data indicating that mu or beta rhythm-based cursor control does not depend on concurrent muscle activity (e.g., Vaughan et al. 1997), suggest that the effects of imagery are more relevant for EEG-based communication than are the effects of movement.

While subjects sat quietly during data collection, without visible arm or hand movements except as required for the movement trials, it remained possible that low-level, perhaps largely unconscious muscle activity occurred in some subjects during motor imagery. However, the fact that movement and imagery effects differed in form as well as in magnitude suggests that such muscle activity was not responsible for the effects of imagery. This conclusion is supported by a recent study (Vaughan et al. 1998) showing that limb muscle activity is not a significant factor in EEG-based cursor control.

It is conceivable that the effects of motor imagery on brain activity might depend on the instruction given to the subject. For example, the instruction to imagine the sensation of moving might produce desynchronization over motor cortical areas, while the instruction to visualize movement might produce desynchronization over visual cortical areas. In the present study, subjects were simply asked to imagine moving. This instruction seems comparable to the instruction to imagine the sensation of moving, and this is supported by the finding that imagery was predominantly associated with desynchronization over motor cortical areas.

In summary, the results support the conclusion that imagery could be an effective way to control mu and/or beta rhythm amplitude, and thus might play an important role in EEG-based communication. Indeed, subjects who learn to use mu or beta rhythms as control signals often report using motor imagery, especially early in training (Wolpaw et al. 1991; Wolpaw and McFarland 1994). Thus, relatively simple and ordinary cognitive operations provide a strategy through which subjects can begin to learn EEG-based communication.

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