International Journal of Psychophysiology 91 (2014) 10–15

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Mobile EEG and its potential to promote the theory and application of imagery-based motor rehabilitation

Cornelia Kranczioch [a,b], Catharina Zich [a], Irina Schierholz [a], Annette Sterr [c,*]

[a] Neuropsychology Lab, Department of Psychology, European Medical School, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany
[b] Neurosensory Science Research Group, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany
[c] Brain and Behavior Research Group, School of Psychology, University of Surrey, Guildford, UK

ARTICLE INFO

Article history:
Received 23 August 2013
Received in revised form 8 October 2013
Accepted 10 October 2013
Available online 18 October 2013

Keywords:
Mobile EEG
Wireless EEG
MI
Motor imagery
Neurofeedback
Neurological rehabilitation
BCI
Brain computer interface

ABSTRACT

Studying the brain in its natural state remains a major challenge for neuroscience. Solving this challenge would not only enable the refinement of cognitive theory, but also provide a better understanding of cognitive function in the type of complex and unpredictable situations that constitute daily life, and which are often disturbed in clinical populations. With mobile EEG, researchers now have access to a tool that can help address these issues. In this paper we present an overview of technical advancements in mobile EEG systems and associated analysis tools, and explore the benefits of this new technology. Using the example of motor imagery (MI) we will examine the translational potential of MI-based neurofeedback training for neurological rehabilitation and applied research.

1. Introduction

Understanding human behavior is one of the big challenges for humankind. In the last 20 years neuroscience has emerged as a key area of research and there is a recognition that understanding brain function in general, and brain–behavior relationships in particular, is vital to advance solutions for major public health issues such as mental health, dementia, obesity, or impairments remaining after suffering from stroke or traumatic brain injury. Immense improvements in the availability of neuroimaging methodologies together with high-profile initiatives, such as the decade of the brain, have brought a wealth of new insights into brain function and are already leading to new forms of treatment. However, a major challenge still is to understand the brain in its natural state. This would not only enable the refinement of cognitive theory but also to get a true understanding of cognitive function in the type of complex and unpredictable situations that constitute daily life. For example, how does our brain enable us to function in a highly complex situation such as navigating through a grocery shop while selecting products from a vast range of goods? How are these processes influenced by internal physiological states such as hunger or low mood? How does our brain help us to prioritize some actions and inhibit others? What are the brain correlates of impaired, challenging or maladaptive behavior expressed in typical life situations? These are of course hugely demanding questions, which cannot be easily answered. Yet with the mobile electroencephalogram (EEG), researchers now have a tool to explore these questions. In contrast to all other techniques presently available, mobile EEG truly allows us to take neuroscience into the field and study everyday brain function.

In this paper we will examine the benefits of mobile EEG and the challenges it has to meet to provide a fully fledged research tool in cognitive and clinical neuroscience, as well as a tool for clinical interventions and BCIs. We will exemplarily show how the technical challenges involved in mobile EEG have been addressed by recent advancements in the field. The focus will then be shifted to yet another opportunity associated with mobile EEG, which is the support of brain computer interface (BCI) based treatment delivery in the home environment. This will be done through the example of motor imagery (MI).

2. Why do we need mobile EEG?

EEG studies are typically conducted in a laboratory, and many arguments can be found in favor of this practice. For example, the environment is controlled and recording conditions are kept consistent across subjects. Laboratories are often electrically shielded and noise attenuated to reduce factors that may negatively affect data quality such as line noise. Moreover, the laboratory set-up allows for full control

* Corresponding author at: Lewis Carroll Building, School of Psychology, University of Surrey, Guildford GU2 7XH, UK. Tel.: +44 1483 682883; fax: +44 1483 682914.
E-mail address: a.sterr@surrey.ac.uk (A. Sterr).

0167-8760/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpsycho.2013.10.004

of the amount and type of information a participant is exposed to at any time of the experiment. In addition, participants are typically asked to keep their heads still and relax their jaws and necks so as to avoid contamination of the EEG by muscle artifacts. Even more serious sources of artifacts are eye movements and blinks. To avoid those, participants are normally asked to fix their eyes on a particular point on the screen and, in many cases, also to blink only during specified periods in the trial (also called blink holidays). All these characteristics are designed to instigate methodological rigor. However, the methodological strength of the laboratory-based approach comes at the expense of ecological validity.

This drawback has been recognized in the research community, and let for instance to the development of what has become known as the mobile brain/body imaging (MoBI) approach. The MoBI approach is motivated by the ambition to understand brain activity supporting embodied human cognition, i.e. cognition linked to our own motor behavior and that of other individuals (e.g. Makeig et al., 2009, for a recent review see Gramann et al., 2011). In MoBI, brain and body dynamics are recorded simultaneously by combining high-density scalp EEG and motion capture. The EEG setup works with standard amplifiers, which are fixed somewhere above the participants' head. The participant walks on a treadmill while solving cognitive tasks. Research has shown that it is possible to record good-quality cognitive ERPs with the original MoBI (e.g. Gramann et al., 2010) and with variations of the original setup (De Sanctis et al., 2012). However, while certainly being a large step forward, due to its reliance on traditional EEG hardware the mobility of MoBI is still strongly limited, and it therefore cannot solve the problem of ecological validity satisfactorily.

