Gert Pfurtscheller*
Reinhold Scherer
Robert Leeb
Claudia Keinrath
Laboratory of Brain-Computer Interfaces
Institute for Knowledge Discovery
Graz University of Technology
Graz, Austria

Christa Neuper
Institute for Psychology
University of Graz
Graz, Austria

Felix Lee
Horst Bischof
Institute of Computer Graphics and Vision
Graz University of Technology
Graz, Austria

Viewing Moving Objects in Virtual Reality Can Change the Dynamics of Sensorimotor EEG Rhythms

Abstract

We studied the impact of different visual objects such as a moving hand and a moving cube on the bioelectrical brain activity (i.e., electroencephalogram; EEG). The moving objects were presented in a virtual reality (VR) system via a head mounted display (HMD). Nine healthy volunteers were confronted with 3D visual stimulus presentations in four experimental conditions: (i) static hand, (ii) dynamic hand, (iii) static cube, and (iv) dynamic cube. The results reveal that the processing of moving visual stimuli depends on the type of object: viewing a moving hand results in a stronger desynchronization of the central beta rhythm than viewing a moving cube. This provides further evidence for some extent of motor processing related to visual presentation of objects and implies a greater involvement of motor areas in the brain with the observation of action of different body parts than with the observation of non-body part movements.

1 Introduction

In experiments where visual feedback is necessary, as for example in neurofeedback training (e.g., Egner, Zech, & Gruzelier, 2004) or brain-computer interface (BCI) research (Wolpaw, Birbaumer, McFarland, Pfurtscheller, & Vaughan, 2002; Pfurtscheller & Neuper, 2001), it is of importance to know how different types of visual stimuli affect the electroencephalogram (EEG) activity. According to the work of Rizzolatti, Fogassi, and Gallese (2001) there is evidence that a mirror neuron system exists in a monkey's ventral premotor cortex (Area F5). These neurons are activated both when the monkey performs specific goal directed hand actions and when it observes another monkey or another person performing the same or a similar action (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti et al., 1996). There is increasing evidence from experiments carried out with neurophysiological, behavioral, and brain imaging studies that a mirror neuron system also exists in humans. For example, several transcranial magnetic stimulation (TMS) studies have shown enhanced motor evoked potentials when subjects observe a person performing object-oriented actions (Gangitano, Mottaghy, & Pascual-Leone, 2001; Strafella & Paus, 2000). Functional neuroimaging studies reported the involvement of Broca's area and the dorsal premotor cortex during observation

Presence, *Vol. 16, No. 1, February 2007, 111–118*

---

*Correspondence to pfurtscheller@tugraz.at.

of body movement (Buccino et al., 2001; Grafton, Arbib, Fadiga, & Rizzolatti, 1996). This finding seems interesting given the proposed homology of Broca's area with monkey area F5 (Rizzolatti & Arbib, 1998). In addition, studies of event-related magnetic fields have demonstrated a special temporal sequence of brain activations during the observation of a precision grip. This sequence begins in the occipital cortex, projects to the inferior parietal lobule and to Broca's area, and finally reaches the motor cortex. Altogether these findings suggest a shared motor representation between the cortical processes underlying movement observation and execution, in line with the concept of a system coupling perception with motor production (Decety & Grezes, 1999).

Results of human electrophysiological recordings showed that the rhythmic activities of primary sensorimotor areas, specifically the beta (~20 Hz) and mu (~10 Hz) rhythms, exhibit modulations by observation of experimental hand grasp (Cochin, Barthelemy, Lejeune, Roux, & Martimeau, 1998; Muthukumaraswamy et al., 2004). Additionally, these results contribute to the assumption that the neural substrates that generate these rhythms play a functional role in the human mirror neuron system (Muthukumaraswamy, Johnson, & McNair, 2004; Hari et al., 1998; Gastaut & Bert, 1954).

