1. Publishable summary

Brain-computer interfaces (BCIs) with Rapid Automated Interfaces for Nonexperts (BRAIN ICT-2007-224156) aimed to develop BCIs into practical assistive and information and communication technology (ICT) tools to enhance inclusion for a range of different disabled users. Many of these people would otherwise have little or no opportunity to interact with loved ones, carers, home appliances and assistive devices, or personal computer and internet technologies. To this end, BRAIN improved BCI reliability, flexibility, usability, and accessibility while minimizing dependence on outside help. These improvements entailed upgrades to all four components of a BCI system – signal acquisition, operating protocol, signal translation, and application. By incorporating existing, well established methods, combined with the strengths of a multidisciplinary consortium (three academic: University of Bremen, University of Ulster, University of Warsaw; three industrial: Philips Electronics Nederland, Telefonica I+D (TID), Twente Medical Systems International (TMSi); and the user expert: The Cedar Foundation), these goals were attainable.

The BRAIN project has delivered a number of scientific and technical advances as originally proposed in the description of work. Hardware and software components of a new practical BCI system have been developed and a fully integrated system is available. The components of BCI for which BRAIN has provided advances are: electrodes, cap, amplifier, signal processing, user interface, application and user testing. BRAIN has delivered advances in the development of a new water based EEG sensor, and the design of an easy to donned/doffed prototype cap. Figure 1 shows the final BRAIN acquisition system developed by TMSi that makes preparation much faster and easier, eliminating the need for unpleasant conductive gel or expert help. The **water electrodes** function for at least eight hours if regular tap water is applied. Unlike conventional electrodes, the new water system does not require abrading the skin, applying electrode gel, washing the cap, or shampooing the hair. This potentially promotes wider acceptance of the BCI technology. Tests have shown that the impedance of the water electrodes is even lower and DC characteristics are comparable or better than commercially available standard electrodes.

Figure 1 BRAIN acquisition system.

The water electrodes have been successfully integrated in a new and comfortable **head wrap** that is easy to use and reduces movement artefacts. The Mobita, a smaller more portable **amplifier** completes the BRAIN acquisition system. The Mobita was used for testing the water electrodes. This amplifier is equipped with a WLAN module and can handle 32 channels at 1000 Hz sampling frequency. The Mobita has been designed in full compliance with CE regulations.

BRAIN has developed automated **signal processing** software that identifies the best BCI parameters for each subject and customises the operating protocol accordingly. Two BCI approaches were explored: steady-state visual evoked potentials (SSVEP) and event-related desynchronization and synchronization (ERD/S). Signal processing activities undertaken in BRAIN have provided three SSVEP options and one ERD/S option. The option adopted by the University of Bremen uses an adaptive signal processing approach that continuously recalculates the spatial filter during BCI operation. For medium frequencies, four pre-selected frequencies may be used based on domain knowledge (population statistics). A classification window illustrates (on-line) performance, allowing operator tuning of frequency and classification threshold. The SSVEP approach used in BRAIN has been mainly to apply flickering frequencies in the high frequency range (>30 Hz) in order to diminish the stimulus annoyance and lower the risk for photo induced epilepsy. For those frequencies, a level of automation of these software components had been achieved using a **Wizard** approach, which can potentially optimise the selection of these parameters and hide the complexity of this process from the operator. In parallel, advanced SSVEP signal processing tools have been developed by Philips to enable detection of high frequency SSVEPs (HF-SSVEP) in the EEG. The first approach selected four best frequencies and then calculated the parameters of an individualized spatial filter that remained fixed during BCI operation. Selection of best frequencies and filter parameters has been achieved using the Wizard. Results have shown that selecting various stimulation frequencies is especially challenging in the high frequency range because only few of them can elicit sufficiently high SSVEPs for BCI purposes. Therefore, Philips had introduced an optimisation of the HF-SSVEP by using a dominant frequency, with variations of phase to represent commands. The phase-based SSVEP BCI was successfully tested using a 2D maze test application on a population of 28 participants, from which 11 were Cedar tenants (see Figure 2a). At this stage of evaluation, the phase-based BCI was not integrated into the Wizard, but the final version of the Wizard integrates all three SSVEP options.