Without doubt, laboratory studies on the neural correlates of human behavior have revealed many hugely important insights. However, the laboratory setting is far removed from natural behavior, and does not adequately reflect the complexity of information processing required for a person to function ‘normally’ in everyday life. For instance, tasks are typically investigated in isolation, and without the distractors a person would have to deal with in the real world, such as environmental background noise. In addition, cognition and behavior are studied while seated or at least when being more or less ‘stationary’, rather than moving around. Laboratory studies therefore strongly limit the de facto simultaneity of cognitive processes and, and critically, the need to perform actions/having to respond with complex actions. Data acquired in laboratory settings therefore limit our understanding of how the brain controls cognitive processes and behavior to situations that are not representative of the complex information processing associated with natural behavior. The latter not only leaves a gap in knowledge, but also hinders the development of cognitive theory reflecting the association of brain function and behavior more realistically. Thus, unless we are able to move outside the laboratory and study the brain during natural behavior, theory development is bound to be ‘circular’ in the sense that theories derived from laboratory research are likely be confirmed when tested in yet another laboratory study.

The current advancements in the ability to record and make use of EEG signals outside the laboratory are technically fascinating, and they will certainly be followed with great interest by those inspired by the idea that computers can be controlled through thought. But the relevance of the technical advancements in mobile EEG goes far beyond technical fascination as it allows for the first time to study how the brain processes makes use and responds to complex information and situations, and hence to derive a noninvasive neural marker of natural behavior in humans. Moreover, mobile EEG will also greatly extend the range of EEG-based therapeutic applications, and the availability of high-quality BCIs, as it allows the provision of these methods outside specialized clinical or laboratory settings. Because of the comparatively low costs of EEG systems and the relative ease of application, such BCIs could also be used to establish home-based therapeutic interventions that require regular training over a long period of time but that, to a certain degree, can be run by patients themselves. We will return to this aspect of mobile EEG later in this paper. But before doing so we will present a short overview of the most prominent systems presently available on the market and detailed discussion of current advancements in the use of mobile EEG in cognitive neuroscience.

3. Mobile EEG systems and current advancements

Mobile EEG systems have been available for a number of years now. But which requirements shall a true mobile EEG system fulfill? Obviously mobile EEG systems should allow natural body movements, which imply the use of non-stationary EEG systems that are ideally fully head-mounted. Systems therefore should be small, lightweight and transmit data wirelessly. Moreover a head-mounted cap-amplifier design ensures minimal isolated movements of individual electrodes, cables or the amplifier, which minimizes disturbances of EEG by electromagnetic interference and therewith dramatically improve EEG signal quality. Furthermore mobile EEG systems should first consist of a sufficient number of electrodes to enable spatial filter based artifact attenuation (Makeig et al., 2009) and allow flexible placement of these electrodes so that the same EEG system can be applied to different research questions. One possible way to increase the applicability of mobile EEG systems even more, which is especially important for EEG based BCIs, is the use of dry electrodes which require no conductive gel. However, since hardly any study has shown a comparable signal quality between dry and wet electrodes, especially not during gross body movements as walking, dry electrodes are not as common as one might expect.

Over the years, the devices develop rapidly, which not only means that they are becoming easier and faster to apply, but also that they become less costly and thus increasingly accessible. Most of the systems currently available are commercial systems designed for the gaming or advertising industry, or marketing research. Only a few devices are obtainable that were specifically designed for neuroscience research.

One of the first devices able to record brain activity in a mobile wireless mode was the MindWave (Neurosky Inc., San Jose, CA, www.neurosky.com). The device consists of a single EEG sensor comprising a dry electrode, which makes the MindSet easy and fast to apply. The downside is that the single sensor can only be placed on the forehead, making the system very inflexible and limited in its application. Power for the device is supplied by an AAA battery, which, according to the manufacturer, allows a nonstop 10-hour recording. The system provides the raw EEG data and information about the frequency content of the EEG. The additionally available software eSense claims to visualize current levels of attention and meditation, which are supposed to be usable for controlling devices (www.neurosky.com).

Another low-cost pocket-sized device has been developed by Avatar EEG Solutions Inc (Avatar EEG solutions Inc., Calgary, Canada, www.avatareeg.com). The system comes without electrodes but features eight channels, which can be configured in several different bipolar or monopolar montages, and which therefore allow to record EEG as well as electrooculogram (EOG), (electromyogram) EMG or electrocardiogram (ECG). The system supports various electrode types such as surface electrodes, intracranial and subdural electrodes. It is light and small ($76 \times 53 \times 38$ mm; 60 g). The power is provided by two rechargeable AA lithium batteries, which should suffice for 24 hours of continuous recordings. The collected data can either be viewed in real-time on a smart phone over a maximal distance of 30 m, or they can be written to a removable onboard Micro SD card (8 GB–32 GB) for subsequent offline analysis. The developers highlight the system's low energy consumption and variable electrode configurations. They see applications for their system primarily in sleep research, but also in ambulatory neuroscience studies.

The system Enobio (Neuroelectrics, Barcelona, Spain, http://neuroelectrics.com/enobio) offers the possibility to record between