It is well established that activation of sensorimotor areas is accompanied by characteristic response patterns of central mu and beta rhythms in the EEG, either in the form of an event-related desynchronization (ERD) or event-related synchronization (ERS; Pfurtscheller & Lopes da Silva, 1999; Neuper & Pfurtscheller, 2001). Under consideration of prior findings in movement execution (Pfurtscheller & Neuper, 1994) it is of special interest if motor involvement in viewing a moving object can be found by studying event-related changes of central mu and beta rhythms.

In the present study, we compared visual processing of a moving body part (i.e., hand) and of a moving geometrical object (i.e., cube) with static baseline conditions that used pictures taken from the corresponding stimulus material. Virtual reality (VR) technology together with a head mounted display (HMD) were used to guarantee a realistic and controllable visual stimulus presentation. The goal of this paper was to investigate whether there are differential effects on brain oscillations in the alpha and beta band as a function of viewing either a static or moving object, and whether these effects depend on the object viewed (i.e., hand versus cube). In particular, we expected a higher involvement of motor processing in the brain when the subject observes a moving body part compared with a geometric object.

2 Material and Methods

2.1 Experimental Setup

For this study the Graz-BCI (Pfurtscheller & Neuper, 2001; Guger et al., 2001; Scherer, Schlögl, Müller-Putz, Pfurtscheller, 2004) and the augmented reality framework called Studierstube (Schmalstieg et al., 2001) were combined. The BCI was used as an acquisition system for EEG signals, and for the timing of the experimental protocol (by sending commands to the VR system which in turn generated the static on moving objects). The communication between the equipment was realized by using a network connection and the user datagram protocol (UDP). The resulting system is shown in Figure 1.

The Graz-BCI is based on Matlab (MathWorks, Inc., Natick, MA, USA) and works on standard personal computers and laptops with DAQ-hardware (National Instruments Corporation, Austin, TX, USA) running a Microsoft Windows operating system (Microsoft Corporation, Redmond, WA, USA).

The Studierstube framework runs on a standard personal computer with the Debian Linux operating system (Public Interest Inc., Indianapolis, IN, USA). The ATI Radeon 9700 graphic card (ATI Technologies Inc., Ontario, Canada) combined with the Virtual Research V8 (Virtual Research Systems Inc., Aptos, CA, USA) HMD were used for 3D stereoscopic visualization. The HMD had a resolution of 640 × 480 pixels and a refresh rate of 60 Hz. For rendering the image the Coin graphics library (Systems in Motion, Oslo, Norway) based on OpenGL, was used.

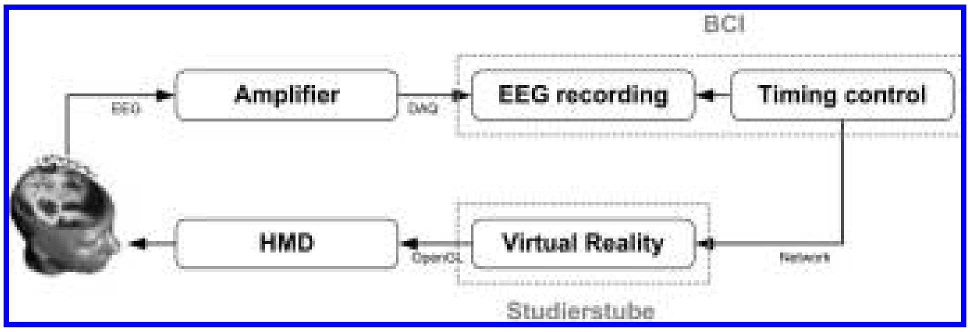

Figure 1. *BCI-VR system: Data acquisition with the Graz-BCI system and visual object presentation with the Studierstube-VR system.*

2.2 Modeling 3D Objects

The 3D modeling software Maya (Autodesk, Inc., San Rafael, CA, USA) was used for the generation of the 3D objects and the OpenInventor file format (Silicon Graphics, Mountain View, CA, USA) for the data interchange to the VR system.

