International Journal of Psychophysiology 91 (2014) 54–66

Contents lists available at ScienceDirect

International Journal of Psychophysiology

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

Smartphones as pocketable labs: Visions for mobile brain imaging and neurofeedback

Arkadiusz Stopczynski *, Carsten Stahlhut, Michael Kai Petersen, Jakob Eg Larsen, Camilla Falk Jensen, Marieta Georgieva Ivanova, Tobias S. Andersen, Lars Kai Hansen

Technical University of Denmark, Department of Applied Mathematics and Computer Science, Section for Cognitive Systems, Building 303B, DK-2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 10 May 2013
Received in revised form 24 July 2013
Accepted 12 August 2013
Available online 29 August 2013

Keywords:
Mobile sensor
Real-time
EEG
Neuroimaging
Source reconstruction
Brain monitoring
Brain-computer interface

ABSTRACT

Mobile brain imaging solutions, such as the *Smartphone Brain Scanner*, which combines low cost wireless EEG sensors with open source software for real-time neuroimaging, may transform neuroscience experimental paradigms. Normally subject to the physical constraints in labs, neuroscience experimental paradigms can be transformed into dynamic environments allowing for the capturing of brain signals in everyday contexts. Using smartphones or tablets to access text or images may enable experimental design capable of tracing emotional responses when shopping or consuming media, incorporating sensorimotor responses reflecting our actions into brain machine interfaces, and facilitating neurofeedback training over extended periods. Even though the quality of consumer neuroheadsets is still lower than laboratory equipment and susceptible to environmental noise, we show that mobile neuroimaging solutions, like the *Smartphone Brain Scanner*, complemented by 3D reconstruction or source separation techniques may support a range of neuroimaging applications and thus become a valuable addition to high-end neuroimaging solutions.

1. Introduction

Only recently have wireless neuroheadsets, capable of capturing changing electrical potentials from brain activity through electrodes placed on the scalp using Electroencephalography (EEG), made mobile brain imaging a reality. The emergence of low-cost EEG sensors and the increasing computational power of smartphones may transform neuroimaging from constrained laboratory settings to experimental paradigms, allowing us to model mental state in an everyday context. This presents a paradigm shift, making it possible to design new types of experiments that characterize brain states during natural interaction over extended periods of time. Until recently most neuroimaging experiments have been performed with subjects who are at rest, under the assumption that the brain responses being measured will not be influenced by subjects sitting or laying down. However, this may be inaccurate, as animal studies using mice indicate that neurons in the visual cortex double their visually evoked firing rates if they run on a treadmill rather than stand still (Niel and Stryker, 2010). Since the discovery of parietal–frontal circuits of mirror neurones, which fire both when we grasp an object and when we observe others doing the same (Pellegrino et al., 1992; Gallese et al., 1996), the sensorimotor system can no longer be considered as only involved with motion. Consequently, these mechanisms should rather be understood as forming an integral part of cognition, allowing us to generalize the goals of actions based on motor representations in the brain (Rizzolati and Sinigaglia, 2010).

While there is already significant literature concerned with dynamic brain states during natural complex stimuli in conventional laboratory experiments (see e.g., Hasson et al., 2004; Bartels and Zeki, 2004; Dmochowski et al., 2012), there has been a growing call to design studies that relax the constraints of the lab and widen the focus to map out how we perceive our surroundings under naturalistic conditions (Makeig et al., 2009). For example, natural motion has been incorporated into laboratory experiments using tools such as the MoBi Lab Matlab plugin (2009) in order to correlate motion capture data of moving limbs with the brain responses being triggered (Gramann et al., 2011). Even adding a few degrees of freedom may provide an understanding of how cortical responses differ by simply changing posture (Slobounov et al., 2008), either by measuring how theta brainwave activity is attenuated in sleepy subjects once they stand up (Caldwell et al., 2003), or by analyzing the modulation in spectral power within alpha and beta brainwaves appearing when one foot hits the ground and the other foot is lifted, as subjects are no longer transfixed on a chair in front of a computer screen (Gwin et al., 2011). This provides a foundation for extending standard EEG paradigms, such as the P300 event-related potential, to measure how we consciously perceive visual objects when participants are no longer required to sit motionless but are able to walk on a belt during the experiment (Gramann et al., 2010). It also makes it

---

* Corresponding author. Tel.: +45 45253899.
E-mail addresses: arks@dtu.dk (A. Stopczynski), csta@dtu.dk (C. Stahlhut), mkai@dtu.dk (M.K. Petersen), jaeg@dtu.dk (J.E. Larsen), cbfj@dtu.dk (C.F. Jensen), mgiv@dtu.dk (M.G. Ivanova), toban@dtu.dk (T.S. Andersen), lkai@dtu.dk (L.K. Hansen).

0167-8760/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpsycho.2013.08.007

possible to eventually move a P300 experiment outside the lab, as has recently been demonstrated by Debener and colleagues (2012) by combining the wireless hardware from a consumer neuroheadset[1] with standard EEG cap electrodes[2] and using a laptop to record the cortical responses, thus providing a portable lab which can be stored in a backpack and easily carried by the subjects participating in the experiment.