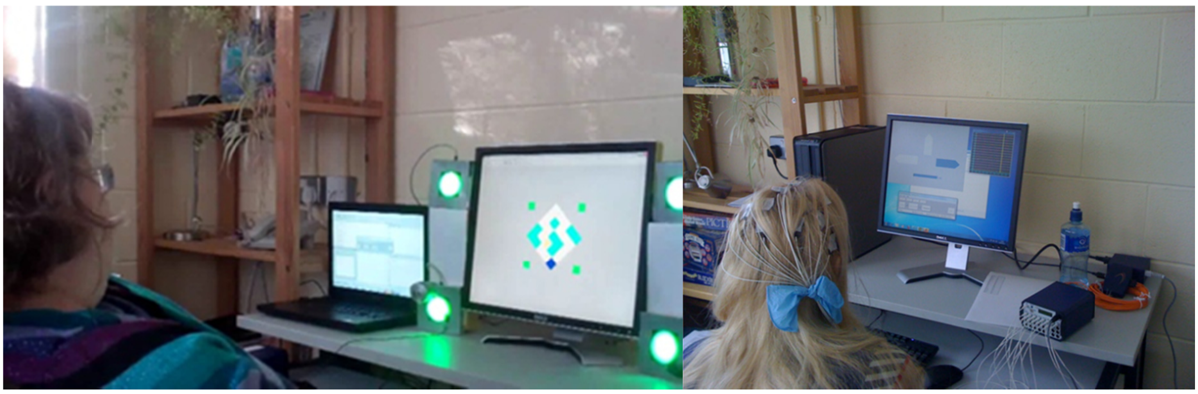

Figure 2 User testing in the community (a) High Frequency SSVEP phase-based testing and (b) ERD/S operation at Cedar Residential Home.

Advances in ERD/S signal processing has focused on improving signal translation. The University of Warsaw has developed a new mathematical approach and software to determine best individual frequency ranges, relevant electrode sites, spatial filters and relevant features to train a multinomial logistic regression classifier for the online detection of three different motor imagery classes (e.g., right hand, left hand, and feet). The University of Bremen has complemented the ERD/S solution with the BCI **trainer**, which consists of a training application that helps users to train motor imagery skills (see Figure 2b); and a maze application that demonstrates the usability of the signal processing algorithms in a real application. The BCI trainer testing was carried out at the University of Bremen on 32 healthy subjects and at the University of Ulster (one subject underwent training for at least 12 sessions). User testing was also conducted at TID (7 healthy subjects) and Cedar (5 subjects with brain injury). Although automation has been introduced to the ERD/S solution, the need for interaction with MATLAB introduced complexity for the intended operator (outside the laboratory).

The BRAIN system is complemented with an intuitive universal interface (IUI) that enables control of a range of existing applications. The IUI consists of two main components: the intuitive graphical **user Interface** (IGUI) and the universal application interface (UAI). The general architecture of the IGUI interface has stood the test of time throughout the lifetime of the project, allowing both flexibility and customisation for various paradigms. Versions of the IGUI have been produced for SSVEP and ERD/S allowing some degree of matching to the needs of both the paradigm and the user. Figure 3 shows an example of the IGUI screen customised for ERD/S using three mental tasks. The use of icons has provided a more aesthetically appealing interface, with enhanced usability. This has also provided the option for 'high level' communication of state (i.e., without a speller). For example a user can indicate frequent interactions, e.g. 'I am hungry'. This approach provides a good opportunity for further development and investigation. User interface tools have allowed experimentation (BCI Emulator) and usability testing to be conducted (BCI Catcher and BCI Accessibility).