Realistic models of a right hand and a single-colored cube were created. The hand performed a finger extension (hand open) and flexion (hand closed). To create some variation in the stimulus material, three different positions of the hand were chosen (side view, top view, and bottom view). The color of the cube was painted in the same color as that of the hand. Due to spatial distortions of pixels in the border area of the HMD (lens), the objects were presented from a keyhole point of view (see Figure 2).

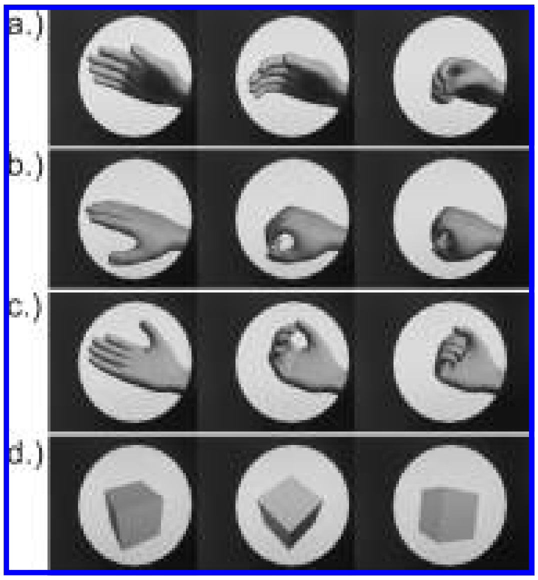

Figure 2. *Motion sequence of the right hand with three different points of view (a–c) and of the cube (d).*

2.3 Experimental Paradigm

The experiment included four experimental conditions: (i) static hand, (ii) dynamic hand, (iii) static cube, and (iv) dynamic cube. According to a predefined repetitive time-scheme, each of the four conditions were presented to the subjects via the HMD. The duration of each trial was 8 s (see Figure 3). The object was displayed from second 2 to second 7. The initial position of the object was chosen randomly. The period of motion for the dynamic conditions was from second 4 to second 7. The cube rotated in a randomly selected direction at a randomly selected speed. The hand performed an open-close cycle twice. In order to avoid adaptation, an inter-trial interval with a randomly selected duration of up to 2 s was added between the trials.

Each condition was presented nine times within one run. The different points of view of the hand were uniformly distributed. The order of appearance of the classes was selected randomly. Six runs were performed for each subject.

2.4 Subjects, Data Acquisition, and Signal Processing

Nine healthy student volunteers (mean age 26 ± 3 yr) took part in the experiment. All subjects were right-handed and had no history of neurological disease.

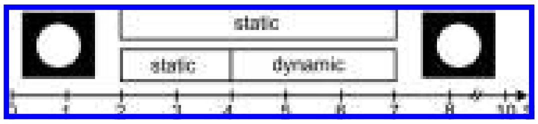

Figure 3. *Timing of the paradigm.*

The subjects sat in a comfortable armchair and were instructed to relax and to simply look at the presented objects. Four bipolar channels were recorded. The electrodes were placed 3.5 cm anterior and posterior to the positions C3, Cz, and C4 and lateral to the position Oz (i.e., position O1 and O2). Electrode positions are labeled according to the international 10/20 system. The channels are further named C3, Cz, C4, and Oz. Position AF3 was used as ground electrode. The EEG was amplified (Guger Technologies, Graz, Austria), analog bandpass filtered between 0.5 and 30 Hz, and sampled at 125 Hz.

In order to display band power changes during object observation, ERD/ERS maps were calculated for each EEG channel. ERD/ERS maps provide plots of significant ERD and ERS in predefined frequency bands within the entire frequency range of interest. For one map, 2 Hz frequency bands with 1 Hz overlap in the range between 6 and 40 Hz were calculated. The band power in each time frequency segment was compared to the mean band power in the reference interval (0.5–1.5 s). The reference interval corresponded to the idling phase of the paradigm (see Figure 3). Confidence intervals for the ERD/ERS values were calculated by the t-percentile bootstrap algorithm with a significance of $\alpha = 0.01$. An ERD/ERS value was considered significant when both confidence intervals showed the same sign. Only significant values are displayed in ERD/ERS maps. A more detailed description of the calculation of ERD/ERS maps can be found elsewhere (Graimann, Huggins, Leyine, & Pfurtscheller, 2002).