Taking the idea of bringing EEG into the wild one step further, the *Smartphone Brain Scanner* (SBS2) open-source software project (http://github.com/SmartphoneBrainScanner) introduced in Stopczynski et al. (2011, 2013), makes it possible to build brain imaging applications for real-time 3D source reconstruction or neurofeedback training. By combining a wireless EEG cap with an Android smartphone or tablet, the SBS2 allows for presenting time-locked audiovisual stimuli such as text, images, or video, and it allows for capturing elicited neuroimaging responses on the mobile device, thereby transforming low-cost consumer hardware into a pocketable brain imaging lab. As the *Smartphone Brain Scanner* project potentially allows for designing novel types of brain imaging paradigms, we have initially validated the SBS2 framework in three experiments related to BCI motor control, embodied semantics, and neurofeeedback interfaces in order to illustrate the feasibility of capturing mental state in a mobile context. In the following sections we briefly review existing mobile EEG sensors, outline the architectural design of the *Smartphone Brain Scanner* system for real-time 3D reconstruction, describe aspects of source separation and spatial filtering in relation to mobile brain imaging, and give examples of applications built on top of the open-source software framework for mobile Android devices related to imagined finger tapping, emotional responses to text, and design of neurofeedback interfaces (Fig. 1).

2. Mobile EEG acquisition

A wide range of prototype electrode designs, suitable for mobile neuroimaging, are currently under development, based on MEMS microelectromechanical systems utilizing spring-loaded dry contact pins or hard carbon nanotubes that press against the scalp (Ruffini et al., 2008). For long-term EEG measurement without gel, another option is electrodes made from soft foam covered with conductive fabric (Lin et al., 2011), or new types of non-contact high input impedance sensors capable of capturing EEG signals on the basis of capacitive coupling (Chi et al., 2012), even when resting on top of several layers of hair. In contrast to gel-based EEG electrodes, dry contacts need no skin preparation, and can therefore more easily be utilized for neuroimaging as participants are able to put on a neuroheadset without any assistance. However, even though pin or nanotube contacts easily penetrate the hair and therefore offer more possibilities for placement than conductive foam-based sensors attached to the skin of the forehead, a spring-like setup may still be susceptible to noise when users move. Capacitive sensors provide an alternative for unobtrusive physiological monitoring, but require an integrated ultra-high impedance front-end for non-contact biopotential sensing (Chi et al., 2011). So-called Ear-EEG is a promising technology for long-term EEG data collection, offering improved comfort and esthetics (Looney et al., 2012). Benchmarks of prototype capacitive non-contact and mechanical sensors in an experiment related to decoding a steady state visual evoked potential in the 8–13 Hz frequency band showed only little signal degradation when compared to standard gel-based Ag/AgCl electrodes (Chi et al., 2012), showing that these novel sensors may, in longer term, provide the increased usability that may assure the transformation of neuroimaging from fixed laboratory setups to an everyday mobile context.

Fig. 1. SBS2 mobile EEG recording with real-time 3D source reconstruction, on an Android smartphone connected wirelessly to an Easycap 16 electrode setup based on Emotiv hardware.

Among existing commercial solutions, the ThinkGear module manufactured by NeuroSky[3] provides the foundation for several EEG consumer products which integrate a single dry electrode along with a reference and a ground attached to a headband. It provides A/D conversion and amplification of one EEG channel, is capable of capturing brain wave patterns in the 3–100 Hz frequency range, and records at 512 Hz sampling rate. Even a single-channel EEG setup, using a passive dry electrode, such as the NeuroSky, positioned at the forehead and a reference (typically an earlobe), may allow for measuring mental concentration and drowsiness by assessing the relative distribution of brainwave frequencies (Yasui, 2009). More comfortable neuroheadsets using conductive Ni/Cu covered polymer foam, such as Mindo[4], measure brain activity from the forehead on three EEG electrodes plus a reference channel attached to the earlobe. Integrating analog to digital conversion at 256 Hz sampling rate for acquisition of bandpass filtered signals in the 0.5–50 Hz range, the neuroheadset offers 23 h of battery life and wireless Bluetooth communication, and has been demonstrated in BCI brain machine interfaces used in games based on controlling the power of alpha brainwave activity (Liao et al., 2012). Other consumer neuroheadsets such as the Emotiv EEG, provide both wireless communication via a USB dongle and analog to digital conversion of 16 EEG channels (including reference and ground) at 128 Hz sampling rate while using moist felt-tipped sensors which press against the scalp with a simple spring-like design. Originally designed as a mental game controller capable of tracing emotional responses and facial expressions, the majority of electrodes are placed over the frontal cortex and have no midline positions (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4 with P3/P4 used as reference and ground). However, as mentioned earlier, Debener and colleagues (2012) recently demonstrated that it is possible to merge the wireless hardware from the Emotiv neuroheadset with high quality, conductive, gel-based electrodes in a standard EEG cap. Repackaging the electronics and battery into a small box (49 mm × 44 mm × 25 mm) which can be attached to the EEG cap and rewired through a connector plug to 16 sintered Ag/AgCl ring electrodes can occur, thus providing a fully customizable montage which allows the electrodes to be freely placed in the EEG cap according to the 10–20 international system (in the present

---

[1] http://www.emotiv.com.

[2] http://easycap.de/easycap.

[3] http://www.neurosky.com/Products/ThinkGearAM.aspx.

[4] http://www.mindo.com.tw/en/index.php.