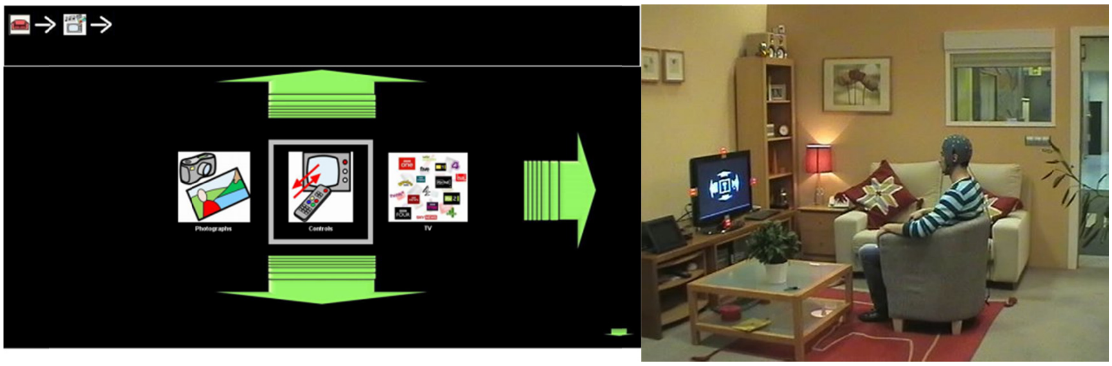

Figure 3 (a) ERD/S IGUI interface (b) Handling domotic devices with the SSVEP BCI at TID.

The UAI has provided the coupling between the IGUI and **applications**. Switching on/off lights, radio, fan etc. has demonstrated the utility of the approach, by using the X10 protocol. A media player application utilising UPnP technology within an OSGi environment allows for generalisation of media services on a large scale (e.g., a Smart Home development with many different media servers, clients and media sources). A more robust optimisation has been produced which provides more straightforward set up for smaller scale deployment (e.g., a single client with their own media library). Opportunities for dynamic update of IGUI media content have been built into the architecture, which thus provides protection against obsolescence. If the user's media library is updated the IGUI can learn this and potentially be updated.

As components of BRAIN have become available during the project, testing has occurred in host laboratories and where appropriate additional technical testing has taken place at University of Ulster. The individual paradigms of BRAIN (SSVEP, ERD/S) have been tested on a variety of user populations; healthy volunteer subjects at Telefonica and University of Ulster, healthy volunteers and patient groups at Cedar and the wider public at Hanover Fair (2010) and CeBIT (2011). The main achievement of BRAIN in **user testing** was to really engage with end users, i.e., people with disabilities within all parts of the research process. All BRAIN deliverables emphasise usability across a range of different users with disabilities and limitations. A critical factor of the development of the BRAIN BCI system was to move beyond the labs and work directly into the homes of people with a disability.

Knowledge was disseminated through several international conferences, workshops and academic publications (6 journal papers, 8 book chapters, 19 conference papers, 1 PhD thesis and 1 technical report). Tutorial lectures were given at five international conferences. Within the scope of the BRAIN project two high impact research studies with 86 and 71 subjects from volunteered visitors to the BRAIN booth were carried out at the International exhibition Hanover Fair in April 2010 and CeBIT in March 2011, respectively. The first study examined correlations among BCI performance, personal preferences, and different subject factors such as age or gender for two sets of SSVEP stimuli: one in the medium frequency range and another in the high frequency range. Results showed that most people, despite having no prior BCI experience, could use the SSVEP BCI system in a very noisy field setting. Moreover, demographic and other parameters did not have significant effect on the SSVEP performance. The second study demonstrated the control of a virtual maze using the ERD/S BCI system and evaluated the water-based electrodes together with the operation of the SSVEP BCI using again two set of frequencies: four pre-selected medium and four calibrated high frequencies using the Wizard. The BRAIN[1] public website has been available after month 6 of project commencement and has been updated to highlight the contributions of BRAIN to the state-of-the-art. Final versions of the TMSi acquisition module, ERD/S and SSVEP signal processing modules for BCI2000; the BCI Wizard; the BCI Trainer; the IGUI and UAI have been released as open source software under the General Public License (GPL) and are available for download via this website. The commercial exploitation of the BRAIN system will be led by TMSi, and the prospective launching of the system has been set for 2013. The envisaged system will include following components: the water based electrodes system, SSVEP evoked by high frequency flicker stimulation with phase tagging, a flexible visual stimulation appliance, the wizard software for automatic customization of the flicker stimulation, the IUI to interface the BCI with existing applications, and an open software platform for BCI development (OpenBCI). The latter is a complete software system for BCI developed by the University of Warsaw and inspired by BRAIN. This development will be demonstrated at the CeBIT 2012 in Germany.

[1] www.brain-project.org