2.5 Statistical Analysis

The main purpose of the statistical analysis was to compare the beta ERD of the four experimental conditions (hand static, hand dynamic, cube static, and cube dynamic). For this, the average percentage band power (i.e., 16–24 Hz) obtained from channels C3, C4, and Oz were aggregated over a 1-s time window from second 5 to 6 (see Figure 3). A three way repeated measures ANOVA with the factors CONDITION (hand vs. cube), MODALITY (static vs. dynamic) and REGION (central vs. occipital) was performed. Interactions were studied in detail by the Newman-Keuls posttest.

3 Results

3.1 Statistical Analysis

Significant results were found for the main effects CONDITION ($F(1.8) = 7.8831$; $p = .0229$), MODALITY ($F(1.8) = 8.7037$; $p = .0184$) and REGION ($F(1.8) = 16.371$; $p = .0037$) as well as for the interactions MODALITY × REGION ($F(1.8) = 6.1218$; $p = .03846$) and CONDITION × MODALITY × REGION ($F(1.8) = 9.1987$; $p = .0162$). Inspection of the respective means shows that the visual presentation of a hand resulted in a stronger ERD (mean = –30.13) than the presentation of a cube (mean = –19.55). Moreover, dynamic object presentation resulted in higher ERD (mean = –30.74) than static presentation (mean = –18.95). Overall, ERD was significantly higher at occipital (mean = –35.12) than at central recording sites (mean = –14.57).

Post hoc comparisons of the significant two-way interaction MODALITY × REGION showed that, at the occipital brain region, dynamic objects yielded significantly higher ERD (mean = –43.42) than static objects (mean = –26.82), whereas no differences between static and dynamic objects were found for the central electrodes. Taking into account the factor CONDITION, however, there was a significant difference in the central region between static and dynamic presentation of the hand (see Figure 4), but no significant MODALITY difference with respect to the cube.

3.2 Time-Frequency Maps

Seven out of nine subjects displayed desynchronization patterns in the alpha and beta bands. Figure 5 illus-

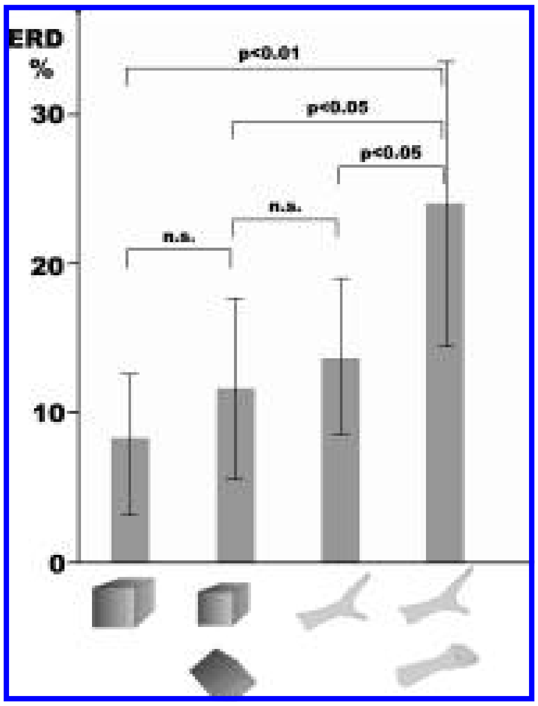

Figure 4. *Mean ERD ± SD over central regions for different conditions and modalities.*

trates characteristic results from one of these subjects obtained from channel C3. For all four viewed objects a strong alpha band ERD can be seen, but only during observation of hand movement (dynamic hand) a beta ERD is present. This indicates that in contrast to observation of a static object (hand or cube), observation of a moving hand induced a stronger beta desynchronization in the hand representation area.

In two out of nine subjects, however, observation of static or dynamic objects resulted in a synchronization of the hand area mu rhythm. This mu ERS was found during observation of a static or dynamic cube and was strongest, surprisingly, during observation of hand movement (see Figure 6).

Of interest is the strong alpha band ERD in all four conditions, not only in channel C3 but also in the other channels (not shown in Figures 5 and 6) including the channel Oz. This can be the result of the anterior-posterior recordings with relatively large interelectrode distances over the centro-parietal area.

4 Discussion

The results agree with the findings of Cochin et al. (1998) that observation of hand movement results in a desynchronization of mu and central beta rhythms, similar to that found during the execution of hand movement. A decrease of the mu rhythm amplitude during observation of an object-directed grasp was also reported by Muthukumaraswamy et al. (2004). This mu attenuation was similar in magnitude when the subject observed the experimenter's precision grip of a manipulation with the self-paced execution of the grip, but was clearly smaller during observation of a flat (static) hand. This means that observation of a moving hand results in a larger desynchronization of central rhythms than observation of a static hand, which corresponds with our findings.

Of interest is that the presentation of a cube had smaller effects on sensorimotor rhythms than the presentation of a hand. In this respect the work of Altschuler et al. (2000) has to be mentioned. They found a blocking of mu waves only with observation of a person moving but not with observation of an equivalent movement of an inanimate object (a ping-pong ball going up and down). Also, Cochin et al. (1998) reported a larger mu and beta power decrease during observation of a moving person compared to observation of flowing water.

Our results concur with the important work of Rizzolatti et al. (2001). The neuro-physiological mechanism underlying the understanding of imitation of movement can be seen in the mirror neuron system as a particular class of visuomotor neurons, originally discovered in the premotor cortex of a monkey. They hypothesized that the mirror neuron system maps the visual representation of the observed movement onto the motor cortex representation of the same movement. A similar activation pattern at the cortical level is therefore expected in the case of hand movement observation and hand movement execution.

In contrast to the expected EEG desynchronization pattern found in the majority of subjects, two subjects displayed the opposite, namely the synchronization of Rolandic mu rhythms. This mu ERS was present in all

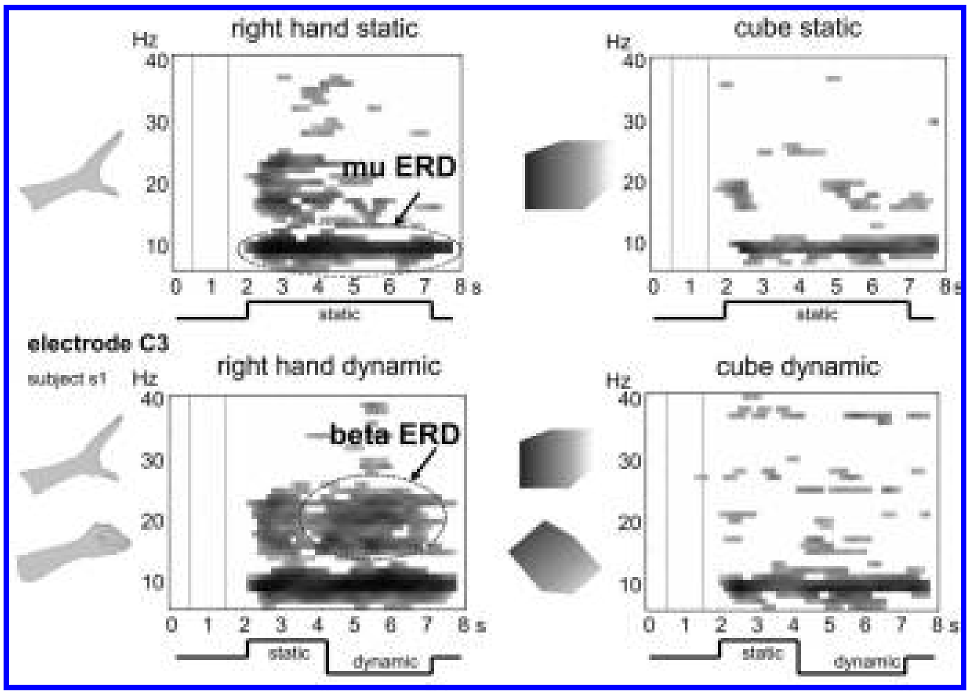

Figure 5. *ERD/ERS time-frequency maps (6–40 Hz, 0–8 s) from bipolar recording over left cortical hand representation area of subject S1. A significant ERD in the alpha band in all four conditions is visible, along with an initial beta ERD during static and dynamic hand presentation and a further beta ERD only during observation of hand movement.*

conditions except observation of static hand. Whether an explanation of this mu synchronization during objects' observation is an intermodal interaction between motor and visual systems termed "focal ERD/surround ERS" (Suffczynski, Pijn, Pfurtscheller, & Lopes da Silva, 1999) can only be speculated. When the motor area is not involved in a task, either directly by execution of a motor act or indirectly by observation of, for example, a cube movement, the motor cortex neurons may be in a deactivated (inhibited) state, characterized by mu rhythm synchronization. Such a synchronization of the hand area mu rhythm during visual processing was reported by Koshino and Niedermeyer (1975) and Pfurtscheller (1992).

In summary it can be stated that viewing of a hand movement resulted in a desynchronization of cortical sensorimotor rhythms in the majority of subjects. This can be explained as a human correlate of the activation of the mirror neuron system which is in line with several prior studies on action observation (Rossi et al., 2002; Muthukumaraswamy et al., 2004). In a minority of subjects no significant response of the central beta rhythm could be found, but in these cases the mu rhythm displayed synchronization during observation of cube and hand movement. The effect of viewing an object on bioelectrical brain activity depends on the type of object and is greater with the observation of action of different body parts than with the observation of non-body part movements.

5 Conclusion

Although the perception and elaboration of actions in reality results in a more specific cortical activation (Perani et al., 2001) compared to virtual reality (VR), the latter provides an excellent tool to study procedures that might be applied subsequently in reality.

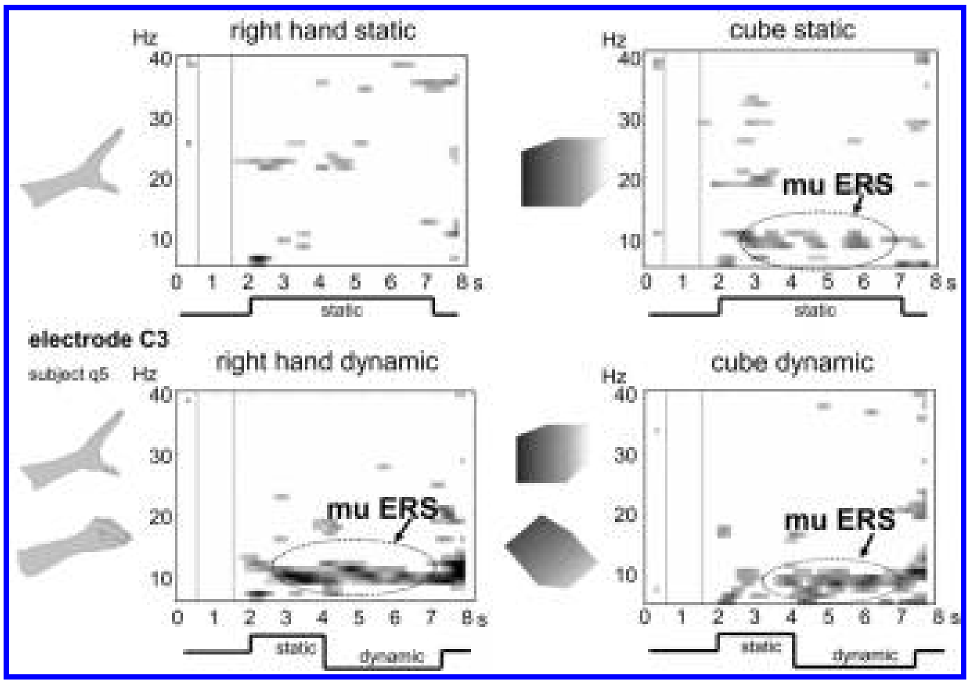

Figure 6. *ERD/ERS time-frequency maps (6–40 Hz, 0–8 s) of subject Q5. A mu rhythm synchronization (mu ERS) is present during all viewing tasks, except observation of a static hand.*

So, for example, patients with an amputated limb can learn to control their movement by using a VR-correlate, before the electromechanical device is built. Another important application of VR is to enhance rehabilitation after stroke. In this case VR is used to give feedback about motor task performance and enhance the motivation to endure (Holden, 2005). VR enhanced patient motivation is the key to recovery. If, for example, the EEG is used as input signal to a BCI system that controls neurofeedback (e.g., in stroke patients), it is important to realize that observation of real or artificial moving body parts can have a strong impact on sensorimotor oscillations and can interfere with, for example, motor imagery.

Acknowledgments

This work is supported by the “Fonds zur Föderung der wissenschaftlichen Forschung” in Austria, project 16326-BO2 and funded in part by the European Union research project PRESENCCIA IST-2006-27731.

References

Altschuller, E. L., Vankov, A., Hubbard, E. M., Roberts, E., Ramachandran, V. S., & Pineda, J. A. (2000). Mu wave blocking by observation of movement and its possible use as a tool to study theory of other minds. *Society of Neuroscience Abstracts, 26,* 68.

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Galese, V., et al. (2001). Action observation activates premotor and parietal areas in somatotopic manner: An fMRI study. *European Journal of Neuroscience, 13,* 400–404.

Cochin, S., Barthelemy, C., Lejeune, B., Roux, S., & Martineau, J. (1998). Perception of motion and EEG activity in human adults. *Electroencephalography and Clinical Neurophysiology, 107,* 287–295.

Decety, J., & Grezes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cognitive Science, 3*(5), 172–178.

Egner, T., Zech, T. F., & Gruzelier, J. H. (2004). The effects of neurofeedback training on the spectral topography of the electroencephalogram. *Clinical Neurophysiology, 115*(11), 2452–2460.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996).

Action recognition in the premotor cortex. *Brain*, *119*(2), 593–609.

Gangitano, M., Mottaghy, F. M., & Pascual-Leone, A. (2001). Phase-specific modulation of cortical motor output during movement observation. *NeuroReport, 12,* 1489–1492.

Gastaut, H. J., & Bert, J. (1954). EEG changes during cinematographic presentation. *Electroencephalography and Clinical Neurophysiology, 6,* 433–444.

Grafton, S. T., Arbib, M. A., Fadiga, L., & Rizzolatti, G. (1996). Localization of grasp representations in humans by positron emission tomography: Observation compared with imagination. *Experimental Brain Research, 112,* 103–111.

Graimann, B., Huggins, J. E., Levine, S. P., & Pfurtscheller, G. (2002). Visualization of significant ERD/ERS patterns in multichannel EEG and ECoG data. *Clinical Neurophysiology, 113*(1), 43–47.

Guger, C., Schlögl, A., Neuper, C., Walterspacher, D., Strein, T., & Pfurtscheller, G. (2001). Rapid prototyping of an EEG-based brain-computer interface (BCI). *IEEE Transactions of Neural Systems Rehabilitation Engineering, 9*(1), 49–58.

Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., & Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: A neuromagnetic study. *Proceedings of the National Academy of Science USA, 95,* 15061–15065.

Holden, M. K. (2005). Virtual environments for motor rehabilitation: Review. *Cyberpsychology Behavior, 8*(3), 187–211.

Koshino, Y. D., & Niedermeyer, E. (1975). Enhancement of rolandic mu-rhythm by pattern vision. *Electroencephalography and Clinical Neurophysiology, 38,* 535–538.

Muthukumaraswamy, S. D., Johnson, B. W., & McNair, N. A. (2004). Mu rhythm modulation during observation of an object-directed grasp. *Brain Research Cognitive Brain Research, 19*(2), 195–201.

Neuper, C., & Pfurtscheller, G. (2001). Evidence for distinct beta resonance frequencies in human EEG related to specific sensorimotor cortical areas. *Clinical Neurophysiology, 112,* 2084–2097.

Perani, D., Fazio, F., Borghese, N. A., Tettamanti, M., Ferrari, S., Decety, J., et al. (2001). Different brain correlates for watching real and virtual hand actions. *Neuroimage, 14*(3), 749–758.

Pfurtscheller, G. (1992). Event-related synchronization (ERS): An electrophysiological correlate of cortical areas at rest. *Electroencephalography and Clinical Neurophysiology, 83,* 62–69.

Pfurtscheller, G., & Lopes da Silva, F. H. (Eds.). (1999). *Event-related desynchronization. Handbook of electroencephalography and clinical neurophysiology* (Rev. ed., Vol. 6). Amsterdam: Elsevier.

Pfurtscheller, G., & Neuper, C. (1994). Event-related synchronization of mu-rhythm in the EEG over the cortical hand area in man. *Neuroscience, Letters, 174,* 93–96.

Pfurtscheller, G., & Neuper, C. (2001). Motor imagery and direct brain-computer communication. *Proceedings of the IEEE, 89*(7), 1123–1134.

Rizzolatti, G., Fadiga, L., Matelli, M., Bettinardi, V., Paulesu, E., Perani, D., et al. (1996). Localization of grasp representations in humans by PET: 1. Observation versus execution. *Experimental Brain Research, 111*(2), 246–252.

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neuroscience, 21,* 188194.

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *National Review of Neuroscience, 2,* 661–670.

Rossi, S., Tecchio, F., Pasqualetti, P., Ulivelli, M., Pizzella, V., Romani, G. L., et al. (2002). Somatosensory processing during movement observation in humans. *Clinical Neurophysiology, 113,* 16–24.

Scherer, R., Schlögl, A., Müller-Putz, G. R., & Pfurtscheller, G. (2004). Inside the GrazBCI: rtsBCI. In *Biomedizinische Technik: 2nd International BCI Workshop and Training Course, 49*(1), 81–82.

Schmalstieg, D., Fuhrmann, A., Hesina, G., Szalavari, Z. S., Encarnao, L. M., Gervautz, M., et al. (2001). The Studierstube Augmented Reality Project. *Presence: Teleoperators and Virtual Environments, 11*(1), 32–54.

Strafella, A. P., & Paus, T. (2000). Modulation of cortical excitability during action observation: A transcranial magnetic stimulation study. *NeuroReport, 11*(10), 2289–2291.

Suffczynski, P., Pijn, J. M. P., Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related dynamics of alpha band rhythms: A neuronal network model of focal ERD/surround ERS. In G. Pfurtscheller, F. H. Lopes da Silva (Eds.), *Event-related desynchronization and related oscillatory phenomena of the brain. Handbook of electroencephalography and clinical neurophysiology* (Rev. ed., Vol. 6) (pp. 6785). Amsterdam: Elsevier.

Wolpaw, J. R., Birbaumer, N., McFarland, D. J., Pfurtscheller, G., & Vaughan, T. M. (2002). Brain-computer interfaces for communication and control. *Clinical Neurophysiology, 113,* 767–791.